

Joint Report

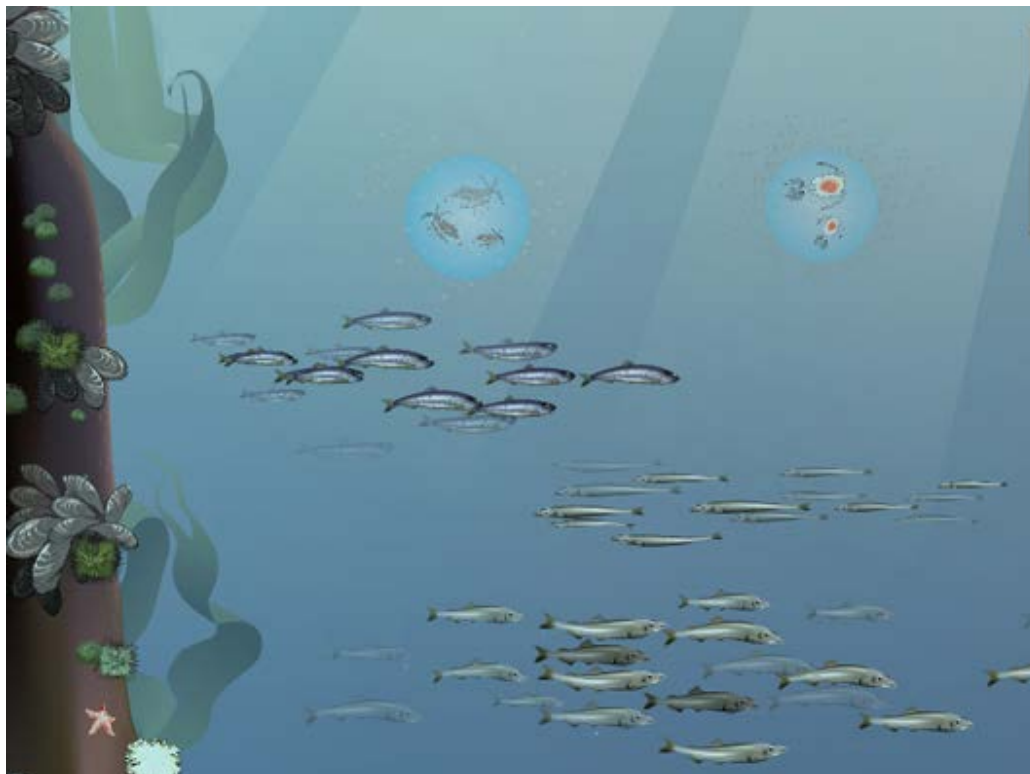
Impact and restitution model - Water column

ERA Acute for water column exposed organisms

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Water column
Exposure
Fish stock
Restitution

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ABSTRACT

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ERA Acute – water column compartment

Exposure to oil components in the water column in ERA Acute can be modelled using either of two alternative options in the oil spill model OSCAR. While the option based on the Critical Body Residue (CBR) takes changing oil properties/toxicities and exposure time into account and therefore represents a scientifically more valid approach, an alternative and more conservative option based on the modelled maximum total hydrocarbon (THC) concentrations over the whole water column is also described.

A global fish restitution model has been developed based on historical recruitment data, and demonstrating strong links between the climatic regime and natural fluctuations of fish stocks. Restitution modelling shows that as long as impact is assessed on the reproductive unit (spawning stock), even a major oil spill will not have a measurable effect on fish stocks. Higher risk may apply if fish larvae are considered representing a valuable resource in itself, e.g. as a planktonic food source of predating organisms, but this is not within the scope of this project.

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A global fish restitution model has been developed based on historical recruitment data, and demonstrating strong links between the climatic regime and natural fluctuations of fish stocks. Restitution modelling shows that as long as impact is assessed on the reproductive unit (spawning stock), even a major oil spill will not have a measurable effect on fish stocks. Higher risk may apply if fish larvae are considered representing a valuable resource in itself, e.g. as a planktonic food source of predating organisms, but this is not within the scope of this project.

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SINTEF F26670 QSAR in Environmental Risk Assessment

SINTEF F26671 Suggested OSCAR design for application with ERA Acute

EXECUTIVE SUMMARY

General objective

The objective of the ERA Acute project is to develop a globally applicable environmental risk assessment tool for acute oil spills. The tool employs two levels of detail for the impact calculation methodology:

1. **Level A** – a risk screening methodology to quantify potential impact in a defined area
2. **Level B** – a full risk assessment methodology quantifying the impact (magnitude and duration) for species and habitats.

ERA Acute uses results from an oil spill model (OSCAR) to calculate impact from exposure to the spilled oil in the compartments sea surface, shoreline, water column and sea floor. The oil spill model is run in stochastic mode to combine possible effects with a frequency for an effect in order to calculate environmental risk. Stochastic simulations allow for running of hundreds of simulations, each simulation calculating effects and each having a frequency within the ensemble.

While for Level A, the grid cell-based impact is summarised over all grid cells in the area of analysis, the impact calculations for Level B quantify both magnitude and impact duration, as defined by the calculated restitution time for the impacted species or habitat.

Impact in ERA Acute is calculated based on a continuous impact function (dose/response curve) rather than on fixed damage categories as in MIRA1.

Methodology

Common to all compartments is the following impact calculation:

$$Imp_{r,cell,sim} = p_{exp,r,cell,sim} \times p_{let,r,cell,sim} \times N_{r,cell} , \text{ with}$$

- r = the resource of interest, cell = each grid cell in the analysed area, sim = each (oil spill) simulation.
- p_{exp} - probability for exposure.
- p_{let} - probability for lethal effect from simulated exposure.
- N - resource unit (abundance of r).
 $N = 1$ if there are no resource data (Level A.1). The most sensitive resource is assumed to be everywhere.
 $N = 0$ or 1 if presence/no presence data (e.g. polygons of areas) (Level A.2) .
 $N = 0-1$ if fractions of a population, fraction of a "whole" valued resource etc., (the chosen resource unit) (Level A.3 and B).

ERA Acute level B incorporates restitution time into the impact equation and the impact is calculated as the integral of the time-dependent impact function (the sum of the geometric area) with:

$$Imp_{r,cell,sim} = \left(\frac{1}{2} t_{imp} + t_{lag} + \frac{1}{2} t_{res} \right) Imp_{r,cell,sim} , \text{ with}$$

- t_{imp} - impact time, defined as the time until full impact on the resource is achieved.
- t_{lag} - lag time, defined as time until growth- and reproduction-inhibiting factors (i.e. contamination) are reduced to a level at which restitution is possible.
- t_{res} - restitution time, defined as the time from restitution starts until the time when the affected population is assumed to be back at 99% of the pre-spill level.

¹ Metode for miljørettet risikoanalyse (2007),
<https://www.norskoljeoggass.no/PageFiles/6588/OLF%20veiledning%20MIRA%20revisjon%202007.pdf>

ERA Acute calculations for the water column compartment

The methodology for water column organisms is divided into two different approaches for the impact calculations. Although fish eggs and larvae have been identified as the most sensitive and relevant water column resources, due to their abundance across time and space, impact can in theory be calculated for any water column resource, and using both approaches, by adjusting the effect level and/or the dose-response curve. The developed restitution model is however specific for fish.

Oil in the water is transported in three dimensions while constantly changing its chemical properties as a result of weathering. While oil weathering is also relevant for the other ERA Acute compartments (sea floor, shoreline and sea surface), the effects are less pronounced in these compartments due to their two-dimensional nature and different transport regimes.

Thus, in addition to the complex and varying composition of oil, the main challenges for computing the impact of oil on water column organisms include the temporal variation in both chemical and physical properties of the oil, as well as temporal and spatial variations in oil concentrations due to dilution. During the course of the ERA Acute project (from EIF Acute in 2005 to ERA Acute phase 3 in 2013) it was therefore decided to include Critical Body Residue (CBR) calculations, with QSARs for toxicity as an integrated part of the oil spill model OSCAR, in addition to the "THC_{max}" approach.

This means that two alternative approaches for impact calculations in the water column are available:

- 1) The first approach ("THC_{max}") calculates the lethal impact from the maximum THC (total hydrocarbon concentrations) computed by the oil spill model in each cell, and using an effect level (LC₅) to parameterize a dose-response curve with a standard deviation (SD) of 0.32 as suggested by Nilsen *et al.* (2006) during EIF Acute. Oil composition and exposure time is not considered using this approach which calculates instant lethal effects in response to (potentially) toxic oil concentrations.
- 2) The second approach ("QSAR") computes time-dependent mortality of sensitive species (fish eggs and larvae, adult fish, corals and sponges) within OSCAR together with oil transport and fate via CBR and QSARs. A dose-response curve analogue to approach 1) is used to compute potential mortality in each grid cell.

It should be noted that the THC_{max} approach calculates mortalities using both the dissolved fraction ("aromatic fraction") and dispersed oil droplets ("alkane fraction"). Furthermore, THC concentrations reported by the OSCAR model represent the maximum concentration in the whole water column in each grid cell, from the sea surface to the seafloor. The QSAR approach, on the other hand, only considers the dissolved oil fraction, accounting for a total of 25 pseudo-components and their individual concentrations, with varying oil composition over time as a result of oil weathering.

ERA Acute calculations for the water column compartment will also be applied to seafloor organisms exposed through the water column, e.g. corals and sponges.

Impact calculations via THC_{max}

Calculating $Imp_{r,cell,sim}$ with the THC_{max} approach will include the following steps:

1. OSCAR modelling of a set of scenarios with different discharge rates and durations, each scenario having a specific probability.
The result of this step is a UTM grid in two dimensions for each simulation within the set of scenarios containing the maximum total hydrocarbon concentration in each grid cell.
2. ERA Acute software (ERA SW) will import the results from 1) and compute impact using the general function:

$$Imp_{r,cell,sim} = P_{exp,r,cell,sim} \times P_{let,r,cell,sim} \times N_{r,cell}$$

- a. The potential fraction killed (p_{let}) is computed from a dose-response curve with median value (LC50) = 193 ppb THC, effect level (LC5) = 58 ppb THC and SD 0.32, using a cumulative distribution function:

$$F(x) = \frac{1}{2} [1 + \operatorname{erf}(\frac{x-\mu}{SD\sqrt{2}})]$$
 with μ representing the median value (193 ppb THC), and erf representing the non-elementary Gauss error function.
- b. For water column organisms, p_{exp} is always = 1
- c. N represents the fraction of the resource in each grid cell

Impact calculations via QSAR

Calculating $\operatorname{Imp}_{r,cell,sim}$ with the QSAR approach will include the following steps:

1. Oil spill modelling of a set of scenarios, each set having a defined probability. In addition to transport and fate modelling, oil spill modelling will also include exposure modelling. Exposure modelling is by default parameterized for zooplankton but can be adapted via a sensitivity factor and different dose/response relationship ("slope") to other water column resources including fish eggs and larvae. Recommended values are given in section 9.1.

The result of this step is a UTM grid in two dimensions for each simulation within the set of scenarios containing p_{let} (probability of lethal effect) for each grid cell.

3. ERA Acute software (ERA SW) will import the results from 1) and compute impact using the general function:

$$\operatorname{Imp}_{r,cell,sim} = p_{exp,r,cell,sim} \times p_{let,r,cell,sim} \times N_{r,cell}$$

- a. For water column organisms, p_{exp} is always = 1
- b. N represents the fraction of the resource in each grid cell

Lag phase water column

The model does not take into account any lag phase as a result of an acute oil spill. The rationale is that (fish) spawning occurs with an annual cycle. The current model is thus based on the qualified assumption that no habitat will be lost as a result of an acute oil spill, i.e. oil levels in the water column will not affect choice of spawning area, spawning success, or survival of fish larvae, when fish spawn for the first time after an oil spill. The lag phase is thus by default set to zero for the water column ($t_{lag} = 0$).

Restitution modelling

Restitution modelling relies on the expected natural survival from the egg stage and up until recruitment. By recruitment we mean the age at which fish start appearing in groups and reach a size where they represent a viable target for the commercial fishery. For long-lived fish the recruitment age is typically 2-4 years (for Barents Sea cod it is 3 years), and for short-lived fish including capelin it is typically 1 year. Reasons for basing restitution modelling on natural survival up until recruitment are that more and better data are available for recruits than for younger stages, and also that recruitment represents a gateway for significant natural mortality in all fish stocks.

Thus impact on long-lived fish species, represented by Barents Sea cod, is calculated from natural survival from the egg stage until recruitment after 3 years, and based on historical recruitment data in the Barents Sea. The history shows strong links between climatic factors and recruitment success (in the Barents Sea and globally), and this is built into the model as a set of relative recruitment factors ("look-up tables"), defining the expected number of surviving recruits in three general climatic regimes. The

recruitment factors as well as the duration of a certain climatic regime are awarded different probabilities, again based on historical data from the Barents Sea, and representing the stochastic part of the model. There is hence no natural mortality rate of eggs and larvae that is used to calculate the real impact from an acute oil spill, but the model allows for a certain number of surviving recruits, and this number will be higher in a favourable than in an unfavourable climatic regime.

The global fish restitution model is programmed in Visual Basic and runs via a macro in Microsoft Excel, which is part of our delivery. A full algorithm programming guide is found in Appendix C.

Input data

The calculated total oil-induced impact (Imp_{total}) on fish eggs and larvae, representing the entire year class 0 of the analysed resource, serves as input data to the restitution model, which expresses impact on the reproductive unit (spawning stock). It makes no difference if Imp_{total} is calculated based on the QSAR or the THC_{max} approach, oil-induced impact on eggs and larvae is just a number representing the starting point for restitution modelling. Furthermore, restitution modelling can be performed with the same functionality and flexibility regardless of what approach is used to calculate impact on eggs and larvae (QSAR or THC_{max}).

To be able to run the model the user needs to define some basic parameters of population biology: Age at recruitment, age at first spawning, maximum age, and natural mortality of immature and mature fish. The latter does not include fishing-related mortality which, if wanted, is defined separately (see further down). We present these input data (“look-up tables”) for two model species; a general long-lived species, represented by Barents Sea cod (*Gadus morhua*), and a general short-lived species, represented by capelin (*Mallotus villosus*), however input data may need to be adjusted for other resources.

Critical density

We have explored critical density of fish stocks and present historical data from the Barents Sea showing that heavily exploited fish stocks (Barents Sea cod and Norwegian spring-spawning herring, *Clupea harengus*) are able to recover also from historically low levels. Described minimum levels go down to approximately 5% of the long term maximum stock size. Based on these data we suggest a global critical density of 5% of the long-term maximum, representing the “carrying capacity” of the resource. The parameter *Critical density* (default 5%) has been built into the model and expresses the threshold for when a direct relationship is modelled between the size of the spawning stock and recruitment:

If the analysed fish stock $>$ *Critical density*, the model calculates the expected recruitment as the long term average recruitment, i.e. recruitment is fully independent of the size of the spawning stock.

If the analysed fish stock $<$ *Critical density* (in this example: 5%), the model calculates the expected recruitment (E_{Recr}) as the long term average recruitment ($Recr_{average}$), multiplied by the current spawning stock ($SS_{current}$) divided by 5% of the long term average spawning stock: $E_{Recr} = Recr_{average} * (SS_{current}/0.05 * SS_{average})$.

Critical oil mortality and “gate model”

The parameter *Critical oil mortality* enables the user to choose the level of conservatism for impact modelling of acute oil spills. *Critical oil mortality* (in percentage) represents the threshold mortality of

eggs and larvae for which a proportionate relationship is calculated between killed larvae and reduced recruitment:

If $Imp_{total} < Critical\ oil\ mortality$, the model calculates impact using the “gate model” (see below), i.e. using modelled natural survival up until recruitment as a reference level against which oil impact on eggs and larvae is measured. This is the recommended and scientifically most valid approach.

If $Imp_{total} > Critical\ oil\ mortality$, the model calculates impact from a proportionate relationship between oil-induced mortality of larvae, and reduced recruitment (“one lost larvae results in one lost recruit”). If, for example, *Critical oil mortality* is set to 30%, any oil-induced impact on eggs and larvae >30% will reduce recruitment with the same percentage. This is a conservative approach similar to what is used in MIRA today.

The parameter *Critical oil mortality* therefore represents a user option for impact modelling “the old way” (e.g. MIRA) or using a scientifically more relevant approach.

We present literature data on natural mortality rates of early life stages of fish and calculate typical, natural mortality rates during egg and larval stages for a long-lived and a short-lived fish species, respectively. Based on this we recommend setting the parameter *Critical oil mortality* to 99% for all modelled species (i.e. for both short-lived and long-lived species).

The “gate model”, which is activated when $Imp_{total} < Critical\ oil\ mortality$, calculates impact based on natural survival from the egg stage and up until recruitment. Natural survival is calculated from a set of relative recruitment factors (“look-up tables”) defining the number of surviving recruits in three generalized climatic regimes. The “gate model” thus sets a limit for the number of recruits which will survive in a given climatic regime rather than imposing a mortality rate for early life stages. The relative recruitment factors are used differently when the model is run in stochastic and deterministic mode (see separate section below).

Stochastic / deterministic modelling

The model can be run in either stochastic or deterministic mode. Stochastic modelling take natural variation of fish stocks into account and thereby represents the scientifically most valid approach to express impact on fish. If the user finds it important to compare impact between different compartments on the same scale (expressed as the Resource Impact Factor, RIF), i.e. using a fixed stock level of 99% against which restitution is measured deterministic modelling is the preferred option.

In stochastic mode ($Clima=1$), natural survival from the egg stage and up until recruitment is calculated using a set of different relative recruitment factors and their individual probabilities. Recruitment factor e.g. 1.25 means that each spawning female will give rise to 1.25 recruits (with a certain probability).

The recruitment factors are linked to three generalized climatic regimes (“favourable”, “unfavourable” and “shift”). The climatic regimes “favourable” and “unfavourable” have an equal probability of 0.2 (20%) to last for 2, 3, 4, 5, or 6 years (and a 0% probability to last for 1, or >6 years). The climatic regime “shift” has by definition a duration of 1 year and is coupled to particularly high relative recruitment factors. In this regard, the climatic regime “shift” only applies when the climate shifts from unfavourable to favourable, not the other way around.

The different probabilities for each relative recruitment factor as well as for the duration of “favourable” and “unfavourable” climatic regimes thus represent the stochastic part of the model, with modelled durations and relative recruitment factors being picked from Monte Carlo simulations.

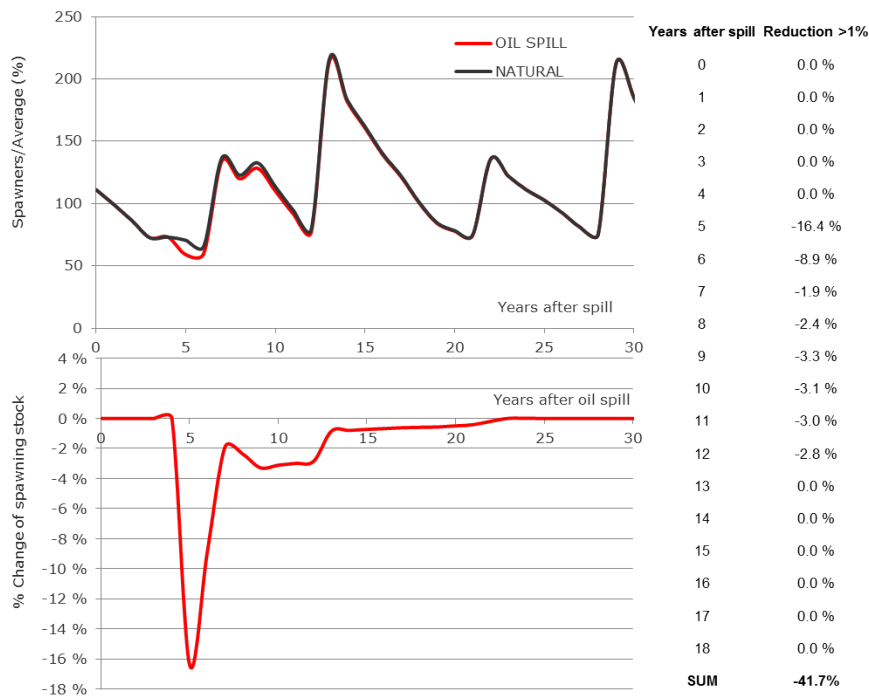
The relative recruitment factors (and their probabilities) incorporated into the model are based on extensive historical records from the Barents Sea, where recruitment success is linked to the extent of inflow of relatively warmer seawater into nursing areas of the southern Barents Sea. Different relative recruitment factors with different probabilities may apply to other parts of the world, however the general outline of the model with natural variation linked to stochastic changes of climatic parameters is globally applicable.

When the model is run in deterministic mode ($Clima=0$), natural variation of the fish stock related to climatic shifts is inactivated. As long as the modelled fish stock is at a level above the defined *Critical density*, recruitment is modelled as a fixed recruitment factor which has been normalized to 1.0 with probability 100%, and representing the long term average recruitment of the resource. In deterministic mode the model thus projects a reference level (“straight line”) of an undisturbed fish stock during the entire modelling period (default: 100 years post spill). For a modelled fish stock at a level below the defined *Critical density*, recruitment is modelled according to what is described above in section **Critical density**. Also in deterministic mode, the user can choose between impact modelling with or without “the gate model” activated (via the parameter *Critical oil mortality*).

Resource impact factor

The Resource Impact Factor (RIF) is expressed as *spawning stock reduction years* in percentage of the undisturbed state which is modelled in parallel to the impacted state. Based on the natural (undisturbed) state of the analysed fish stock, 99% of the undisturbed state is used as a threshold for the resource impact calculation. We have chosen 99% as threshold to enable comparison with other compartments using a restitution level 99% of the pre-spill level.

All years with a spawning stock reduction of at least 1%, compared with the undisturbed state, are thus summed up to give the overall impact on the resource, according to the example presented below for a long-lived species. In the example below, oil-induced impact of eggs and larvae was set to 95% and the parameter *Critical oil mortality* (see definition above) was set to 90%. The model has thus calculated impact on eggs and larvae as being proportionate to recruitment reduction (i.e. expected recruitment of the impacted year class was reduced by 95%). In this simulation the RIF is calculated to -41.7% *spawning stock reduction years*. It is worth underlining that the same oil-induced impact on eggs and larvae (95%) has no measurable impact on the spawning stock when *Critical oil mortality* is set to 99%, which is the recommended value (example not shown). In that case the model calculates impact using the “gate model”, i.e. based on relative recruitment factors related to the three defined climatic regimes.



The model generally demonstrates that, when a scientifically relevant value is set for the parameter *Critical oil mortality*, even an extreme, oil-induced mortality of eggs and larvae (99%) will not result in a measurable impact on adult fish (spawning stock). The rationale is that the overall natural mortality from the egg stage and up until recruitment is significantly higher than 99%

It should be noted that a restitution level of 99% does not represent a scientifically correct measure of restitution in a stochastic environment, where natural variation will oscillate with much higher amplitude than 1%. The scientifically recommended restitution level would be one corresponding to 2 SD of the long term average stock level and is hence a resource specific level. This is a possible improvement area of the model.

Fishing pressure

An added feature of the model is that the user can define the expected fishing pressure, expressed as the annual percentage of harvested immature and mature fish, respectively, during the entire modelling period following an acute oil spill (default: 100 years). Fishing pressure is added in the same spreadsheet as oil-induced mortality ("extra mortality"). In the example simulation above demonstrating how the RIF is calculated, the fishing pressure was set to zero during the entire modelling period (100 years) to highlight the impact from a thought oil spill in year 0.

Comparison with MIRA

In the table below, a comparison is made between the ERA Acute methodology and the damage-based fish risk assessment approach laid out in OLF (2008). Fish is not an integrated VEC in the MIRA methodology (OLF, 2007).

Subroutine	OLF (2008)	ERA Acute (phase III)
Impact	<ul style="list-style-type: none"> Global effect level for eggs and larvae based on toxicity data for the most sensitive, adult fish species (DNV GL approach): Based on maximum modelled concentration of THC in water column, with a linear function from LC₁ (100 ppb THC) to LC₁₀₀ (1000 ppb THC). Oil weathering / composition, and exposure time are not considered (conservative approach) 	<ul style="list-style-type: none"> Global effect level for eggs and larvae based on toxicity data for fish larvae and zooplankton THC_{max} approach: Based on maximum modelled concentration of THC in water column, with a continuous function from LC₅ (58 ppb THC) to LC₁₀₀. Oil weathering / composition, and exposure time are not considered (conservative approach) QSAR approach: Based on critical body residue, thereby taking oil weathering, oil composition, detoxification and exposure time into account
Lag phase	<ul style="list-style-type: none"> Not considered 	<ul style="list-style-type: none"> Not considered
Restitution	<ul style="list-style-type: none"> Three species-specific restitution models established; cod, herring, capelin (no flexibility) A rigid factor 10 in survival variation of fish larvae is built in to reflect natural variation (and hence climatic variations), based on average historical recruitment over a long time period, and resulting in different outcomes with different probabilities Assuming that larvae killed by an oil spill would have survived until first spawning Not possible to address impact from fishing Restitution time (in deterministic environment) defined as time until the stock is back at 99% of the pre-spill level Defined damage categories (minor/moderate/considerable/serious) based on predicted restitution time. The level of impact is not addressed 	<ul style="list-style-type: none"> Global restitution model with high level of flexibility regarding species Restitution modelling is based on natural survival from egg stage until recruitment, based on historical data from the Barents Sea. There is no natural mortality rate of eggs and larvae built in. Possible to model impact on fish stocks in stochastic and deterministic environment. In stochastic mode, relative recruitment is coupled to three general climatic regimes Possible to choose level of conservatism from the parameter <i>Critical oil mortality</i> (default 99%) Possible to set <i>critical density</i> level of assessed resource (default 5%) Possible to address impact from fishing Impact (in stochastic or deterministic environment) defined as the summed

		<p>up reduction for years displaying a spawning stock reduction of at least 1% (restitution level 99%), and expressed as <i>spawning stock reduction years</i> in percentage of an undisturbed stock</p> <ul style="list-style-type: none"> • No defined damage categories
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Conclusions

Exposure to oil components in the water column in ERA Acute can be modelled using either of two alternative options in the oil spill model OSCAR. While the option based on the Critical Body Residue (CBR) takes changing oil properties/toxicities and exposure time into account and therefore represents a scientifically more valid approach, an alternative and more conservative option based on the modelled maximum total hydrocarbon (THC) concentrations over the whole water column is also described.

A global fish restitution model has been developed based on historical recruitment data, and demonstrating strong links between the climatic regime and natural fluctuations of fish stocks. Restitution modelling shows that as long as impact is assessed on the reproductive unit (spawning stock), even a major oil spill will not have a measurable effect on fish stocks. Higher risk may apply if fish larvae are considered representing a valuable resource in itself, e.g. as a planktonic food source of predating organisms, but this is not within the scope of this project.

1 INTRODUCTION

ERA Acute uses results from an oil spill model to calculate impact from exposure to acute oil spills in four different compartments; sea surface, shoreline, water column and seafloor. The oil spill model is run in stochastic mode to combine the impact with a probability for the impact in order to calculate environmental risk.

The main challenges in computing the impact of crude oil on organisms in water, in addition to the complex composition of oil, is the temporal variation in both chemical and physical properties of the oil, as well as temporal variation in water column concentrations. In the following we describe how population loss can be predicted with the application of SINTEF's Oil Spill Contingency and Response (OSCAR) model based on Critical Body Residue calculations with QSARs for toxicity.

In order to cope with the extremely high number of individual oil compounds the OSCAR model uses 25 pseudo-components that represent groups of chemicals with similar properties. The partitioning of components between oil and water in time and space is calculated based on the physical and chemical properties of each pseudo-component and the effects of the physical environment.

The basis for the mortality predictions is the interaction between organisms and oil, and in the current version of OSCAR the exposure to oil in the water column is associated to the dissolved fraction only. The calculation of toxicity is based on acute effects assuming non-specific narcosis as the mode of action.

The LC_{50} for individual compounds contained in crude oil are derived from empirical data or extrapolated to compounds with unknown toxicity using a simple QSAR based on the octanol/water partitioning coefficient (K_{OW}) which may either be experimentally determined or estimated from chemical structure. LC_{50} are documented in Johansen (2005). K_{OW} are derived from K_{OC} values stored in the oil properties database (French, Reed, & Javko, 1996)².

² We are aware that this might add complications. The new version of the exposure model implements K_{OW} values consistent with the used LC_{50} values from the database.

2 IMPACT FROM ACUTE OIL SPILLS ON WATER COLUMN ORGANISMS VIA OSCAR METHODOLOGY FOR ESTIMATING LOSS OF INDIVIDUALS (LETHALITY)

Exposure in the water column is highly variable due to dilution and weathering processes, as well as uneven or patchy distributions of organisms in space and time. For this reason the methodology described here calculates a time-dependent body residue based on the time-varying exposure. Body residue is a parameter well suited for impact- and risk assessment of marine oil spills in the water column:

- Changing exposure can be calculated via realistic time integration (uptake kinetics).
- Body residue can be verified *in nature* through chemical analysis of biota and therefore verify model calculations (LC/EC₅₀ cannot).
- Body residue is linked to EC/LC-curves through known relationships.

SINTEF's OSCAR model in its current version (per today: MEMW7.0) can calculate body residue in organisms exposed to dissolved oil components in the water column in stochastic mode and relate it to a critical body residue for computing lethality.

2.1 QSARs for calculating EC/LC50

The proposed methodology requires that the oil spill model represents oil in the water column with a chemical profile that is sufficiently detailed so as to reflect changes in toxicology associated with changes in the composition of the water-accommodated fraction (WAF) over time. OSCAR, for example, represents oil using 25 pseudo-components, each representing a number of distinct but related chemical components in the oil (see (Johansen, 2005)). The present version of OSCAR (7.0) predicts the lethality of the average temperate pelagic crustacean. Toxicity is calculated via regressions based on empirical data for single non-polar oil components (non-polar narcosis) and phenols (polar narcosis). The origin of the data is from established databases and publications and the criteria for selection and subdivision is discussed elsewhere (Johansen, Nordtug, & Nilsen, 2005; Nilsen, Greiff Johansen, Nordtug, & Johansen, 2006). In general a regression is made for a defined group of animals (e.g. pelagic crustaceans or fish). Thus the line describing the regressions represents the median LC₅₀ as a function of K_{ow}. According to the basic theory of non-specific narcosis the LC₅₀ values should be expressed as molar concentrations. Components considered relevant for acute toxicity are those having a log K_{ow} below approx. 6 and are expected to be dissolved in the water phase to some extent. The currently used values are a dataset of quality assured and time corrected LC₅₀ values extracted from available databases and literature (Johansen, 2005).

2.2 Establishing critical body residue CBR

For narcotic chemicals the body concentration of an individual is related to acute effects and the Critical Body Residue (CBR). CBR is the body concentration that corresponds to 50% mortality. Thus, *CBR* is given from steady state equilibrium condition as

$$CBR_i = BCF_i \cdot LC_{50i} \quad (2-1)$$

For each pseudo-component i . The bio concentration factor (BCF) is related to K_{OW} and is found from established QSARs.

2.3 Temperature compensation

There is currently no compensation for temperature in the toxicity calculations. However, a compensation for temperature may be included in a sensitivity factor that is used to compensate for the sensitivity of different species (Figure 2-1).

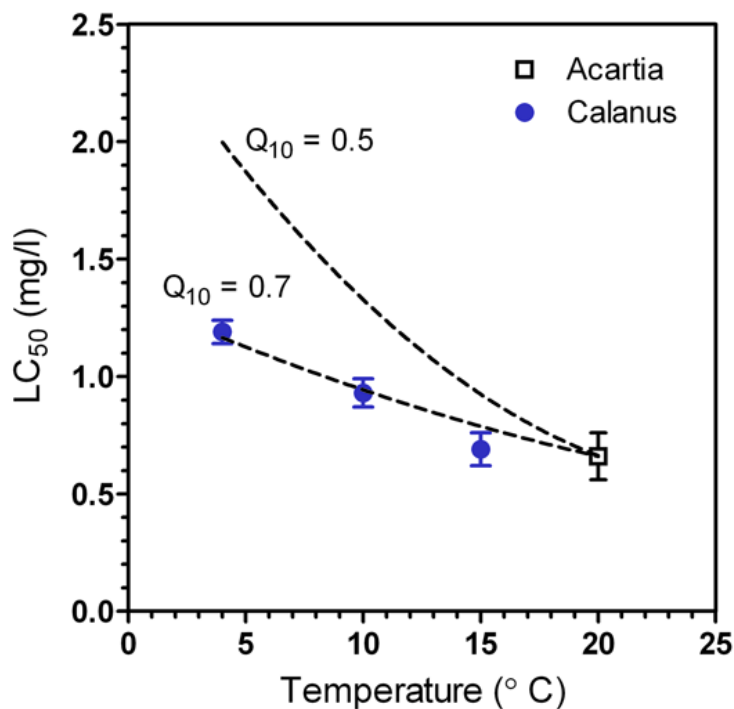


Figure 2-1 Toxicity of 3,5-dichlorophenol (DCP) using the standard *Acartia tonsa* test (ISO 14669:1999) and corresponding tests with *Calanus finmarchicus* acclimated and tested at different temperatures. Dashed line corresponds to different Q_{10} value of 0.5 as an example. Vertical bars indicate the 95% confidence interval (adapted from (Nordtug, Altin, Einarson, & Ystanes, 2007)).

The Q_{10} temperature coefficient is a measure of the rate of change of a biological or chemical system as a consequence of increasing the temperature by 10°C . We have previously shown that the sensitivity of the related arctic species *Calanus glacialis* tested at 2°C is lower than for *Calanus finmarchicus* tested at 10°C for selected oil component mixtures (Hansen, Altin, Rørvik, & Øverjordet, 2011). Some studies have used a Q_{10} compensation for LC_{50} of 0.33 (French-McCay, 2002). This corresponds to a 3-fold increase in LC_{50} at 10°C temperature reduction. When comparing the LC_{50} of *C. finmarchicus* acclimated and tested with 3,5-dichlorophenol at three temperatures in the range 4 to 15°C with the LC_{50} of *Acartia tonsa* tested at 20°C (Nordtug et al., 2007) the Q_{10} for LC_{50} (48 hours) in *C. finmarchicus* in the range 4 to 15°C was about 0.7. In Figure 1 these data are compared to *A. tonsa* LC_{50} assuming a Q_{10} of 0.5.

2.4 Body residue calculations

OSCAR represents oil as 25 pseudo components. For each of the 25 components and each computational time step OSCAR solves the equation:

$$\frac{dC_B}{dt} = k_1 C_A - k_2 C_B \quad (2-2)$$

or
$$\Delta C_B = (k_1 C_A - k_2 C_B) \Delta t \quad (2-3)$$

with

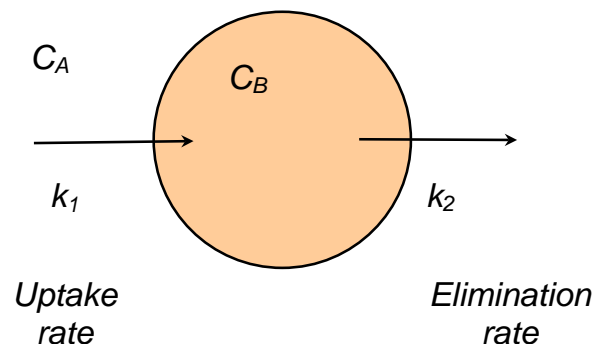
C_A = ambient concentration of the component

C_B = concentration in tissue (body residue) of the component

k_1 = uptake rate

k_2 = depuration rate

Δt = time step



From French-McCay (2002) the rate coefficients are given as:

$k_2 = a(K_{ow})^b$ with $a = 29.5$, $b = -0.414$ with k_2 in units 1/day. k_1 is calculated from the bio-concentration factor for the component:

$$k_1 = BCF \cdot k_2 \quad (2-4)$$

with a QSAR for the BCF, $BCF = \alpha(K_{ow})^\beta$ and $\alpha = 0.048$, $\beta = 1$ (from Mackay, 1982).

Calculating toxicity in the critical body residue model is based on acute toxicity data for different species exposed to single oil components. The most extensive data available are of zooplankton (pelagic crustaceans). These are the basis for the calculations made in OSCAR (LC₅₀ values available in oil properties database). Zooplankton also shows the highest sensitivity to oil components.

Exposure Calculation
 Standard deviation of response curve:
 Species sensitivity:

The exposure calculations themselves are species independent; since the LC_{50i} values are based on data for zooplankton the stochastic simulation setup for Exposure Calculations includes a sensitivity factor ("Species sensitivity"). The database LC_{50i} values will be divided by this factor, accounting for more (factor > 1) or less (factor < 1) sensitive organisms.

This sensitivity factor might also be used to account for temperature effects as described above or chronic effects by reducing the LC_{50}^i to an e.g. \overline{LC}_5^i for the components. Conservative approaches often use 10 as a sensitivity factor to calculate no observed effect concentration (NOEC) levels (like EIF calculations for produced water).

The CBR_{mix} for the current composition of pseudo-components is given by:

$$CBR_{mix} = \frac{C_B}{\sum \frac{C_{Bi}}{CBR_i}} \quad (2-5)$$

with C_B being the total body residue of all components and C_{Bi} and CBR_i the body residue and critical body residue for each component, respectively.

2.5 Mortality via concentration-effect relationships (dose response curves)

With a known critical body residue (CBR) the mortality at any given body residue (C_B) may be calculated from a concentration - effect or dose - response curve. In OSCAR it is assumed that the dose - response curve follows a log-normal distribution with a standard deviation equal to that of the dose response curve for lethal concentration (McCarty & Mackay, 1993, Nilsen et al., 2006).

The mortality P_{let} (potential "fraction killed") corresponding to the given body residue C_B is derived from a concentration - effect curve which is implemented as:

$$P_{let} = \Phi(x, 0, \sigma) \quad (2-6)$$

where Φ is the cumulative normal distribution with argument x , mean value 0 and standard deviation (SD) σ , $x = \log\left(\frac{C_B}{CBR}\right)$ or $\log\left(\sum \frac{C_{Bi}}{CBR_i}\right)$ and $\sigma = 0.32$ (Figure 2-3).

Smit et al. (2001) discussed standard deviations for dose-response curves in environmental risk assessment. Slopes for effect - concentration curves were determined for more than 300 test populations and showed an average of 0.65 corresponding to an EC_{50}/EC_5 ratio of 2.9. Median slopes for 96h test were significant steeper for fish and molluscs compared to those for algae and crustaceans.

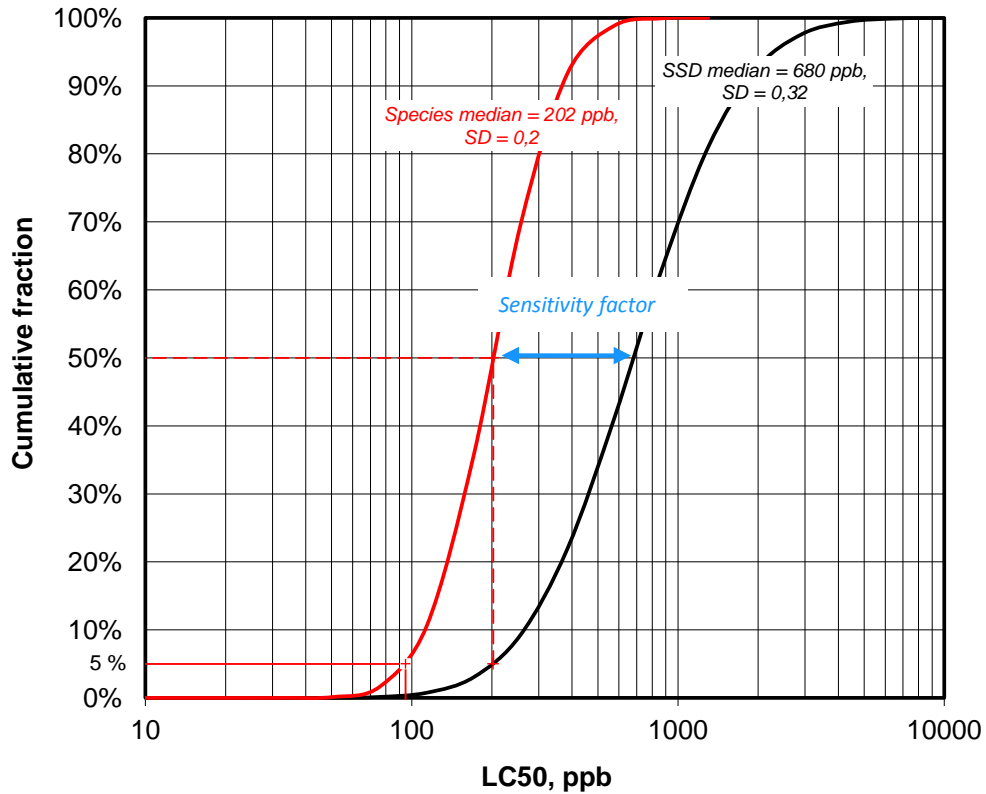


Figure 2-3 Theoretical example of a species sensitivity distribution (SSD) curve (black) and the dose response curve for a sensitive species (red) at the 5% level of the SSD-curve, equalling a sensitivity factor of 3.4 (680/202).

Mortality in the exposure calculations can only increase or be constant, i.e. after each time step t we have:

$$P = \text{Max}(P(t), P(t - 1))$$

3 IMPACT FROM ACUTE OIL SPILLS ON FISH LARVAE VIA THC CONCENTRATION LEVELS

3.1 Oil threshold level for lethal effects in fish larvae

In EIF produced water the PNEC_{water} for dispersed oil was calculated to 40.4 ppb THC from no observed effect concentrations (NOECs) obtained in chronic exposure experiments (Scholten *et al.*, 1993). This is a general effect level designed to ensure protection of 95% of all aquatic organisms worldwide by making use of an appropriate assessment factor (EU, 2003).

During EIF Acute, Nilsen *et al.* (2006) calculated a lethal effect level (LC₅) of 58 ppb THC for dispersed oil in sensitive species, represented by fish larvae. The effect level is extracted from a species sensitivity distribution (SSD) based on a dataset compiled by the National Research Council of the National Academies (2005), and using a standard deviation (SD) of 0.32. The SSD contains 24 different LC₅₀ data points obtained in laboratory experiments with various marine organisms exposed to crude oil with added dispersant. All data used for the SSD rely on measured rather than nominal exposure concentrations. The SSD has a median value of 650 ppb, thus considered a representative LC₅₀ for marine organisms exposed to dispersed oil. The concentration representing a lethal dose level to 5% of all marine organisms (193 ppb in the SSD) is considered representative of a sensitive species and used to construct a parallel dose/response curve with SD 0.32 and a median value of 193 ppb THC. The 5% effect level in this parallel effect curve (58 ppb THC) is then considered a representative LC₅ for sensitive water column organisms including fish eggs and larvae. The rationale for how the lethal effect level was identified in EIF Acute is shown in Figure 3-1.

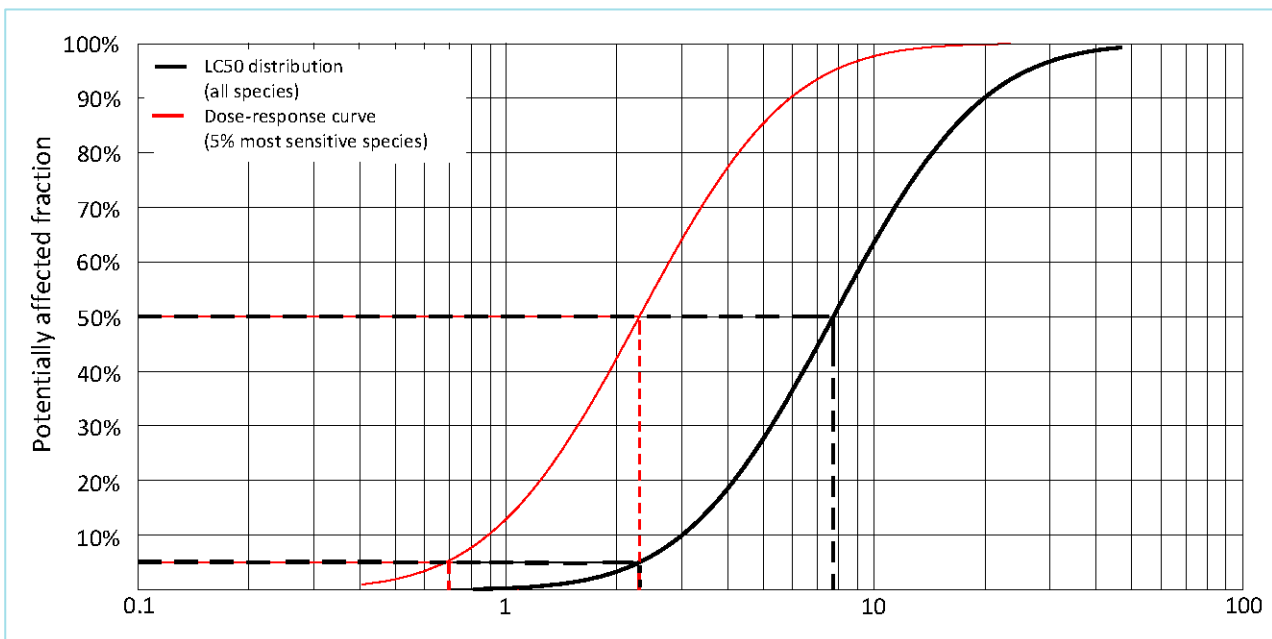


Figure 3-1 Principle sketch showing how the LC₅ effect level of dispersed oil was defined for water column organisms in EIF Acute (Nilsen *et al.*, 2006).

Smit *et al.* (2009) calculated an EC₅ for growth, reproduction and survival of marine organisms of 70.5 ppb THC based on laboratory experiments performed at IRIS (Norway). The dataset included organisms representing five different phyla (fish, crustaceans, polychaets, echinoderms and molluscs).

Vikebø *et al.* (2013) used 1 ppb total PAHs (TPAHs) as the lethal effect level (and 0.1 ppb TPAHs as the sublethal effect level) to simulate the impact on cod larvae from a major oil spill originating from various locations outside the Norwegian coast, and coinciding with the spawning season of Barents Sea cod (*Gadus morhua*).

An effect level expressed as TPAH will translate to different THC levels in different oil types, with different relative PAH contents. Table 3-1 shows measured PAH contents in four oil types produced on the NCS with densities ranging from 0.793 to 0.914 kg/L: Kristin Condensate, Oseberg Øst, Norne and Svale. Based on these representative oil types, the effect limits used by Vikebø *et al.* correspond to a THC concentration 92-200 ppb for lethal effects, and 9-20 ppb THC for sublethal effects. As a rule of thumb, light oils (represented by Kristin condensate) have a higher PAH content than heavy oils (represented by Svale oil), although Table 3-1 shows that there is no direct relationship between densities and PAH contents.

TPAH effect levels used by Vikebø *et al.* (2013) are largely based upon documentation from laboratory studies and field observations following the Exxon Valdez incident, demonstrating that the embryonic and larval stages of fish are particularly sensitive to PAHs (e.g. Carls & Meador, 2009). In weathered oils, the toxicity is primarily explained by the concentration of PAHs (Neff *et al.*, 2000).

Table 3-1 Total PAH content in representative oil types produced on the NCS.

Oil type	Density (kg/L)	Total PAHs (wt %)	Reference
Kristin condensate	0.793	1.09	SINTEF (2006)
Oseberg Øst	0.842	0.56	SINTEF (2012)
Norne blend	0.868	0.74	SINTEF (2010)
Svale	0.914	0.50	SINTEF (2010)

In a risk assessment of the impact on early life stages of Barents Sea cod and Norwegian spring-spawning herring (*Clupea harengus*) following an acute oil spill outside Lofoten, DNV & SINTEF (2010) calculated a lethal effect level (LC₅) of 0.74 ppb TPAH, based on a dose/response curve with SD 0.32 (with SD=0.2 the effect level was calculated to 1.19 ppb TPAH). The effect level is based on a literature study and exposure experiments with Balder oil performed by SINTEF on first-feeding cod larvae. In Balder oil (density 0.863 kg/L, TPAH content 0.67 wt.%) 0.74 ppb TPAH corresponds to a THC concentration of 110 ppb (DNV & SINTEF, 2010). A summary of proposed lethal effect levels cited above is found in Table 3-2, showing that alternative effect levels are in the range 40.4 - 200 ppb THC.

Table 3-2 THC lethal effect levels in fish larvae proposed in the literature.

Effect level (ppb THC)	Comment (calculation method)	Reference
40.4	PNEC _{water} (chronic NOEC/assessment factor)	Scholten <i>et al.</i> (1993)
58	LC ₅ for growth, development and mortality in marine organisms (SSD)	Nilsen <i>et al.</i> (2006)
70.5	EC ₅ for growth, development and mortality in marine organisms (SSD)	Smit <i>et al.</i> (2009)
≈92-200 (depending on PAH content)	Lethal effect level (LC ₅ ?) in early life stages of fish (Literature/estimate)	Vikebø <i>et al.</i> (2013)
110 ppb	LC ₅ for early life stages in fish calculated for Balder oil from effect level 0.74 ppb TPAH (Literature/experiments)	DNV & SINTEF (2010)

We propose to keep the lethal effect level (LC₅) in fish eggs and larvae developed in EIF Acute (Nilsen *et al.*, 2006) and defined to 58 ppb THC. One reason is that this effect level is on the conservative side and based on THC rather than TPAH, hence analogous with other ERA Acute compartments. However, the main reason for keeping this effect level is that it is not just a “threshold” but also accompanied with a dose-response curve with defined slope (SD 0.32).

3.2 Impact function for calculating *Plet*

The sensitivity variation of individuals within a test population is assumed to resemble a certain mathematical distribution. Sigmoid curves are obtained when effect (impact) is plotted against the logarithm of the test concentration (Finney, 1971). The slope of a dose/response curve resulting from a toxicity experiment is a measure of the variability of sensitivity between individuals within the test population, and hence directly related to the standard deviation (SD).

Plet in each simulation and each grid cell is given as a normal distribution function:

$$Plet = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{x - \mu}{SD\sqrt{2}} \right) \right] \quad (3-1)$$

Where x = the concentration in ppb related to the *Plet*; μ = the median value of the curve (193 ppb), SD = the standard deviation (0.32), and *erf* = the Gauss error function, which is a non-elementary function of sigmoid shape that describes diffusion.

Regarding the proposed standard deviation of the dose/response curve (SD 0.32), Smit *et al.* (2001) concluded that the slope is more related to the taxonomic group than to the theoretical mode of action of different groups of contaminants. For fish exposed to miscellaneous compounds (heavy metals, pesticides and petroleum hydrocarbons) they calculated SD to 0.34. This is similar to what was calculated by Nilsen *et al.* (2006) based on oil exposure experiments with added dispersants.

Impact on eggs and larvae in each grid cell (representing one year class of the entire population) is calculated from $Plet * N$, where N represents the fraction of the total number of eggs and larvae present in each grid cell. In the water column, the probability of exposure, P_{exp} , is always set to 1.

4 LAG PHASE

The model does not take into account any lag phase as a result of an acute oil spill. The rationale is that fish spawn with an annual cycle. The current model is thus based on the qualified assumption that no habitat will be lost as a result of an acute oil spill, i.e. oil levels in the water column will not affect choice of spawning area, spawning success, or survival of fish larvae, when fish spawn for the first time after an oil spill. The lag phase is thus zero for the water column.

5 RESTITUTION MODELLING

5.1 Natural variation of fish stocks

5.1.1 Background

The first important steps towards a scientific understanding of why fisheries show significant and seemingly unpredictable fluctuations were taken during the second part of the 19th century e.g. by Helland-Hansen & Nansen (1909) and Hjort (1914), and focusing on herring and cod. While the oceanographers believed that variations in physical parameters had great influence on the biological conditions of various fish species, and that temperature variations in the sea "are the primary cause of the great and hitherto unaccountable fluctuations in the fisheries" (Helland-Hansen & Nansen, 1909), the fish biologists believed that variation in year-class strength mainly results from changes in the availability of planktonic food for fish larvae after exhaustion of their yolk supply ("The Critical Period Hypothesis" proposed by Hjort, 1914). After more than 100 years of investigations of fish population dynamics, the conclusion is that recruitment is the result of many complex and interacting factors of both biological and oceanographic origin.

By "recruitment" we mean the aggregation of young fish (juveniles) in larger groups in the water column. Before recruitment, young fish are associated with nursery habitats and mainly feed from the seafloor, which depending on the species can be both in shallow (coastal) and deep waters. After recruitment, fish become available for commercial fishery and subject to stock assessment. The age at recruitment varies between different fish resources. For the model species "short-lived" (represented by capelin) and "long-lived" (represented by Barents Sea cod) age at recruitment is set to 1 and 3 years, respectively.

Already in 1918 the Danish fish biologist Petersen calculated that flatfish in the Kattegat consumed only 1-2% of the available biomass, while invertebrate predators, chiefly starfish, consumed the rest. Later investigations of marine stocks (herring, mackerel, cod, etc.) have added support to the idea that adult fish populations do not take advantage of the whole carrying capacity of their habitats. It thus seems that in most fish populations, recruitment is not sufficient to fill up the total vacant space available for the adult stock.

Furthermore, there appears to be no quota for the acceptance of recruits in good years. In many fish stocks, the total biomass can increase several fold from one year to the next when a strong year class is recruited. However, exceptionally strong year classes do not normally affect the growth and natural mortality of fish populations, again indicating that food supply and habitat are not limiting.

At the time of recruitment, the number of young fish is no longer correlated with the size of the parental stock. For example, the enormous year classes of Norwegian herring in 1904, 1950, 1959, and 1960 were not the results of large parental stocks. It is still an open question why the number of surviving offspring is independent of the size of the spawning stock. Thus, it is rather surprising that the abundance of the heavily exploited Barents Sea cod stock has returned to historical maximum levels in recent years, accompanied by habitat expansions eastwards and northwards in the Barents Sea.

With so many uncertainties at hand, the classical population models, which are successfully used to predict populations of marine mammals, cannot be directly applied to fish populations.

5.1.2 The critical period of fish larvae

Most fish populations of high abundance follow a similar life cycle:

- (1) Migration to the spawning area,
- (2) production of a large number of eggs which is far in excess of the final number of individuals surviving up to the age at recruitment and spawning,
- (3) migration to the feeding grounds, and
- (4) migration to the areas where the species stay inactive, usually at deep water during the winter months.

Each population has its own variant of this generalized scheme, but the consensus is that the most vulnerable period for disturbance, e.g. in relation to an acute oil spill, are the first months of the life cycle as eggs and larvae.

To survive, the hatched larvae need access to prey, not only immediately after the yolk sac is exhausted, but during the entire period when larvae drift with the currents. Although microalgae are often found in the guts of fish larvae in their first stages of active feeding, the young fish subsist on copepod nauplii (Lebour 1918a,b & 1919). However, the production cycle of copepods is variable in timing, in amplitude and in propagation (Colebrook, 1965) and since the spawning period of fish in temperate oceans is relatively fixed in time (Cushing, 1969), the access to nauplii may fluctuate significantly between years due to substantial inter-annual variability in the timing of the spring bloom at a given location (Sakshaug *et al.*, 2009).

Hjort (1914) proposed the “critical period” hypothesis in order to explain the huge variability in the abundance of the year classes of fish. When the yolk reserve is exhausted, the larvae must capture prey in the plankton and a successful “first feeding” is a prerequisite for survival. Thus, according to this hypothesis food limitation at the time of first feeding is the primary regulator of recruitment success. Hjort’s “critical period” concept was extended by Cushing (1975, 1990) who formulated the “match–mismatch” hypothesis, arguing that the timing of the production of fish larvae versus their prey organisms represents the major factor determining recruitment success (Figure 5-1).

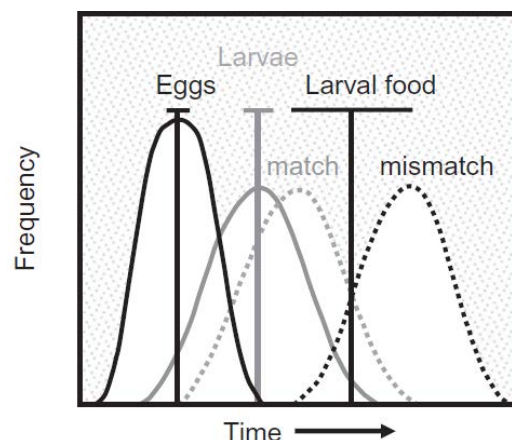


Figure 5-1. The “match–mismatch” hypothesis suggests that most of the variability in recruitment success can be related to the degree of temporal overlap between early feeding larvae and their prey. From Cushing (1990).

Even so, within the same region (e.g. Lofoten/Vesterålen), the timing of the spawning season varies little from year to year. Spawning starts early March, peaks in the first week of April, and terminates early May (Sundby & Bratland, 1987; Sundby & Nakken, 2008). This stability in spawning period has been interpreted as an indication that increased daylight is the main trigger for spawning in cod (Sundby & Nakken, 2008).

A number of additional hypotheses have been proposed, some based upon aspects of feeding, and others based on the importance of oceanographic processes. However, all recruitment hypotheses acknowledge the importance of larval fish encountering suitable prey (reviewed by Houde, 2008). Many fish biologists have argued that more emphasis should be put on the impacts of physical processes. The warming of surface waters and the strength of winds and associated mixing (micro-turbulence) have been considered as critical for larval survival (Lasker, 1978; Rothschild & Osborn, 1988; Cury & Roy, 1989). This incorporates the idea that important processes act on the individual level, such as thin layers of phyto- and zooplankton (e.g. Lasker, 1975). Other studies have focused on the importance of changes in ocean circulation to alterations in population structure, life cycle closure and recruitment success (Illes & Sinclair, 1982; Sinclair & Tremblay, 1984). Most of these different hypotheses were developed for particular marine fish species in specific regions. Leggett and Deblois (1994) reviewed different field studies to help understand processes acting during “critical periods”. In general, it is now thought that a variety of “integrative processes” determine recruitment success (Houde, 2008; Miller *et al.*, 1988).

Murphy (1961) pointed out that mortality by predation in most fish stocks will be independent of larval abundance because larvae make up only a minor part of the food supply for marine predators. In general, the larval stage is so short, and the larvae drift passively over such long distances that they will not alone supply a build-up of predator populations. Thus, the predatory mortality of larvae is determined by the number of predators present, by their feeding capacity, and by the ability of the larvae to avoid these predators. In many cases, years of high predator abundance are paralleled by rich food abundance for the fish larvae, and fish larvae often feed on the same planktonic resources as their predators. Thus, the early mass mortality in fish larvae due to starvation is likely to be relatively small in those years with high predatory abundance and pressure.

5.1.3 The impact of climatic factors

Climatic factors strongly affect year-to-year variations in growth rate during the early life stages of fish, e.g. Barents Sea cod larvae hatching in early May experience higher water temperatures and thus better growth conditions than those hatching earlier in the season. Based on field observations in Lofoten in 1983–1985, Ellertsen *et al.* (1987) found that the incubation period of cod eggs was 14 days shorter in the warmest versus the coldest year. Analogously, Langangen *et al.* (2013) reported that the egg stage duration in the same species was shorter in years with relatively higher water temperatures,.

Langangen *et al.* (2013) quantified the importance of temperature driven variability in egg stage duration for the cumulative survival of Barents Sea cod eggs. At higher temperature, egg stage duration is shorter and cumulative survival therefore higher (all else being equal). From a 35-year observational dataset on cod eggs at different developmental stages, they estimated that the instantaneous egg mortality rate was on average around 0.17/day, resulting in a cumulative survival of around 3% at the end of the egg stage (20 days duration). In effect, the cumulative survival was estimated to be three times higher in an exceptionally warm year (anomaly +1.10 C) compared with an exceptionally cold year. Further, there

was a nine-fold difference in cumulative egg stage survival among years (Langangen *et al.*, 2013). In comparison, cumulative survival through the larval stages (a period of 2 months or more) has been reported to vary 68-fold among years (Sundby *et al.*, 1989). In this context, Houde (1989) has demonstrated that growth and mortality rates in early life stages are not related to water temperature or latitude, generally speaking. There is hence no reason to believe that the cold climate makes Barents Sea cod and capelin any different than temperate or tropical fish species in terms of variations in natural mortality of early life stages.

Temperature-dependency has also been described for survival of larvae, e.g. Opdal *et al.* (2011) predicted 3-4x higher probability of survival in Barents Sea cod larvae originating from spawning grounds outside Møre and Romsdal, compared to larvae originating from Finnmark, as a result of exposure to warmer water.

Thus, in the Barents Sea relatively warmer conditions, associated with increased inflow of Atlantic water, are commonly considered to be necessary, but not sufficient for high survival and ultimately a strong cod year class (Sætersdal & Loeng, 1987; Ottersen & Loeng, 2000). Survival increases in warm years due to both direct temperature effects in terms of higher growth rates (Ottersen & Loeng, 2000), and indirect temperature effects in terms of greater food availability (Sysoeva & Degtereva, 1965).

Ottersen & Loeng (2000) showed that growth and survival of Barents Sea cod (as well as of haddock and herring in the Barents Sea) until reaching the age-0 stage, was positively correlated with temperature, and that the combination of abundance and mean length at the age-0 stage was a good predictor of recruitment.

The climatic variations in the Barents Sea depend mainly on the activity and properties of the inflowing Atlantic water (Midttun & Loeng, 1987). Climatic variations therefore can be recorded in cross sections of the Atlantic current. Figure 5-2 shows the temperature anomalies in the Kola section 1930-1988 based on data from Midttun *et al.* (1981) and Bochkov (1982). After 1945 the observations have been carried out on a monthly basis.

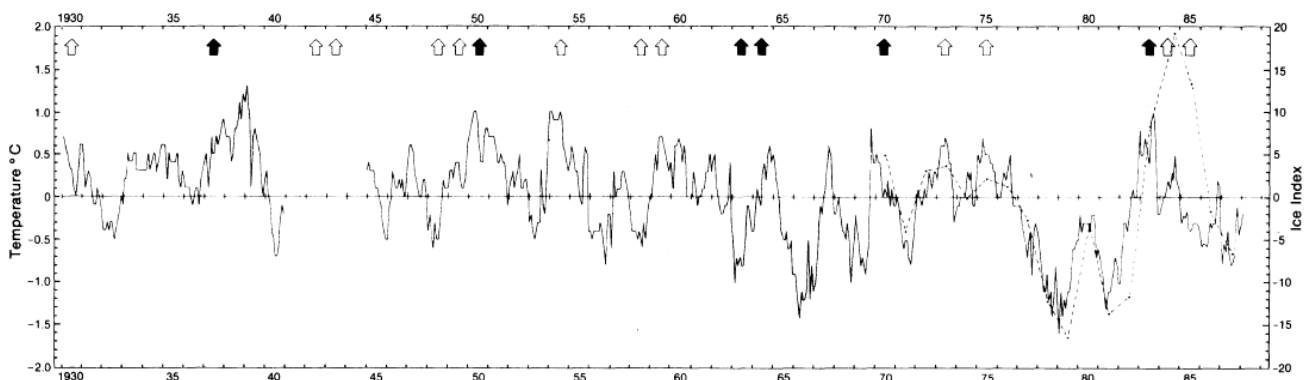


Figure 5-2 Temperature anomalies in the Kola-section (along 33.30° E) in the period 1930-88 (solid line) together with the ice index during the period 1970-88 (dashed line). Black arrows indicate years of high recruitment of Barents Sea cod, white arrows indicate years of medium recruitment, while years with no arrows indicate years with low recruitment. From Midttun *et al.*, 1981; Bochkov, 1982; Sætersdal & Loeng, 1987.

The intensity of Atlantic inflow to the Barents Sea also influences the geographical distribution of fish larvae. An easterly distribution of the 0-group of both cod and herring is probably caused by high activity of the Atlantic inflow as indicated by Randa (1984) and Mukhina *et al.* (1987). In both of these studies temperature was used as indicator but it is likely that years of stronger inflow of Atlantic water coincide with years of higher temperature. In relatively warm years, the favourable feeding areas for cod larvae in the Barents Sea are expanded towards the east (Sætersdal & Loeng, 1987). Furthermore, in the early part of a warm period, there will be fewer predators in this area, rendering the conditions in the eastern Barents Sea particularly favourable for 0-group cod.

Sætersdal & Loeng (1987) conducted a detailed analysis of the relationship between temperature and variations in recruitment of Barents Sea cod. They concluded that the major part of the years with high and medium recruitment are either associated directly with positive temperature anomalies in the early part of a warm period in the Barents Sea, or they occur immediately prior to a shift to a warmer regime. Referring back to Figure 5-2, the high recruitment in 1948 and 1958 are good examples of this. Figure 5-2 also shows that the strong recruitment of cod in 1963 and 1985 represent the only clear exceptions to a regime of increasing temperature, or positive temperature anomalies.

The results for the whole period 1902-87 is summarized in Table 5-1, showing that years with low relative recruitment are most frequent (66% of all years) and evenly distributed between cold and warm years. By "cold" and "warm" we refer to temperature anomalies in the Kola section in the period 1930-1988 (Figure 5-2), i.e. temperatures lower than the average are defined as "cold", while temperatures higher than the average are defined as "warm". Analogously, "low", "medium" and "high" recruitment refers to average recruitment 1902-1987.

From 1902 to 1987, medium recruitment have occurred twice as often in warm years than in cold years, while high recruitment have occurred 12 times more often in warm years than in cold years. If we take into account that each strong year-class on average corresponds to two medium, and ten weak year-classes (Saetersdal & Loeng, 1987), the influence of warm years on cod recruitment becomes even clearer. As an example, the mean production of Barents Sea cod during the warm period 1970-76 was 3-4 times higher than in the cold period 1977-82. In relation to climatic variations, high recruitment was observed in 1970 and 1983, while medium recruitment was observed in 1973, 1975, 1984 and 1985. During the prolonged cold period 1977-82, low recruitment was observed in all years.

Table 5-1 Relative recruitment of Barents Sea cod in relatively cold and warm years in the Barents Sea, 1902-87.

Temperature regime	Relative recruitment of cod (percentage occurrence)		
	Low	Medium	High
Cold years	35%	7%	1%
Warm years	31%	14%	12%

Since climatic variations are expressed on a large scale, it is plausible to assume that also other fish stocks spawning in the same area as cod are affected in a similar way. In fact, Dragesund (1971) and Sætersdal & Loeng (1987) identified several years of high, parallel recruitment in cod, haddock and

herring, thus providing convincing evidence of a close relationship between water temperature and survival of fish larvae. The favourable physical conditions seem to be related to increased heat transport in the Atlantic current (Sætersdal & Loeng, 1987; Mukhina *et al.*, 1987).

Refer to section 5.2.2 for a detailed introduction to how variations in climatic factors have been built into the model.

5.1.4 Natural mortality of early life stages of fish

For Barents Sea cod, Marshall *et al.* (2006) estimated a typical total number of eggs originating from the same Barents Sea cod population to 10^{14} in April. Average abundance of 4-5 months cod larvae in September has been reported to 7×10^{10} (Eriksen *et al.*, 2009), indicating a typical mortality rate in Barents Sea cod during egg and larval stages of 99.93%.

Each mature female capelin carries approximately 12,000 eggs (Huse & Gjøsæter, 1997). Based on a spawning stock of 300,000 tonnes with 50% females and an average fish weight of 25 g, a total number of capelin eggs of 7.2×10^{13} can be expected each spawning season (Bjarte Bogstad IMR, personal communication). The average number of 4-5 months capelin larvae in September is 2.2×10^{11} (Eriksen *et al.*, 2009), indicating a typical mortality rate in capelin during egg and larval stages of 99.7%.

These results show that typical mortality rates in pelagic spawners are well above 99% already at the end of the larval stage (4-5 months). For 0-group and juvenile fish, natural mortality continues to be high, or very high, however with strong fluctuations related to environmental factors as exemplified from the time series of recruitment of 3-year old Barents Sea cod in Figure 5-3.

Predation and starvation are the two ultimate causes for larval mortality in most stocks of marine fish. There is clear evidence that mortality rates rapidly decline with increasing body size (Peterson & Wroblewski, 1984). Thus, it is critical that marine fish larvae find good habitats for feeding and growth so that they can more rapidly move through the period of high predation pressure. A variety of studies have documented the inter-annual variability in the strength of selective mortality of slower, smaller individuals (e.g. Meekan & Fortier, 1996).

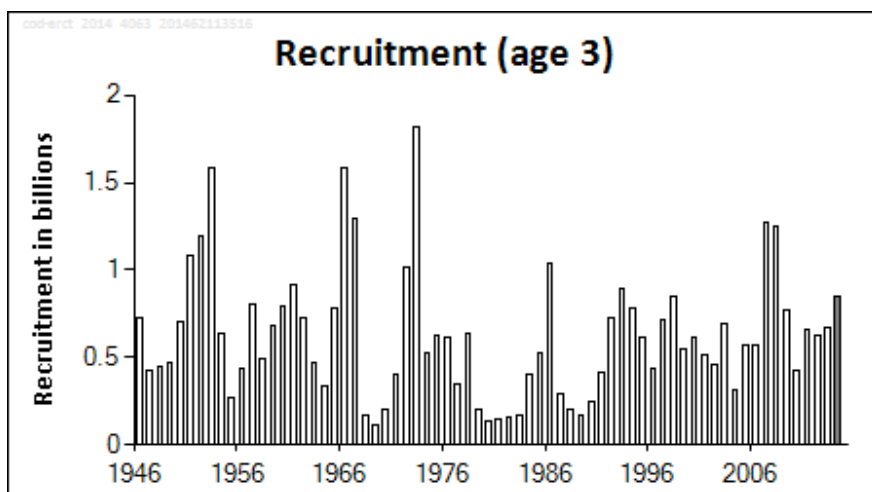


Figure 5-3 Recruitment (age 3) of Barents Sea cod in the period 1946-2013. Data from ICES (<http://ices.dk/marine-data/tools/Pages/stock-assessment-graphs.aspx>).

5.1.5 Stock recruitment curves

Theoretical models predict a quantitative relationship between the spawning population and the recruits (e.g., Ricker, 1954; Beverton & Holt, 1957; Murphy, 1961; Beverton, 1962). However, the stock–recruitment relationship in marine fish is usually weak (Hilborn & Walters, 1992; Koslow, 1992), and particularly the forecasting of recruitment remains a significant challenge (Houde, 2008).

In Barents Sea cod, there is no evident coupling between recruitment and the size of the spawning stock (Figure 5-4), and a large fraction of the inter-annual variability is apparently determined by other parameters (Ottersen & Sundby, 1995; Marshall *et al.*, 2000; Borisov *et al.*, 2006). This was noted already by Hjort (1914) who observed that in 1904, there were strong year classes of all the major fish stocks spawning along the coast of northern Norway (cod, haddock and herring), hence suggesting strong and simultaneous influence of some other factor(s) than the size of the spawning stock. At this time, the fish stocks were likely almost unaffected by the fisheries such that their egg production always was sufficient for stock recruitment.

Cushing (1990) pointed out that in most years recruitment is not sufficient to fill up the total vacant space available for the adult fish stock. Thus, recruitment to the adult stock seems to vary independently of the size of the parental stock, although the number of eggs spawned per season depends directly on the size and average age of the females in the parental stock.

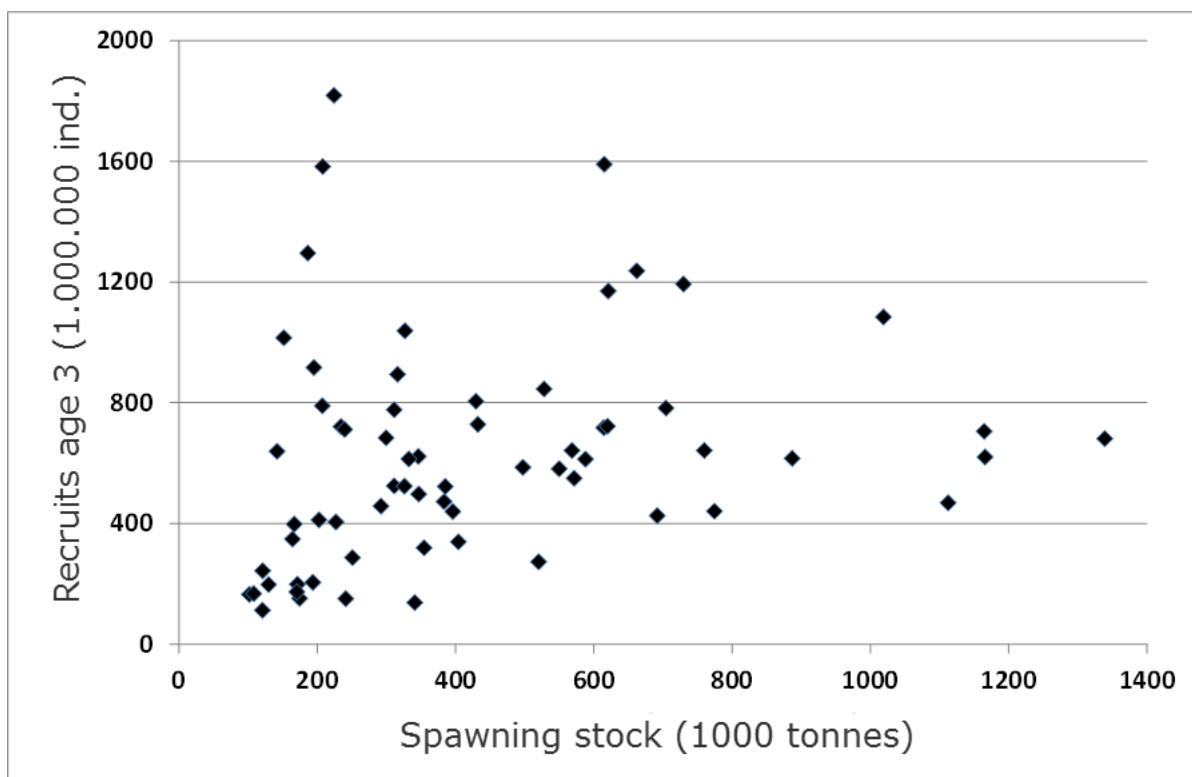


Figure 5-4 Recruitment (number of individuals at age 3) plotted against the spawning stock (biomass) of Barents Sea cod. For each data point, the X value represents “Spawners in year T” and the Y value represents “Recruits at time T+3 years”. Data from ICES (<http://ices.dk/marine-data/tools/Pages/stock-assessment-graphs.aspx>).

5.2 A global fish restitution model

5.2.1 Random and semi-stochastic components of the model

The previous chapter highlights the three major factors which have a profound influence on the survival of fish larvae:

- Access to prey after the yolk sac is exhausted,
- transport by currents to appropriate nursery habitats, and
- favourable climatic conditions in the nursery habitat.

For any fish population we may regard the recruitment as determined by a “gate” which permits only a given number of recruits to pass through. The opening of this gate, i.e. the number of individuals that survive up to the age of recruitment, fluctuates from year to year dependent on a number of parameters:

- (I) At the spawning area and during larval drift: a random component which represents (1) the match-mismatch at first-feeding, (2) the temperature at the spawning area, and (3) the strength of winds and associated mixing (micro-turbulence) along the path of the larval drift.
- (II) In the nursery area: a semi-stochastic, “quasi-cyclic” component representing (4) the climatic regime during larval drift, and (5) the climatic regime of the nursery habitat.

In the nursery habitat the strength of the year class is dependent on both the geographical distribution of the larvae, and the oceanographic conditions. However, it is important to emphasize that, eventually, all processes in the nursery habitat will result in survival of a given number of recruits. This is contrary to the intuitive notion that the processes will induce a specific and natural survival, or rather mortality rate.

The point is that the realized survival rate is equal to the number of recruits divided by the number of larvae surviving the first feeding stage. Since the success of the first-feeding period is stochastic (match-mismatch), it follows that the survival rate in the nursery habitat must necessarily vary from year to year, since the number of recruits is determined as an absolute, numeric quantity.

5.2.2 Modelling of climatic variations

As described in section 5.1, natural and “quasi-cyclic” climatic parameters have profound effects on fish recruitment and, therefore, need to be considered in the model.

Climatic variations can be modelled as a sequence of alternative periods with either favourable (+1) or unfavourable (-1) regimes. Favourable and unfavourable climatic regimes may be represented by different parameters in different parts of the world; temperature, wind, current, degree of upwelling etc. The point is that these parameters oscillate from favourable to unfavourable with a certain, semi-stochastic period which is a globally applicable phenomenon.

We start the simulation by a coin flip, i.e. a uniform distribution cut at the mid interval point (0.50) in order that each alternative (favourable & unfavourable) shall have the same probability of starting the long-term climatic cycle.

Suppose the first draw of the uniform variable is 0.47. Since 0.47 is less than 0.50, the temperature cycle starts with an unfavourable regime. The model input parameter describing this regime is defined $Clima(year\ 0) = u$ (u for unfavourable).

The next step is to determine the duration of this first unfavourable period. Based on historical data from the Barents Sea we set an equal probability of 20% for a climatic regime (favourable or unfavourable) to last 2, 3, 4, 5 or 6 years (Table 5-2).

Table 5-2 Probability distribution for the duration of the two general climatic regimes “favourable” and “unfavourable” when the effects of climatic variations are used in the model (stochastic modelling; $Clima=1$).

Duration of climatic regime (years)	2	3	4	5	6
Probability	0.2	0.2	0.2	0.2	0.2

To continue our example, suppose the random drawing from this distribution gives 3 years. Then $Clima(year\ 1) = u$ and $Clima(year\ 2) = u$. In addition we also know that the following year will be favourable, and since the previous regime was unfavourable, the regime shift is from unfavourable to favourable. This transition from unfavourable to favourable is of biological significance, so it will be marked with s (s for shift), rather than f (f for favourable): $Clima(year\ 3) = s$.

In order to find out how long this new favourable period will last, we have to draw randomly from the distribution above. Suppose we get 5 years, then $Clima(year\ 4) = Clima(year\ 5) = Clima(year\ 6) = Clima(year\ 7) = f$ (favourable). We then know that the next year will be unfavourable, so $Clima(year\ 8) = u$ (the regime “shift” is only relevant for a shift from unfavourable to favourable). Suppose this new unfavourable period lasts 4 years (obtained by random drawing from the same distribution). Then our simulated climatic cycle runs as follows for the first 12 years:

Year	1	2	3	4	5	6	7	8	9	10	11	12
Climatic regime	u	u	s	f	f	f	f	u	u	u	u	s

Continuing this way we obtain a climatic cycle of alternating unfavourable and favourable periods of random lengths. In order to check the realism of this way of modelling climatic cycles, a simulated cycle for the Barents Sea (Figure 5-5) can be compared with the observed temperature (as a proxy for the climatic regime) in the Kola section of the Barents Sea (Figure 5-2). It is seen that the two time series are similar, and the climatic model is therefore regarded realistic.

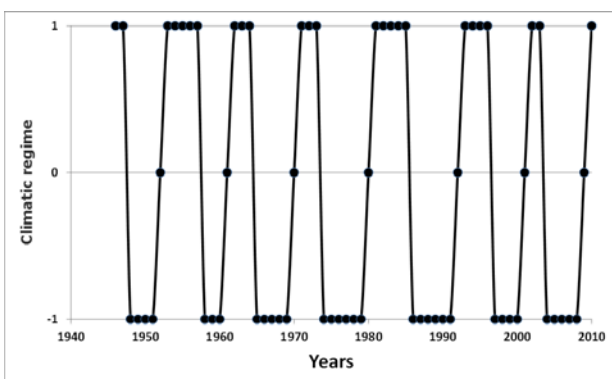


Figure 5-5 Simulated climatic regime in the Barents Sea 1946-2010.

5.2.2.1 Relative strength of recruitment

Having simulated the climatic cycle, the yearly, stochastic recruitment can be modelled as a variable with realistic co-variation with the climatic conditions. For each of the three climatic regimes (f, u, s), three independent variables are created to provide the relative strength of recruitment (Table 5-3). A relative recruitment of 1.0 means recruitment equal to the long term average for the analysed resource.

Table 5-3 is a “look-up table” that is essential for the ERA Acute SW to calculate impact on fish stocks in a stochastic environment. That is to say, the model calculates impact related to acute oil spills based on “natural survival” from the egg stage and up until recruitment, with age at recruitment depending on the analysed resource.

In deterministic mode, the model uses relative recruitment 1.0 (with 100% probability) and representing the long term recruitment of the resource.

The variables in Table 5-3 are based on historical data from the Barents Sea and can, unless other regional data are available, be adapted to all species globally. It is worth underlining that the relative recruitment factors are identical for long-lived and short-lived species. As mentioned previously, the governing climatic regime can be represented by different parameters in different oceans.

Table 5-3 Relative recruitment factors used as input data for impact modelling using climatic variations of fish stocks (stochastic modelling; $Clima=1$). Relative recruitment factors are based on historical data from the Barents Sea and defined for the three climatic regimes favourable (f), unfavourable (u) and shift from unfavourable to favourable regime.

Favourable regime (Clima = f)											
Relative recruitment	0.2	0.3	0.4	0.5	0.7	0.9	1.0	1.5	2.0	2.5	3.0
Probability weight	1	2	3	4	5	6	5	4	3	2	1
Unfavourable regime (Clima = u)											
Relative recruitment	0.05	0.10	0.25	0.50	0.70	0.80	1.00				
Probability weight	1	2	3	4	3	2	1				
Shift from unfavourable to favourable regime (Clima = s)											
Relative recruitment	2.5	5.0	10								
Probability weight	1	2	1								

5.2.3 Example calculations

The data series from the Barents Sea shows that two points are particularly important to take into account when developing the model:

- 1) The degree of natural fluctuation is very high and cannot be explained by fishing pressure alone.
- 2) The natural mortality rate of eggs and larvae is >99% and this must be considered when estimating the real impact of acute oil spills.

As shown in Figure 5-4 there is no direct relationship between the size of the spawning stock and recruitment. The reason is that the factors affecting recruitment represent a mixture of purely stochastic and semi-deterministic processes. We may therefore regard the whole recruitment process as a “gate” that each year allows a certain number of recruits to pass through. The width of this gate fluctuates from year to year in response to a combination of climatic and unknown, random oceanographic and biological factors. It is an important difference worth underlining that our model does not impose a certain mortality rate among the recruits but rather allows a certain number of recruits to pass through a “gate”.

This is to say, the basis for our restitution model is natural survival and not natural mortality, with varying degree of natural survival with varying environmental conditions, expressed as generalized climatic regimes (refer to section 5.2.2). The model encompasses natural survival during all stages from the egg stage and up until recruitment and uses this as a reference against which oil impact is calculated. As mentioned earlier, the age at recruitment will vary with species.

We will now perform example calculations using Barents Sea cod as an example. The functions below serve the sole purpose of demonstration and are for this reason not numbered. Assume that the “gate” on average admits a recruitment of $E(R)$ individuals of age 3. With an age at maturity of 8 years and an average survival s , which is a combination of natural mortality and fishery, the abundance of spawners corresponding to an average recruitment of $E(R)$ is:

$$E(S) = [E(R) * s^{8-3}] + [E(R) * s^{9-3}] + [E(R) * s^{10-3}] + \dots + [E(R) * s^{25-3}]$$

Summing the power series gives:

$$E(S) = E(R) * s^5 * (1-s^{18}/1-s)$$

We let E represent the average number of eggs spawned by an average female adult (a randomly chosen female). With a sex ratio of 1:1, the number of eggs spawned by the entire spawning stock each year will on average be:

$$E(\text{eggs/spawning stock}) = \frac{1}{2} * E(R) * s^5 * (1-s^{18}/1-s) * E(\text{eggs/female})$$

Since only $E(R)$ survive up to three years, the average survival from egg to recruitment is:

$$E(S_{ER}) = E(R)/E(\text{eggs/spawning stock}) = 2 * (1-s) / [s^5 * (1-s^{18}) * E(\text{eggs/female})]$$

where S_{ER} represents survival (S) from the egg stage (E) to recruitment (R) at age 3 (representative for a long-lived fish species).

The corresponding average mortality from egg to recruitment is:

$$E(M_{ER}) = 1-E(S_{ER})$$

Substituting $s = 0.7$ and 4,000,000 eggs per female (representing a long-lived species) renders an average survival of:

$$E(S_{ER}) = 0.0000009$$

This example illustrates that the natural mortality rate from the egg stage and up until recruitment is:

$$E(M_{ER}) = 0.9999991$$

In order to investigate the sensitivity of the chosen parameters, let us use some representative values for a small and short-lived species (e.g. capelin, sardine and anchovy). Substituting $s = 0.5$ and 10,000 eggs per female (representing a short-lived species) gives a survival rate of:

$$E(S_{ER}) = 0.0032$$

Corresponding to a mortality rate from the egg stage and up until recruitment of:

$$E(M_{ER}) = 0.9968$$

The mortality factors used above (0.7 and 0.5 combined for natural mortality and fishery) are representative for a long-lived and short-lived species, respectively. Depending on fishing pressure and data availability other numbers may need to be used for other species.

Taking into account that the young stages are affected by a lot of biological factors (predation, hunting success, etc.) and oceanographic factors (temperature, stratification, upwelling, turbulence, changes in direction and force of current systems, etc.) which induce unequal mortality rates at different stages in the development, we may split the mortality causes into two broad groups:

- (1) All factors regulating the success of first feeding larvae (i.e. the match-mismatch process), and
- (2) all factors regulating the suitability of the nursery grounds (i.e. the processes which ultimately determine the number of larvae that survive the first years).

Without any further knowledge, the best option is to split the survival into two equal parts; that is, the survival upon first feeding after the yolk sac is exhausted, and the survival in the nursery habitats. Thus the chance of surviving each of these stages will approximately be:

$$\sqrt{E(S_{ER})} = \sqrt{2(1-s)} / [\sqrt{s^5} * (1-s^{18}) * E(\text{eggs/female})]$$

Our two numerical examples render two alternative survival rates (S_{ER}):

- | | |
|---------|--|
| 0.00095 | for $s = 0.7$ and 4,000,000 eggs per female, and |
| 0.05657 | for $s = 0.5$ and 10,000 eggs per female. |

The prevailing conditions on the nursery grounds however put a limit to the number of larvae which may be sustained, representing the "gate concept". On average this number is precisely the expected recruitment $E(R)$. This means that the gate specifies the number of surviving larvae rather than inducing a mortality rate.

Let us consider an oil spill inducing an added mortality rate $M_{oil} = 50\%$ of all larvae originating from one fish stock. From an initial egg abundance of E (Eggs/spawning stock), the number of individuals surviving the first phase (match-mismatch) will then be:

$$E(L_1) = E(\text{eggs/spawning stock}) * \sqrt{E(S_{ER})} * (1-M_{oil})$$

The number surviving the second phase (nursery grounds) will be E(R) whatever the value of E(L₁), provided E(L₁) > E(R).

This is an important point in the model and worth underlining: in most situations, the number of surviving individuals E(R) is not likely to be equal to E(L₁) multiplied by some survival parameter representing the “gate”. As mentioned earlier, the model does not include a survival rate because the “gate” determines an absolute number of recruits.

This may be illustrated as follows: For a given oil spill, the survival rate during the second phase is E(R)/E(L₁), or expressed differently:

$$\sqrt{E(S_{ER})} / (1-M_{oil}) = \sqrt{2(1-s)} / [\sqrt{s^5} * (1-s^{18}) * E(\text{eggs/female})] * 1(1-M_{oil})$$

This expression gives the probability of larval survival during the second phase (nursery grounds) after an oil spill killing 100% of all larvae, i.e. M_{oil} = 1. Since the result of the second phase is to allow a fixed number of larvae to survive, the corresponding survival rate will naturally depend on the number of larvae entering the second phase. Thus, removing a fraction of M_{oil} will increase the probability of survival for the other larvae by:

$$1/(1-M_{oil})$$

Let us look at our two examples with an oil-induced mortality of fish larvae of 50%, i.e. M_{oil} = 0.5.

The survival rates of the second phase following 50% oil-induced mortality is:

- 0.00189 for s = 0.7 and 4,000,000 eggs per female (“cod”)
- 0.11314 for s = 0.5 and 10,000 eggs per female (“capelin”)

It is worth noting that the adjusted survival rates following an oil spill are still very low. Since the dynamics is to achieve a fixed number of recruits, the natural mortality during the second phase drops accordingly following an oil-induced mortality of 50%:

- from 0.99905 to 0.99811 for s = 0.7 and 4,000,000 eggs per female (“cod”)
- from 0.94343 to 0.88686 for s = 0.5 and 10,000 eggs per female (“capelin”)

In other words, the added, oil-induced mortality of 50% results in a decrease in natural mortality of:

- 0.1% for s = 0.7 and 4,000,000 eggs per female (“cod”)
- 6% for s = 0.5 and 10,000 eggs per female (“capelin”)

5.2.4 Mortality of fish larvae in large oil spills

Vikebø et al. (2013) predicted an overlap between Barents Sea cod larvae and lethal oil concentrations (effect level 1 ppb TPAH) in the range 0.4% to 9.9% for simulated oil blowout scenarios at various locations off the Norwegian coast (from Haltenbanken in the south to Lofoten in the north). The predictions were based on blowout duration 30 days; from April 1st to April 30th and thus representing an almost complete timely overlap with the spawning season of Barents Sea cod. By taking vertical

migration of larvae into account, the overlap was smaller (0.1 - 6.9% of all larvae in a worst case release scenario of 4500 m³ crude oil/day).

The western population of Atlantic bluefin tuna (*Thunnus thynnus*) has only one described spawning area which is located in the northern/north-western Gulf of Mexico. The uncontrolled blowout following the Macondo incident in 2010 overlapped in time and space with the spawning season of Atlantic bluefin tuna (May-June). Based on overlap analysis between surface oil and larval drift, Muhling et al. (2012) predicted that less than 12% of the larvae were located in waters with potentially toxic oil concentrations, on a weekly basis. They concluded that this is well within the natural variation of survival and that the Macondo incident will not have any measurable effect on the spawning stock.

The studies of Vikebø et al. (2013) and Muhling et al. (2012) may serve as a benchmark of a worst possible impact on fish stocks from acute oil spills. An uncontrolled blowout of petroleum hydrocarbons, overlapping with important spawning grounds in time and space, can be expected to impact up to approximately 10% of all larvae representing age class 0. According to the example calculation performed on cod and capelin above this will have no measurable effect on recruitment.

5.2.5 Critical level of the spawning stock

Section 5.2.3 showed that the number of eggs produced by each spawning female is so large that the total number of larvae produced by the spawning stock will be in great excess of the surviving recruits. We have also shown that no relationship can be established between recruitment and the size of the spawning stock, and that a small relative number of spawners can produce very strong year classes (Figure 5-4). In the Barents Sea cod population strong year classes have been produced when the spawning stock has been down to 10% of its long-term maximum level ("carrying capacity"). Below this level, measures should be taken with regard to the fisheries, but not necessarily with regard to the petroleum industry.

The calculation examples in the previous section clearly demonstrate that also for low abundances of the spawning stock, the egg production would still sustain extra, oil-related mortality of 10% of all larvae, corresponding to a worst-case impact (see previous section).

There are good indications that a spawning stock at approximately 5% of its carrying capacity has a considerable growth potential (Hamre 1990 & 1994). Figure 5-6 shows that when the Barents Sea cod stock was at such low levels it could still sustain fishing, which causes a mortality rate far in excess of what an oil spill may impose (on eggs/larvae). Under favourable environmental conditions, a fish population may exhibit high growth rates seemingly regardless of its relative strength. For example, the spawning biomass of the Barents Sea cod increased from about 250,000 tonnes in the year 2000, to record high levels (since the 1940's) approaching 2,000,000 tonnes in recent years (Figure 5-6). This represents an eight-fold increment of the biomass in 12 years and clearly indicates that even at low population levels a huge surplus of larvae is produced.

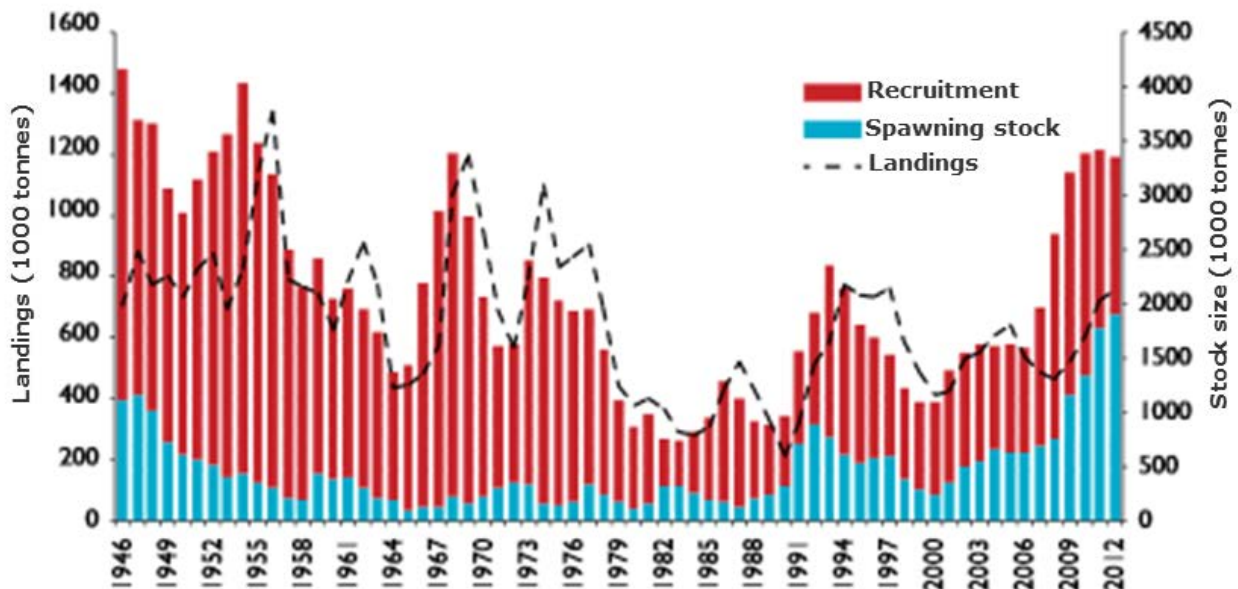


Figure 5-6 Stock assessments and catch records for the Barents Sea cod population 1946-2012. Recruitment in 1000 tonnes (red bars), spawning stock in 1000 tonnes (blue bars), and annual landings in 1000 tonnes (dashed line). Data from ICES (<http://ices.dk/marine-data/tools/Pages/stock-assessment-graphs.aspx>).

Based on the above, we suggest a general and global critical population size to 5% of the carrying capacity of a species, where carrying capacity is defined as the highest historical record available for the species in question. The 5% threshold is considered conservative because history shows that fish stocks will recover from such low levels, and also that recovery can be swift given beneficial environmental conditions.

5.2.6 Fish population model

We shall follow a cohort starting with a recruitment of 1000 individuals, that is $E(R) = 1000$. The relative recruitment strength (Table 5-3) is a factor that modifies the expected recruitment, and thus a relative recruitment (Rel. Recr.) of 0.5 means that the number of recruits in that year is $0.5 \cdot 1000 = 500$. The probability weight (Prob weight) gives the relative probability for each modification factor. For example, the sum of all probability weights under a favourable climatic regime is:

$$\text{Sum Prob weight} = 1+2+3+4+5+6+5+4+3+2+1 = 36$$

In a favourable climatic regime, the probability of obtaining a recruitment of 500 (Rel. Recr. = 0.50) is according to Table 5-3 $4/36 = 0.111$; that is, in 11.1% of the years with a favourable climatic regime, the model predicts a recruitment of 500. In this way we obtain a series of relative recruitment W_1, W_2, \dots

The reason for denoting these quantities by W (Weights) rather than by R (Recruitment) is that the W 's must be calibrated such that their average value becomes 1. This is because the average recruitment must be $E(R) = 1000$ and the W 's are multiplication factors. Thus if the expected lengths of the unfavourable and favourable periods are denoted respectively $E(L)_{\text{unfavourable}}$ and $E(L)_{\text{favourable}}$, the long term probabilities of the three climatic regimes unfavourable, shift and favourable to occur are:

$$P_{\text{unfavourable}} = E(L)_{\text{unfavourable}} / [E(L)_{\text{unfavourable}} + E(L)_{\text{favourable}}]$$

$$P_{\text{shift}} = 1 / [E(L)_{\text{unfavourable}} + E(L)_{\text{favourable}}]$$

$$P_{\text{favourable}} = [E(L)_{\text{favourable}} - 1] / [E(L)_{\text{unfavourable}} + E(L)_{\text{favourable}}]$$

We define the expected recruitment modification in the three climatic regimes $E(W)_{\text{unfavourable}}$, $E(W)_{\text{shift}}$ and $E(W)_{\text{favourable}}$, respectively.

We finally obtain the following function for the expected value of the recruitment modification in a randomly chosen year:

$$E(W) = [P_{\text{unfavourable}} * E(W)_{\text{unfavourable}}] + [P_{\text{shift}} * E(W)_{\text{shift}}] + [P_{\text{favourable}} * E(W)_{\text{favourable}}]$$

The simulated recruitment is finally calculated as:

$$R_1 = 1000 * [W_1 / E(W)], R_2 = 1000 * [W_2 / E(W)], \dots, R_k = 1000 * [W_k / E(W)]$$

The remaining and final task is then to define the population model. We let X_t represent the number of spawning adults in year t . We denote the average abundance of the spawning stock by $E(X)$. In order to establish an iteration equation we need three parameters:

- Annual natural mortality in percentage (m),
- age at recruitment (t_r), and
- age at sexual maturity (t_m).

For the two fish model “long-lived” (represented by Barents Sea cod) and “short-lived” (represented by capelin), the necessary input data, including the maximum age of, respectively, a representative long-lived and short-lived fish species, are summarized in Table 5-4.

Table 5-4 Model input data for the two fish model species (“long-lived” and “short-lived”).

Parameter	Long-lived species	Short-lived species
Annual natural mortality of immatures (%)	20	40
Annual natural mortality of matures (%)	20	40
Age at recruitment	3	1
Age at first spawning	8	5
Maximum age	25	5

On average, the number of first year spawners is:

$$E(R) * [(1-m)^{t_m-t_r}],$$

and average, natural mortality of adults is:

$$X * m$$

In the long run the gain and loss of individuals must balance each other:

$$E(R) * [(1-m)^{t_m-t_r}] = E(X) * m$$

The average abundance of adults corresponding to an average number of $E(R)$ recruits is therefore:

$$E(X) = E(R) * [(1-m)^{tm-tr} / m]$$

Because of the stochastic nature of recruitment, the abundance of the spawning stock will fluctuate around this expected number of spawners according to the iteration equation:

$$X_{t+1} = [X_t * (1-m)] + [R_{t+1-(tm-tr)}] * [(1-m)^{tm-tr}]$$

Refer to Appendix C for a full algorithm programming guide containing 333 functions and interdependencies. The full model, with all functions described throughout chapter 5, has been programmed in Visual Basic and runs via a macro in Microsoft Excel, which is part of our delivery.

5.2.7 Calculating the Resource Impact Factor (RIF) & example simulations

We have produced a global fish restitution model which links high natural mortality of early life stages with natural variation using age at recruitment. The reason for using recruitment as the baseline for calculating impact is that stock assessment data depart from the age at recruitment when fish become available for the fishing industry.

Based on historical data from Barents Sea fish resources natural variations are coupled to a climatic model, with relative recruitment specified for “favourable”, “unfavourable” and “shifting” climatic regimes. It is worthwhile underlining that all fish stocks globally demonstrate significant fluctuations that can be linked to climatic factors, with survival of young stages depending on one or several stochastic parameters. Although the actual recruitment factors and their probabilities may be slightly different in other oceans, the concept of recruitment being linked to stochastic changes in the environment, expressed by climatic regimes, is globally applicable.

The model produces projections for a period of 100 years (default) following an acute oil spill. Two parallel projections, with and without (“natural”) oil spill are produced. The model can either be run in stochastic mode, with relative recruitment linked to climatic regimes, or in deterministic mode, with relative recruitment represented by the long-term average recruitment which is normalized in the model to 1.0, with 100% probability.

To demonstrate how the Resource Impact Factor (RIF) is calculated in compartment water column, two example simulations are shown in Figure 5-7 (“long-lived species”) and Figure 5-8 (“short-lived species”). It is however important to underline that the results in terms of calculated impact are based on very conservative assumptions. According to what has been outlined in previous sections of the report, the model shows that even an extreme and unlikely oil spill killing off 95% of all larvae representing year class 0 of a resource, does not result on a measurable impact on adult fish (spawning stock). This is true as long as impact is calculated using “the gate model”, i.e. by taking high natural mortality during early life stages (from the egg stage through recruitment) into account, and expressed by relative recruitment factors. In the simulations shown below, oil-induced impact on eggs and larvae is conservatively calculated as being proportionate to recruitment reduction: “one killed larvae equals one killed recruit”, analogously with how impact is calculated in MIRA (see section 8). The model parameter enabling impact calculation in this way is the *Critical oil mortality*:

if $Imp_{total} > Critical\ oil\ mortality$, impact on eggs and larvae is calculated as being proportionate to recruitment reduction (“one killed larvae equals one killed recruit”), and according to examples shown in Figure 5-7 and Figure 5-8.

If $Imp_{total} < Critical\ oil\ mortality$, impact on eggs and larvae is calculated based on relative recruitment factors, i.e. using "the gate model". When the model is run in stochastic mode (Clima=1), relative recruitment is linked to natural variation via three climatic regimes. When the model is run in deterministic mode, relative recruitment is normalized to 1.0 and representing long term average recruitment.

The user can therefore choose the level of conservatism to calculate oil-induced impact however for a scientifically correct impact calculation *Critical oil mortality* should be set to 99% and thus impact should be calculated based on relative recruitment factors ("gate model").

In both stochastic and deterministic mode, the restitution level for calculating RIF is set to 99% to enable comparison with other compartments. RIF is thus calculated from all years with at least 1% reduction of the spawning stock and expressed as "spawning stock reduction years" (in percentage). A calculated impact of 41.7% spawning stock reduction years (as in Figure 5-7) can be represented by e.g. a 41.7% reduction of the spawning stock during one year, or by a 4.17% continuous reduction during 10 years.

In the example simulations presented in Figure 5-7 and Figure 5-8, the oil-induced mortality on fish eggs and larvae has been set to 95%, whereas the parameter *Critical oil mortality* is set to 90%. This means that the model calculates mortality on eggs and larvae as being proportionate to recruitment reduction (see above). Example simulations show comparable results for impact modelling in stochastic (Clima=1) and deterministic (Clima=0) mode. It is however important to underline that running the model in stochastic mode will produce a different calculated impact each time the model is run, i.e. there is no built-in function that uses the average impact from a larger number of simulations.

As mentioned above the restitution level has been set to 99% to enable comparison with other compartments. In a stochastic environment however, where natural variation is several-fold higher than 1%, the scientifically correct way to define restitution time is by two standard deviations (2SD) from the long term average stock level, representing the 95% confidence level. This long term average could be determined by the model because it projects 100 years into the future (with the thought oil spill occurring in year 0) however this function is not built in at this stage.

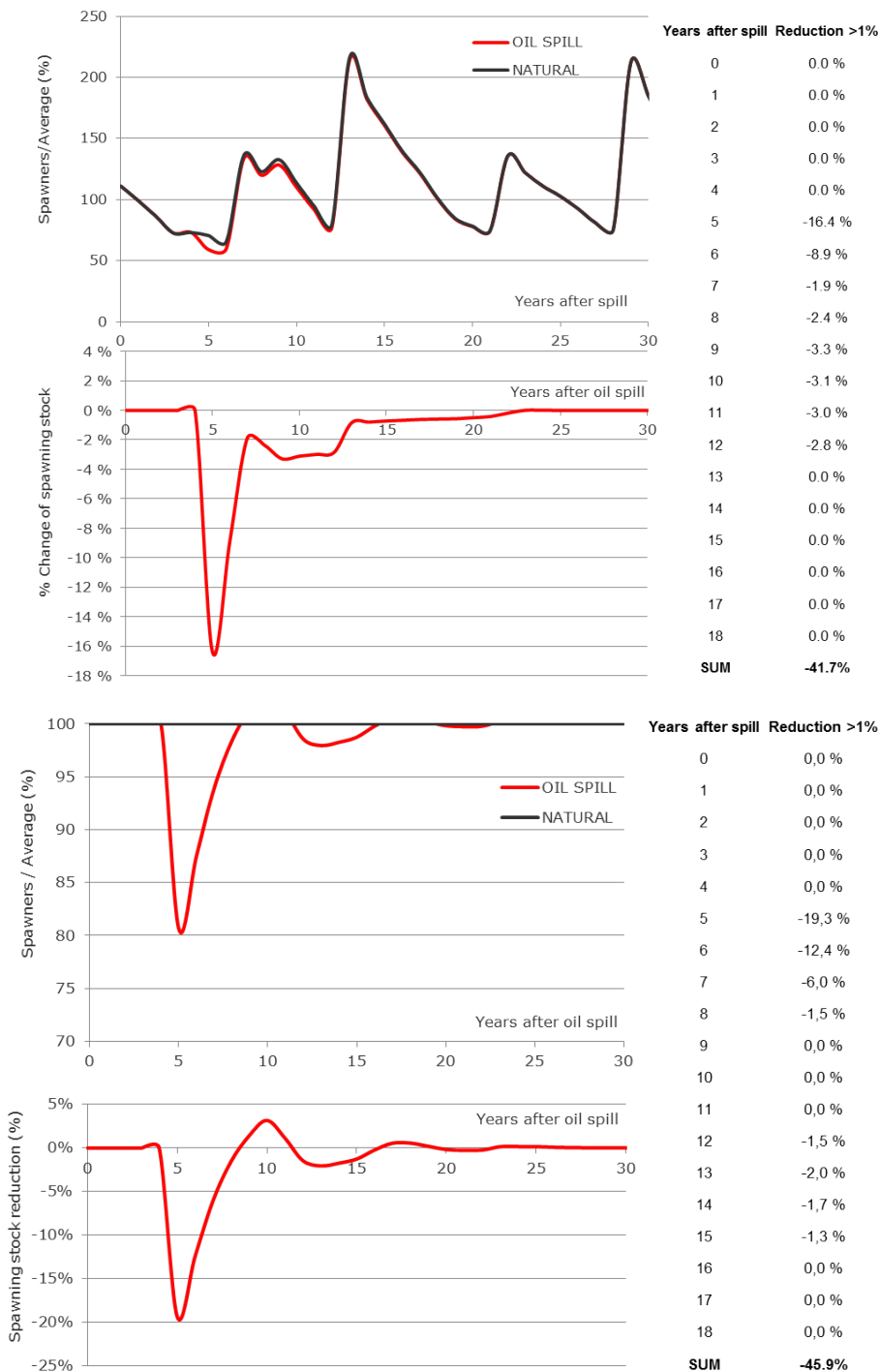


Figure 5-7 Exemplified projection of *long-lived species* following an acute oil spill in year 0 killing off 95% of all eggs and larvae. Impact on eggs and larvae is conservatively calculated as being proportionate to recruitment reduction. Upper panel – **stochastic modelling**; lower panel – **deterministic modelling**. The following input data were used: Age of recruitment 3 years, age of maturation 8 years, maximum age 25 years, natural mortality for immature and mature fish 20%, critical population size 5%. No added fishing pressure was used in the simulations. The Resource Impact Factor (RIF) of the spill is -41.7% (stochastic) and -45.9% (deterministic) spawning stock reduction years, using 99% of the projected, undisturbed state as restitution threshold.

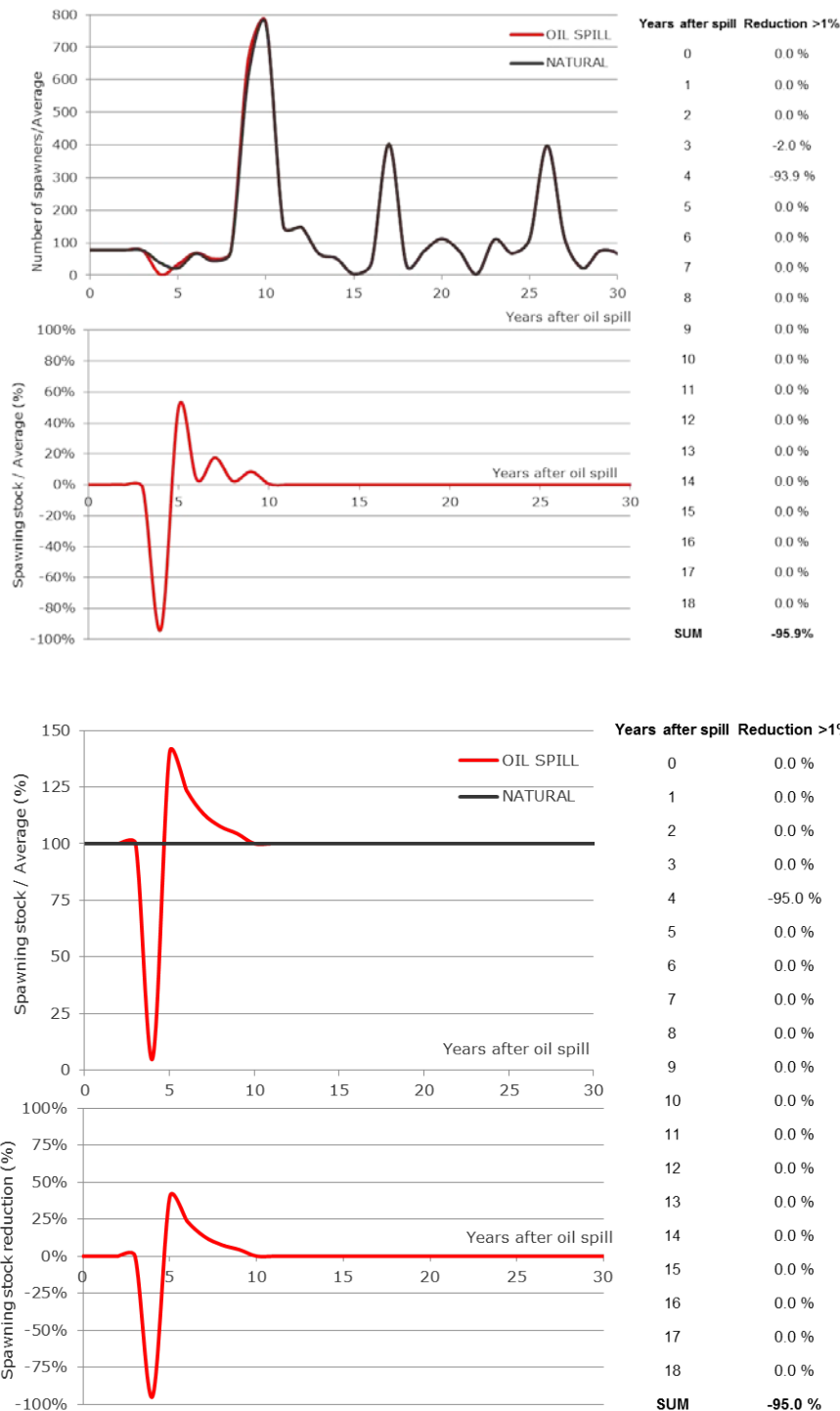


Figure 5-8 Exemplified projection of short-lived species following an acute oil spill in year 0 killing off **95%** of all eggs and larvae. Impact on eggs and larvae is conservatively calculated as being proportionate to recruitment reduction. Upper panel – **stochastic modelling**; lower panel – **deterministic modelling**. The following input data were used: Age of recruitment 1 year, age of maturation 5 years, maximum age 5 years, natural mortality for immature and mature fish 40%, critical population size 5%. No added fishing pressure was used in the simulations. The Resource Impact Factor (RIF) of the spill is -95.9% (stochastic) and -95.0% (deterministic) spawning stock reduction years, using 99% of the projected, undisturbed state as restitution threshold.

5.2.8 Risk Matrix

The example simulations in the previous section demonstrate that impact on the spawning stock level is only measurable if modelling is performed with the same level of conservatism as suggested in OLF (2008), i.e. by assuming that each larvae killed by an oil spill would have survived until first spawning. The user can decide the level of conservatism by adjusting the parameter *Critical oil mortality* to 99% (default value), and thereby model impact from the expected recruitment in generalized climatic regimes based on historical records from the Barents Sea ("gate model"). This is the preferred and scientifically most valid approach.

Regarding the Risk Matrix, if impact is modelled using the "gate model" the assessed risk will always be on the green side of the matrix when impact is measured on the spawning stock level.

Fish larvae may however be regarded as a valuable resource on its own, e.g. as planktonic food source to predating marine organisms. This represents a different Risk Matrix with complex ecological interdependencies that is not the scope of this project. In general however, the risk represented by loss of a certain portion of fish larvae would still be low, because: i) fish spawn with an annual cycle and the restitution time in the water column could therefore not exceed one year, ii) copepods and not fish larvae represent the majority of zooplankton available for predation, and iii) previous studies have calculated up to 10% loss of all fish larvae representing one year class as a result of a major oil spill.

6 VALUED ECOSYSTEM COMPONENTS FOR IMPACT CALCULATIONS (VEC) VIA OSCAR

6.1 Sensitivity of VECs

In order to target specific Valued Ecosystem Components (VECs) a minimum of information about the species sensitivity to petroleum hydrocarbons is needed. If data are available that can relate the sensitivity of a certain VEC to other species - for instance using SSD-curves - the deviation from the median value of the SSD curve can be directly used to establish a sensitivity factor for that particular VEC. At the current state, however, we suggest looking at the more general trends related to compartment and trophic level in addition to geographical regions separated by temperature conditions.

We divide the defined geographic areas seen as particularly interesting by the client, into cold areas (water temperature < 5°C), temperate (5-20°C) and warm areas (>20°C) since toxicity testing experiments are done under standard conditions representative for a specific area, among others temperature and daylight. Cold areas will comprise Canada, temperate areas will comprise Northern Europe and Argentina, and warm areas will comprise Mediterranean Sea, West Africa (Angola) and South Africa, Gulf of Mexico, South China Sea (Indonesia), Australia and Persian Gulf.

Calculating toxicity in the body residue model is based on acute toxicity data for different species exposed to single oil components. The most extensive data available are of zooplankton (pelagic crustaceans). These are the basis for the calculations made in OSCAR (LC₅₀ values available in oil properties database). Zooplankton also shows the highest sensitivity to oil components.

Since the exposure model used in OSCAR is species independent, less sensitive species might be accounted for by applying a sensitivity factor (see 6.2). The above implies that the sensitivity factor for the "average zooplankton" is 1.0. In order to calculate the sensitivity of the other VEC groups we have related available toxicity data on single components to zooplankton to establish an average sensitivity factor for algae, benthic species and fish, fish eggs and larvae.

6.2 Sensitivity factors for algae, fish, benthos

In a previous study data were collected from the ECOTOX database (U.S. Environmental Protection Agency). Only data where LC₅₀ (zooplankton, benthos and fish) or EC₅₀ on growth (plant) were specified, were used. These data were sorted according to group after the following scheme:

Phytoplankton: green algae

Zooplankton: copepods, shrimps, mysids

Benthos: benthic crustaceans, molluscs, echinoderms, polychaete worms

Fish: all fish species regardless of life stage.

Searches were conducted for specified chemicals analysed for the OSCAR model input. Only the chemicals with a log(K_{ow}) less than 5.8 were included and all data were corrected for test duration (French-McCay, 2002).

It is well known that LC₅₀-values show a considerable variation within groups of organisms as well as between groups. This is part of the variation seen in the reported LC₅₀-values. Major factors are the condition of the tested organisms, experimental design and the verification of the exposure

concentration. Significant outliers³ were therefore removed and the averages of the remaining EC₅₀/LC₅₀ values (607 data points) were calculated for each chemical. For chemicals with toxicity data for at least two groups including zooplankton, the sensitivity factor relative to zooplankton was calculated. The average of all sensitivity factors is shown in Table 6-1. Due to recent studies on fish embryos and first-feeding larvae (e.g. Nordtug et al., 2011, J. P. Incardona et al., 2012; John P. Incardona et al., 2013) showing effects at quite low concentrations of oil there may be a need to introduce a separate sensitivity factor for fish egg and larvae.

Table 6-1 Relative sensitivity (= sensitivity factors) of groups of marine organisms based on 607 LC₅₀/EC₅₀ values for oil compounds in the ECOTOX database.

Parameter	Algae EC ₅₀	Zooplankton LC ₅₀	Benthos LC ₅₀	Fish LC ₅₀ *
Sensitivity factor relative to zooplankton	0,41	1	0,38	0,93
Standard deviation of SSD curve	0,10		0,09	0,20

* including fish eggs and larvae. Higher sensitivity for eggs and larvae can be accounted for by the sensitivity factor. While eggs and larvae show acute effects, fish will be prone to delayed and chronic effects.

6.3 Temperature-dependent sensitivity

The basic toxicity data used in creating the QSAR for LC₅₀ is almost exclusively from experiments performed at 20 °C. As discussed in 2.3 above, toxicity is affected by temperature and in order to account for different temperature regions a temperature compensation should be included in the calculations.

In the present version of OSCAR (7.0) this has to be included as part of the sensitivity factor. Most data indicate that the change in LC₅₀ per 10 °C increase in temperature (Q10 for LC₅₀) of temperature acclimated individuals is in the range 0.3 – 0.5; however a SINTEF study showed a Q10 of 0.7 for *C. finmarchicus* (see 2.3).

6.4 Corals and sponges as organisms exposed through the water column

6.4.1 Corals

There is a large amount of literature on effects on corals from discharges from petroleum activities. Most of this literature is related to impacts from sedimentation of drilling discharges. Reports from previous oil spill incidents are mostly related to warm water corals in shallow water. Thus we have not been able to

³ Outliers were defined by criteria for accepting data from the original publications; most of them were removed due to lack of documentation of exposure concentrations.

find consistent data to evaluate the acute sensitivity to water soluble oil components relative to other species groups. According to NOAA (US National Ocean and Atmospheric Administration (NOAA, n.d.) the effects from acute oil spills are more likely to appear as sub-lethal effects that may later cause bleaching⁴ and reduced reproduction rather than acute mortality.

The effects of an oil spill are highly dependent on the conditions of the spill (oil type, depth, habitat). Observed effects from large oil spills might be severe (e.g. (Jackson et al., 1989)), but on the contrary the extent of coral reef damage directly attributable to the world's largest oil spill in the Persian Gulf in January 1991, has been remarkably minor according to NOAA. There are indications of effects on deep water corals after the Deepwater Horizon blow-out in the Gulf of Mexico at distances up to 22 kilometers from the spill site (Fisher et al., 2014). However, due to the many potential sources of oil releases (natural and anthropogenic) in the area it is difficult to estimate the extent of damage caused by the Deepwater Horizon blow-out and even more difficult to estimate the concentrations of oil that caused the effects.

Corals have detoxification systems for organic chemicals (Rotchell & Ostrander, 2011) similar to other marine species and there are no indications that corals are more sensitive to acute oil exposure than other species. The reverse is also true; there are indications that some corals may be quite resistant to acute oil exposure, possibly because of their ability retract into the calcified tube structures. However, due to the scarcity of acute toxicity data we suggest that the sensitivity to dissolved oil components for corals is set equal to marine zooplankton.

6.4.2 Sponges

Just like for corals there is an lack of acute toxicity data on specific oil components or the water soluble fraction (WSF) for sponges. Cebrian and Uriz (2007) studied the effects on larval settlement during a 10 day exposure of two widespread Mediterranean sponges (*Crambe crambe* and *Scopalina lophyropoda*) to a mixture of heavy PAHs (log K_{OW} between 5.8 and 6.7). At the highest concentration of 1µg/L a slight delay in settlement was observed for one of the species. However, there was no significant increase in mortality. Given the high K_{OW} and thus potentially high acute toxicity of the PAHs used compared to PAHs found in the WSF of oil the results indicate that these larvae were not significantly more sensitive than other planktonic organisms.

Assuming that adult sponges are no more sensitive than larvae we therefore suggest using the same average sensitivity for sponges as for corals (which is using the same sensitivity as for zooplankton).

⁴ Corals that are exposed to toxicant causing stress by changes in conditions such as temperature, light, or nutrients, expel the symbiotic algae living in their tissues, causing them to turn white (http://oceanservice.noaa.gov/facts/coral_bleach.html).

7 EXAMPLE SPECIES FOR RESTITUTION / POPULATION MODELLING

We have developed the ERA Acute model using two different model species; a short-lived species represented by capelin (*Mallotus villosus*), and a long-lived species represented by Barents Sea cod (*Gadus morhua*). The results described in this report show that the model works well for both of these “extremes”, wherefore also fish species with an intermediate life span can be modelled.

Although short-lived species are generally at a lower trophic level than long-lived species, and in several aspects represent a different lifestyle, it is worth underlining that the model runs according to the input data it is fed with, i.e. there is no reason to define habitat (e.g. pelagic, demersal, estuarine, coastal) or trophic level (high-intermediate-low). The input data defined for capelin and cod can thus be applied to any other species with comparable life spans.

It is important to emphasize that the more species-specific input data are used in the model, the better predictions will come out from it. However, in some parts of the world, and on short notice following an acute oil spill, it may not be possible to access such data for relevant, local fish resources.

Table 7-1 below provides an overview of exemplified fish species representing long-lived (defined as all fish with a life span exceeding 5 years), and short-lived species (defined as all fish with a life span up to 5 years) in sub-oceans seen as particularly interesting by the client. The overview focuses on pelagic and commercially important species, with catch records extracted from FishStatJ (<http://www.fao.org/fishery/topic/166235/en>).

Table 7-1 Exemplified fish species with long (>5 years) and short (≤5 years) life spans in different sub-oceans of the world with interest to the O&G industry.

Sub-ocean	Exemplified long-lived species	Exemplified short-lived species
Northern Europe	<i>Gadus morhua</i> ; <i>Clupea harengus</i> ; <i>Scomber scombrus</i> ; <i>Micromesistius poutassou</i>	<i>Mallotus villosus</i>
Angola	<i>Thunnus albacares</i> ; <i>Katsuwonus pelamis</i>	<i>Sardinella aurita</i> ; <i>Sardinella maderensis</i> ; <i>Sardinops sagax</i> ; <i>Engraulis encrasicolus</i>
South Africa	<i>Merluccius capensis</i>	<i>Engraulis capensis</i> ; <i>Sardinops sagax</i>
Gulf of Mexico	<i>Epinephelus morio</i> ; <i>Pogonias cromis</i> ; <i>Lutjanus campechanus</i> ; <i>Rhomboplites aurorubens</i> ; <i>Thunnus albacares</i> ; <i>Thunnus thynnus</i>	<i>Brevoortia patronus</i> ; <i>Opisthonema oglinum</i>
East coast of Canada	<i>Gadus morhua</i> ; <i>Clupea harengus</i> ; <i>Scomber scombrus</i>	<i>Mallotus villosus</i>
Mediterranean Sea	<i>Merluccius merluccius</i> ; <i>Mullus barbatus</i> ; <i>Micromesistius poutassou</i> ; <i>Thunnus</i>	<i>Engraulis encrasicolus</i> ; <i>Sardina pilchardus</i> ; <i>Sardinella aurita</i>

	<i>thynnus; Thunnus alalunga; Xiphias gladius</i>	
Argentina	<i>Merluccius hubbsi; Macruronus magellanicus; Micropogonias furnieri; Scomber japonicus</i>	<i>Engraulis anchoita</i>
Australia	<i>Thunnus spp.; Plectropomus leopardus; Micromesistius australis</i>	<i>Sardinops sagax</i>
South China Sea	<i>Trichiurus spp. Larimichthys crocea; Scomber japonicus; Scomberomorus niphonius; Clupea pallasii,</i>	<i>Dussumieria elopsoides; Coilia grayii; Tenuulosa toli; Scomber australasicus</i>
Persian Gulf	<i>Scomberomorus commerson; Argyrops spinifer</i>	<i>Gerres limbatus; Siganus spp.; Sardinella sindensis; Encrasicholina punctifer</i>

8 COMPARISON WITH DAMAGE-BASED RISK ASSESSMENT

In Table 8-1 below, a comparison is made between the ERA Acute methodology and the damage-based fish risk assessment approach laid out in OLF (2008). Fish is not an integrated VEC in the MIRA methodology (OLF, 2007).

Table 8-1 Comparison between impact, lag and restitution calculations performed ERA acute and OLF (2008).

Subroutine	OLF (2008)	ERA Acute (phase III)
Impact	<ul style="list-style-type: none"> Global effect level for eggs and larvae based on toxicity data for the most sensitive, adult fish species (DNV GL approach): Based on maximum modelled concentration of THC in water column, with a linear function from LC₁ (100 ppb THC) to LC₁₀₀ (1000 ppb THC). Oil weathering / composition, and exposure time are not considered (conservative approach) 	<ul style="list-style-type: none"> Global effect level for eggs and larvae based on toxicity data for fish larvae and zooplankton THC_{max} approach: Based on maximum modelled concentration of THC in water column, with a continuous function from LC₅ (58 ppb THC) to LC₁₀₀. Oil weathering / composition, and exposure time are not considered (conservative approach) QSAR approach: Based on critical body residue, thereby taking oil weathering, oil composition, detoxification and exposure time into account
Lag phase	<ul style="list-style-type: none"> Not considered 	<ul style="list-style-type: none"> Not considered
Restitution	<ul style="list-style-type: none"> Three species-specific restitution models established; cod, herring, capelin (no flexibility) A rigid factor 10 in survival variation of fish larvae is built in to reflect natural variation (and hence climatic variations), based on average historical recruitment over a long time period, and resulting in different outcomes with different probabilities Assuming that larvae killed by an oil spill would have survived until first spawning Not possible to address impact from fishing Restitution time (in deterministic environment) defined as time until the stock is back at 99% of the pre-spill level Defined damage categories (minor/moderate/ 	<ul style="list-style-type: none"> Global restitution model with high level of flexibility regarding species Restitution modelling is based on natural survival from egg stage until recruitment, based on historical data from the Barents Sea. There is no natural mortality rate of eggs and larvae built in. Possible to model impact on fish stocks in stochastic and deterministic environment. In stochastic mode, relative recruitment is coupled to three general climatic regimes Possible to choose level of conservatism from the parameter <i>Critical oil mortality</i> (default 99%)

	<p>considerable/serious) based on predicted restitution time. The level om impact is not addressed</p>	<ul style="list-style-type: none"> • Possible to set <i>critical density</i> level of assessed resource (default 5%) • Possible to address impact from fishing • Impact (in stochastic or deterministic environment) defined as the summed up reduction for years displaying a spawning stock reduction of at least 1% (restitution level 99%), and expressed as <i>spawning stock reduction years</i> in percentage of an undisturbed stock • No defined damage categories
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9 ERA ACUTE METHODOLOGY FOR WATER COLUMN EXPOSED ORGANISMS

9.1 Impact

The impact calculation via Critical Body Residue and time-dependent dose-response as described in section 2 is less conservative however more scientifically valid since it takes the change in the oil composition due to oil weathering into account. The DNV GL approach is valid in demonstrating that even with this level of conservatism the impact on adult fish (spawning stock), as a result of a major oil spill killing off 95% of all eggs and larvae representing year class 0 of a resource, is not measurable.

With this recommendation ERA Acute will use results from an oil spill model like OSCAR to calculate impact from time-varying exposure to the dissolved fraction of the oil in the water column. As per today, OSCAR is run in stochastic mode which combines the impact itself with a probability for the impact to calculate environmental risk.

The impact from exposure to dissolved oil in the water column is reported as potential "fraction killed" and "body burden" (= body residue). "Fraction killed" is calculated from "body burden" via a concentration-effect (dose-response) curve where the critical body residue is determined via LC_{50} values.

The methodology is described in three versions since we assess the currently available option as non-optimal. In the previous phase of the project SINTEF suggested improvements to OSCAR which were mostly related to the compartment *sea floor* but would improve available results for the compartment *water column* as well. Newer development of OSCAR and changed availability and costs of computer power and storage enable us to suggest a third version, which would be the preferred one as per today.

The objective of the three versions is to improve the available results without major changes in the ERA Acute methodology.

9.1.1 ERA Acute with OSCAR as available per today

OSCAR

The current version of OSCAR is 6.6.1. OSCAR will be run in stochastic mode, including "Exposure Calculations".

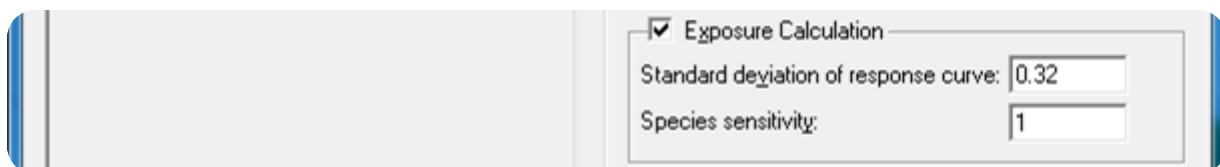


Figure 9-1 OSCAR dialog for specification of Exposure Calculations

Standard deviation and sensitivity have to be specified for the organism of interest. Other than in the other compartments, where the oil spill model results are applied to a population after the model runs, the water column methodology will require the specification of the population's sensitivity before OSCAR is run. This has the disadvantage that only one organism group (sensitivity) can be defined which will have to represent the most sensitive species one wants to consider. For all other populations with organisms less sensitive the results will be somewhat conservative. The alternative is to apply a higher standard deviation of the response curve (slopes of the concentration-effect curves for several species are more gently inclined).

Recommended values are given in Table 9-1. However, these two parameters are used to define the response curve which relates the computed body residue to mortality. Since the maximum body residue itself is available as well, concentration-effect curves may be applied in the ERA Acute software as well.

Table 9-1 Recommended values for exposure calculations with OSCAR version 7.0 (and earlier), switching between areas of interest as required (e.g. winter in Northern Europe). Areas of interest were defined by the customers Total and Statoil.

Cold Areas (Eastern Canada) (<5° C) (Q10 of 0.4 and 0.7 applied assuming standard toxicity testing between 13° and 20° C)		
VEC	Standard deviation of response curve	Species sensitivity
Phytoplankton	0.1	0.41 * 0.4 (=0.164)
Zooplankton	0.32	1 * 0.7 (=0.7)
Fish egg/larvae	0.32	1 * 0.4 (=0.4)
Fish (adult)	0.2	0.93 * 0.4 (=0.372)
<i>Corals & Sponges</i> <i>(from zooplankton)</i>	0.32	1 * 0.4 (=0.4)
Temperate Areas (Northern Europe and Argentina) (5° to 20° C) (assuming standard toxicity testing between 13° and 20° C)		
VEC	Standard deviation of response curve	Species sensitivity
Phytoplankton	0.1	0.41
Zooplankton	0.32	1
Fish egg/larvae	0.32	1
Fish (adult)	0.2	0.93
<i>Corals & Sponges</i> <i>(from zooplankton)</i>	0.32	1
Warm Areas (Mediterranean Sea, West Africa (Angola) and South Africa, Gulf of Mexico, South China Sea (Indonesia), Australia, Persian Gulf) (> 20° C) (Q10 of 0.4 and 0.7 applied assuming standard toxicity testing between 13° and 20° C)		
VEC	Standard deviation of response curve	Species sensitivity
Phytoplankton	0.1	0.41 / 0.4 (=1.025)
Zooplankton	0.32	1 / 0.7 (=1.43)
Fish egg/larvae	0.32	1 / 0.4 (=2.5)
Fish (adult)	0.2	0.93 / 0.4 (=2.325)
<i>Corals & Sponges</i> <i>(from zooplankton)</i>	0.32	1 / 0.4 (=2.5)

Post-processing - Water Column / Concentration Grid

OSCAR computes results in the water column in the four dimensions time, depth, latitude and longitude (t, z, y, and x). Under stochastic simulations these dimensions are reduced from four to three to two dimensions for the final risk maps. This means that a lot of valuable data from the calculations is not available for the ERA Acute software, which is one reason that the exposure calculations in the water column should be executed under run time and not under post-processing.

The following file formats are described for the sake of completeness; they are not used directly for ERA Acute.

Stochastic Run Result (STT Format, OSCAR model engine)

The STT file contains a list of all affected concentration grid cells for each simulation. This file contains four-dimensional data, i.e. the time dimension has been removed by calculating averages and maxima but there is the simulation as a "dimension" (simulation, z, y, and x). Averages are calculated by adding up the concentrations for a grid cell each time the cell contains oil. This sum is then divided by the number of hits⁵. Each entry contains:

1. Dissolved concentration (average, i.e. for each cell the simulation sum divided by number of hits)
2. THC⁶ concentration (average)
3. Mixing depth (average)
4. Arrival time (first time step this cell contained oil)
5. Exposure time (number of time steps times time step length this cell contained oil)
6. Last arrival time (last time step this cell contained oil)
7. Fraction killed (maximum)
8. Body residue (maximum)

Accumulated Stochastic Run Result (STAT Format)

This file contains three-dimensional data; the simulation "dimension" has been removed by applying maxima over all simulations (except for arrival time which is the minimum of all simulations) (z, y x).

The file contains

1. Maximum of STT values for the dissolved concentration (maximum of the averages)
2. Maximum of STT values for the THC concentration (maximum of the averages)
3. Maximum of STT values for the mixing depth
4. Minimum of STT values for the arrival time
5. Maximum of STT values for the exposure time
6. Maximum of STT values for the last arrival time
7. Maximum of STT values for the fraction killed
8. Maximum of STT values for the body residue

UTM grid export (ERA Acute software)

Also the UTM export is generated from the STT file. This file is used in the ERA Acute software. Each line in the text file is a unique combination of scenario number, compartment (Surface, Shoreline, Water-column), and UTM grid cell id. A UTM grid cell comprises all water cells having their (horizontal) centre

⁵ A "hit" is defined as a time step in which a concentration grid cell contained oil during a simulation as oil might enter and leave a cell during the scope of a simulation.

⁶ Note that "Total" in THC does not refer to all components in contrast to specific components but to dissolved fraction and droplet fraction together. Both fractions contain all 25 pseudo components.

within that UTM cell, the water column cell quantities in a vertical column being reduced to a cell in a plane by applying maxima (except for arrival time where minimum is used).

For the water column this results in the following data:

1. Vertical maximum of all average dissolved concentrations
2. Vertical maximum of all average total hydrocarbon concentrations
3. Vertical maximum of all mixing depths
4. Vertical minimum of all arrival times
5. Vertical maximum of all exposure times
6. Vertical maximum of all last times
7. Vertical maximum of all maxima of fraction killed
8. Vertical maximum of all maxima of body residue

ERA Acute software

The ERA Acute software matches the exported UTM grid with resource data in GIS format and optionally performs additional calculations for the impact and risk, respectively. Since the suggested approach here calculates the impact for the chosen sensitivity directly, these results (p_{let} = "fraction killed") may be used directly and further calculations within the ERA Acute software (ERA-SW) are not necessary.

1. OSCAR is run in stochastic mode.
2. Oil spill output and exposure are exported to UTM grid.
3. p_{let} = "fraction killed" from the UTM grid file for each grid cell can be used directly in the ERA-SW.
4. $p_{let} * N$ can be calculated for each UTM cell with N from resource data.

Advantages and shortcomings of this approach

The advantage of using this approach is that there is not too much change to the methodology that was established in the ERA Acute project until now.

However, as mentioned above, it is only possible to calculate impact for one sensitivity-slope pair of values which is why one could argue that the effect-concentration calculations (see 0 and Table 9-1) should be performed within ERA-SW. It should be noted that only the vertical maximum of all maxima of all simulations is available from the UTM export, which would be conservative in the same way or even more than using one sensitivity value for all organisms.

The biggest shortcoming of the current methodology for the water column is the use of vertical maxima, which means that a maximum located in the upper water column might be used for risk assessment in the lower water column or vice versa. This means that organisms like corals and sponges might be "exposed" to concentrations in the upper water column leading to too conservative results when matching resource and oil drift data in ERA-SW.

Another disadvantage is that the implemented CBR model that is used for stochastic exposure calculations is a simplified version of the CBR model that is available for deterministic simulations (see SINTEF report F26670 "QSAR in Environmental Risk Assessment" (Brønner et al., 2014)). K_{OW} values are calculated from K_{OC} data and have a slight deviation from K_{OW} values reported elsewhere. The model is almost unused; activation of the exposure calculations is expected to increase the computational time (which might not be an issue, though). Due to this fact it might be deprecated in the future and / or replaced by other exposure models.

9.1.2 ERA Acute with OSCAR as suggested in phase II, 2012

In phase II of this project, SINTEF suggested enhancements of OSCAR for better environmental risk assessment, among others to address the disadvantage with using the vertical maximum of the water column in the UTM export (Brønner, 2012). The proposal resulted in two files for the UTM grid export, one for the upper and one for the lower water column, where the depth for the two layers would be specified by the user.

OSCAR

OSCAR is run analogously to the first version (9.1.1). The same recommendations for exposure calculations will apply here.

Post-processing - Water Column / Concentration Grid

The UTM export will produce two files for the water column, one for the upper and one for the lower water column. The vertical maxima will apply for the respective part of the water column only. Calculated risk for the water column is reported as before via "fraction killed" and "body residue".

ERA Acute software

The ERA-SW will match the UTM grids for the upper and lower water column with the respective resource data. The lower water column risk will be matched with resource data for corals and sponges, the upper water column data can either be combined with the lower water column data for resources like fish, while resources like zooplankton (copepods) might be matched against one of the files depending on season and their behaviour depending on that season (autumn, winter: lower water column, spring, summer: upper water column).

The same methodology applies as with using OSCAR in its current version: If the "fraction killed" data are used directly there will be no need for additional calculations in ERA-SW.

1. OSCAR is run in stochastic mode.
2. Oil spill output and exposure are exported to UTM grid.
3. p_{let} = "fraction killed" from the UTM grid file for each grid cell can be used directly in the ERA-SW.
4. $p_{\text{let}} * N$ can be calculated for each UTM cell with N from resource data.

Advantages and shortcomings of this approach

While the biggest shortcoming of the first version (0) is addressed in this alternative, the other shortcomings do still apply (simplified implementation, species independent, unused).

9.1.3 ERA Acute with OSCAR as suggested in phase III, 2015

Future versions of OSCAR will probably not employ stochastic simulations in their current form anymore. Standardisation of input and output data formats will allow for more sophisticated statistics that will be produced from ensembles of deterministic runs. This means that the complete set of four (five) dimensional results will be available for statistic post-processing (simulation, time, z, y x).

Per today simulations for stochastic runs are sampled by start time and rate/duration matrices only. The ease of modification of the input data for OSCAR simulations will allow for other sampling as well. In addition, uncertainty will be possible to quantify in the results.

OSCAR

OSCAR is run as a set ("ensemble") of scenarios. Each scenario is run in deterministic mode and will produce a full four (five) dimensional result set.

Bio exposure modelling

The CBR model is currently under development and will be implemented as a particle based model for individuals with uptake and depuration kinetics as described in SINTEF report F26670 "QSAR in Environmental Risk Assessment" (Brønner et al., 2014) using the more advanced kinetics from OMEGA (De Hoop et al., 2013).

The particle based CBR model will account for organism behaviour (planktonic, stationary benthic, swimming) as well as spatial distribution at the beginning of each simulation. The pilot version of this model is planned to be implemented in spring next year.

A more detailed description of OSCAR in this suggested future version and the available output for all four compartments can be found in SINTEF report F26671 "Suggested OSCAR design for future application with ERA Acute" (Brønner, 2015), another deliverable within the scope of this project.

Post processing

Since the complete result set is available after simulation, statistics like average, floating average, distributions or maxima can be calculated from the output and be tailored to the requirements of ERA-SW. *It will be possible to generate the same results as before, i.e. body residue and fraction killed will be available results.*

In addition, data can be filtered by pseudo-component, by layer or whatever is necessary to match the organism data available. The main difference will be that it will be possible to run the exposure calculations for several organisms at the same time with different particles representing different species.

Since the exposure calculations are dependent on the time variable results from the oil drift model, but not vice versa, it is theoretically possible to calculate exposure for different species as post-processing. This approach would have the same disadvantage as the current version, i.e. the spatial distribution of the organisms over time is not accounted for.

Data can be exported as UTM grid as before or post-processed to directly common GIS compatible formats like shape files (Esri ArcGIS), KML (Google Earth), GML (OGC) or NetCDF (OGC).

ERA Acute software

ERA-SW will need to be adapted if the output format from OSCAR is changed.

The new bio exposure model can compute "fraction killed" and "body residue" just like previous versions. Ideally these data will be transferred to ERA-SW as three dimensional data sets to avoid averaging or calculation of maxima over parts of the water column. The data can then be matched with available resource data which would ideally be three dimensional as well. Population models like SINMOD calculate zooplankton like *C. finmarchicus* in 3D.

1. OSCAR is run in ensemble mode. Oil spill output and exposure are post-processed to the required format.
2. P_{let} = fraction killed for each 3D cell can be used directly in the ERA-SW.
3. $P_{let} * N$ can be calculated for each 3D cell with N from resource data. If resource data is not available in 3D, P_{let} will be accumulated to 2D (P_{let}) and matched with the 2D resource data via $P_{let} * N$

A more detailed description of ERA-SW with this suggested future version is included in SINTEF report F26671 "Suggested OSCAR design for future application with ERA Acute" (Brønner 2015).

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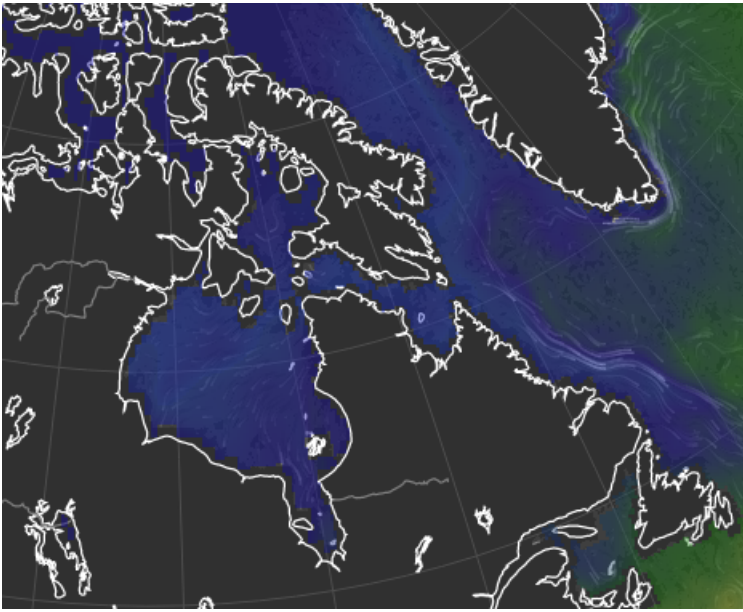
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A Sea Surface temperature for the geographic locations in ERA Acute as basis for categories

East Coast Canada:

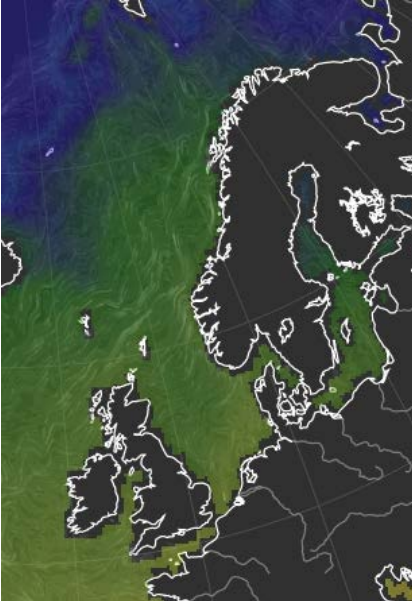


(ocean surface temperatures from http://earth.nullschool.net/#current/ocean/surface/currents/overlay=sea_surface_temp/orthographic)

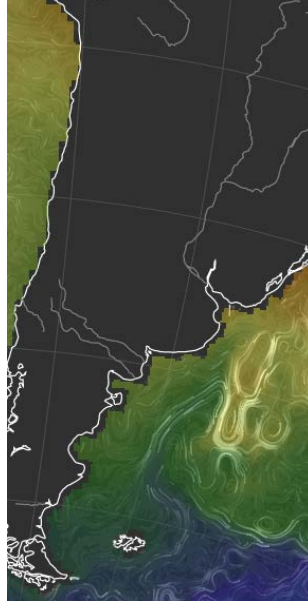


blue: < 5°C, green to yellow: 5-20°C, orange to red: >20°C

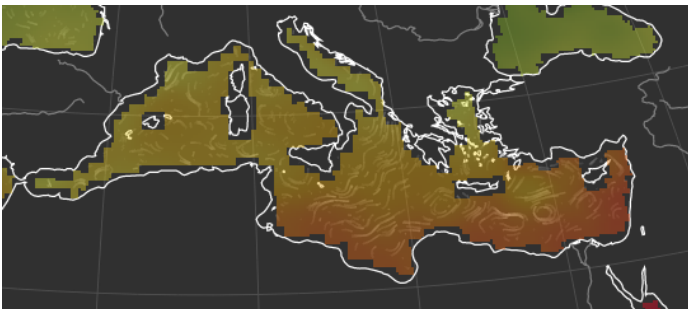
Northern Europe



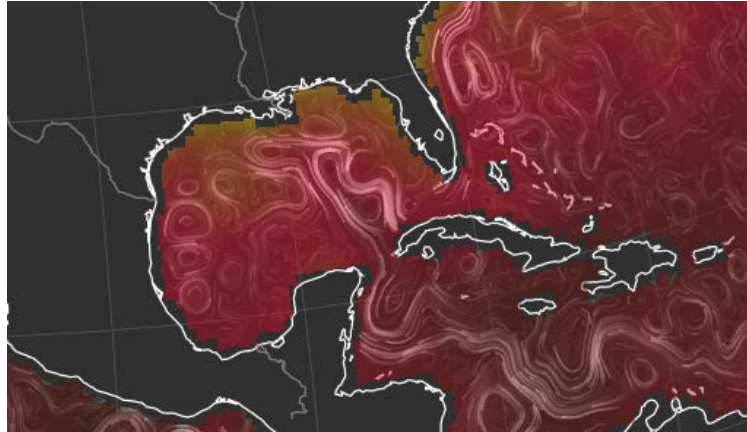
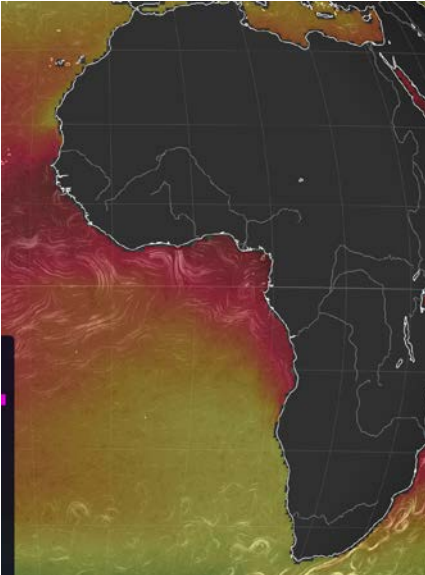
Argentina



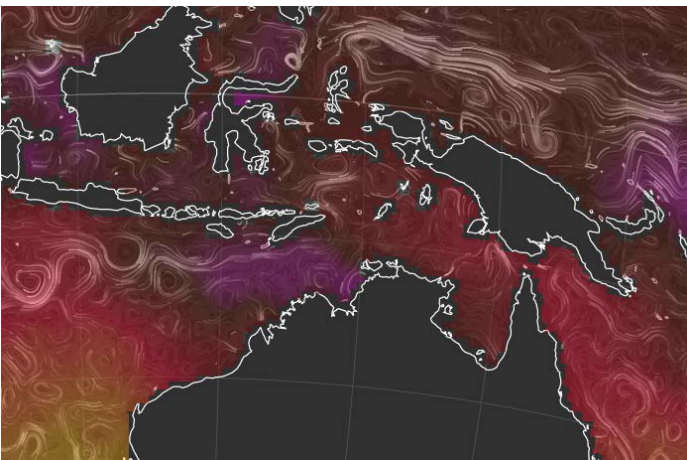
Mediterranean Sea



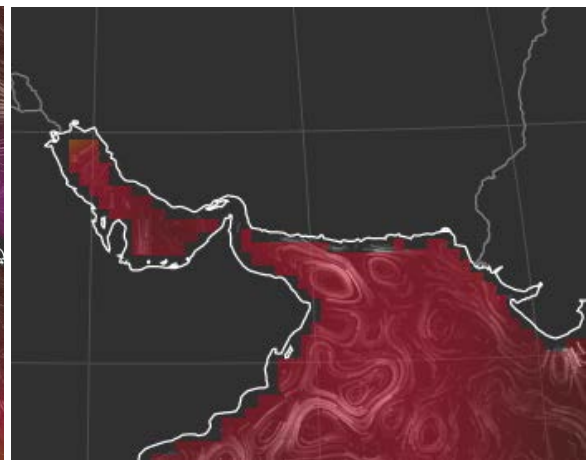
West Africa (Angola) and South Africa, Gulf of Mexico



South China Sea (Indonesia), Australia



Persian Gulf



B Input parameters to the restitution model

nSim	Number of simulations (Default: 100 years). In order to stabilize the population according to the given input parameters, the first 100 iterations are run without any oil spill.
NatMort Immatures	Natural annual mortality (%) of immature individuals; for example 25% means that the annual mortality of 'natural' causes (i.e. not fisheries or oil spill) is 25% among the immatures.
NatMort Adults	Natural annual mortality (%) of adult individuals (sexual mature individuals); for example 20% means that the annual mortality of 'natural' causes (i.e. not fisheries or oil spill) is 20% among the adults.
AGE_RECRUIT	The age at which the species enters the 'measurable' stock.
AGE_FIRST_SPAWN	The age at which the species starts to spawn, i.e. join the adult spawning migration.
AGE_MAX	The maximum age of the considered fish species in years.
CritDens	The minimum size of the spawning stock where there is no relationship between recruitment and the size of the parent spawning stock. Default: 5% of the long term maximum (carrying capacity)
M Small Abund	Natural mortality (%) of adults at abundances < <i>CritDens</i>
tm Small Abund	The age at which the species starts to spawn at abundances < <i>CritDens</i>
CritOilMort	When the percentage of egg/larvae which die in an oil spill is larger than CritOilMort, the recruitment itself is reduced by the same percentage. Recommended value: 99%
E_Recr	The average size of the recruitment, say $E_Recr = E(R) = 1000$
ClimStart	Technically, within the program the 'initial age structure' is the age structure in year 100 since the age structure is then consistent with the input parameters- ClimStart is a Boolean (logical) value for two options: (1) If the initial age structure shall have cohorts originating from the average recruitment value $E(R)$, then $ClimStart = 0$, or, alternatively, (2) if the cohorts shall originate from a variable climate-drive recruitment, then $ClimStart = 1$.
YrWeak(1:20)	The length of the period with unfavourable conditions. Up to twenty different values may be specified. The term "Weak" is used to indicate that under these unfavourable conditions the year classes tend to be lower than average.
P_YrWeak(1:20)	The probabilities for the various lengths of the periods with unfavourable conditions.
YrStrong(1:20)	The length of the period with favourable conditions. Up to twenty different values may be specified. The term "Strong" is used to indicate that under these favourable conditions the year classes tend to be above average.
P_YrStrong(1:20)	The probabilities for the various lengths of the periods with favourable conditions.
RFweak(1:19)	A multiplication factor to the average recruitment when the climate is unfavourable. Up to 19 different values may be specified. Thus, if the value of RFweak is 0.7, the recruitment after tr years will be $RFweak * E_Recr = 0.7 * 1000 = 700$.
P_RFweak(1:19)	The probability weights for the multiplication factor to the average recruitment when the climate is unfavourable. Let their sum be $PWsumweak$ (which is seen to be 16 for the unfavourable conditions). Then there is a chance of $1/16$ that the recruitment after tr years becomes $0.05 * 1000 = 50$.

RFshift(1:19)	A multiplication factor to the average recruitment when the climate shifts from unfavourable to favourable. Up to 19 different values may be specified. Thus, if the value of RFshift is 10, the recruitment after t_r years will be $RFshift * E_Recr = 10 * 1000 = 10,000$.
P_RFshift(1:19)	The probability weights for the multiplication factor to the average recruitment when the climate shifts from unfavourable to favourable. Let their sum be $PWsumshift$ (which is seen to be 4 for this transition). Then there is a chance of $1/4$ that the recruitment after t_r years becomes $10 * 1000 = 10,000$.
RFstrong(1:19)	A multiplication factor to the average recruitment when the climate is favourable. Up to 19 different values may be specified. Thus, if the value of RFstrong is 2, the recruitment after t_r years will be $RFstrong * E_Recr = 2 * 1000 = 2000$.
P_RFstrong(1:19)	The probability weights for the multiplication factor to the average recruitment when the climate is favourable. Let their sum be $PWsumstrong$ (which is seen to be 36 for the favourable conditions). Then there is a chance of $3/16$ that the recruitment after t_r years becomes $2 * 1000 = 2000$.
FishMortJuv(0:100)	The fishing mortalities of immature fish during a period of up to 100 years.
FishMortAd(0:100)	The fishing mortalities of adult fish during a period of up to 100 years.
OilMort(1:100)	Mortality of eggs and larvae due to acute oil spills during a period of up to 100 years.

C Algorithm programming global fish restitution model

```

1. nSIM = Input
2. nSIM = nSIM+100
3. nSIM20 = nSIM + 20

4. NatMortJuv = Input
5. NatSurvJuv = 1 - NatMortJuv
6. NatMortAd = Input
7. NatSurvAd = 1 - NatMortAd
8. t_Rec = Input
9. t_Mat = Input
10. t_Max = Input
11. E_Recr = Input
12. t_Mat_Wait = t_Mat - t_Rec
13. t_RecP1 = t_Rec + 1
14. t_MatM1 = t_Mat - 1
15. t_MatP1 = t_Mat + 1

16. AgeStrucJuv(j, kSim) = 0 for j = 0, ..., 50 & kSim = 0,..., nSIM
17. AgeStrucAd(j, kSim) = 0 for j = 0, ..., 50 & kSim = 0,..., nSIM
18. AgeStrucJuvFO(j, kSim) = 0 for j = 0, ..., 50 & kSim = 0,..., nSIM
19. AgeStrucAdFO(j, kSim) = 0 for j = 0, ..., 50 & kSim = 0,..., nSIM

20. AgeStrucJuv(t_Rec, 0) = E_Recr

21. for k = t_RecP1, ..., t_MatM1:
    AgeStrucJuv(k, 0) = AgeStrucJuv(k - 1, 0) * NatSurvJuv

22. AgeStrucAd(t_Mat, 0) = AgeStrucJuv(t_Mat - 1, 0) * NatSurvAd

23. for k = t_MatP1, ..., t_Max
    AgeStrucAd(k, 0) = AgeStrucAd(k - 1, 0) * NatSurvAd

24. Spawners(0) = AgeStrucAd(t_Mat, 0) + ... + AgeStrucAd(t_Max, 0)
25. K_Spawn = Spawners(0)

26. for kSim = 1, ..., 100:
    AgeStrucJuv(k, kSim) =
        AgeStrucJuv(k, 0) for k = t_Rec, ..., t_MatM1

27. for kSim = 1, ..., 100:
    AgeStrucAd(k, kSim) =
        AgeStrucAd(k, 0) for k = t_Mat, ..., t_Max

28. for kSim = 1, ..., 100:
    Spawners(kSim) = Spawners(0)

29. SpawnCritPercentage = Input
30. SpawnCrit = K_Spawn * SpawnCritPercentage / 100

31. NatMortAdLowD = Input
32. NatSurvAdLowD = 1 - NatMortAdLowD

33. t_MatLowD = Input

34. K_Spawn80 = 0.8 * K_Spawn

35. coefM =
    (NatMortAd - NatMortAdLowD) / (K_Spawn80 - SpawnCrit)

36. t_MatLOWD_M1 = t_MatLowD - 1
37. t_MatLOWD_P1 = t_MatLowD + 1

38. P_Years_Weak(k) = 0 for k = 1, ..., 20
39. P_Years_Strong(k) = for k = 1, ..., 20
40. FWeak(k) = 0 for k = 1, ..., 20
41. FStrong(k) = 0 for k = 1, ..., 20

42. P_Years_Weak(k) = Input for k = 1, ..., 20
43. P_Years_Strong(k) = Input for k = 1, ..., 20

```


44. $F_{Weak}(1) = P_{Years_Weak}(1)$
 45. $F_{Strong}(1) = P_{Years_Strong}(1)$
 46. $F_{Weak}(k) = F_{Weak}(k - 1) + P_{Years_Weak}(k)$ for $k = 2, \dots, 20$
 47. $F_{Strong}(k) = F_{Strong}(k - 1) + P_{Years_Strong}(k)$ for $k = 2, \dots, 20$
 48. $E_{Weak_Years} = 1 * P_{Years_Weak}(1)$
 49. $E_{Strong_Years} = 1 * P_{Years_Strong}(1)$
 50. for $k = 2, \dots, 20$:
 51. $E_{Weak_Years} = E_{Weak_Years} + k * P_{Years_Weak}(k)$
 52. $E_{Strong_Years} = E_{Strong_Years} + k * P_{Years_Strong}(k)$
 53. $SumWeakStrong = E_{Weak_Years} + E_{Strong_Years}$
 54. $P_{Weak_Years} = E_{Weak_Years} / SumWeakStrong$
 55. $P_{Weak_to_Strong_Years} = 1 / SumWeakStrong$
 56. $P_{Strong_Years} = (E_{Strong_Years} - 1) / SumWeakStrong$

57. $nRF_{Weak} = Input$
 58. $RF_{Weak}(k) = Input$ for $k = 1, \dots, nRF_{Weak}$
 59. $W_{RF_{Weak}}(k) = Input$ for $k = 1, \dots, nRF_{Weak}$
 60. $nRF_{WeakM1} = nRF_{Weak} - 1$

61. $nRF_{Shift} = Input$
 62. $RF_{Shift}(k) = Input$ for $k = 1, \dots, nRF_{Shift}$
 63. $W_{RF_{Shift}}(k) = Input$ for $k = 1, \dots, nRF_{Shift}$
 64. $nRF_{ShiftM1} = nRF_{Shift} - 1$

65. $nRF_{Strong} = Input$
 66. $RF_{Strong}(k) = Input$ for $k = 1, \dots, nRF_{Strong}$
 67. $W_{RF_{Strong}}(k) = Input$ for $k = 1, \dots, nRF_{Strong}$
 68. $nRF_{StrongM1} = nRF_{Strong} - 1$

69. $SumW = W_{RF_{Weak}}(1) + \dots + W_{RF_{Weak}}(nRF_{Weak})$
 70. $P_{RF_{Weak}}(k) = W_{RF_{Weak}}(k) / SumW$ for $k = 1, \dots, nRF_{Weak}$
 71. $SumW = W_{RF_{Shift}}(1) + \dots + W_{RF_{Shift}}(nRF_{Shift})$
 72. $P_{RF_{Shift}}(k) = W_{RF_{Shift}}(k) / SumW$ for $k = 1, \dots, nRF_{Shift}$
 73. $SumW = W_{RF_{Strong}}(1) + \dots + W_{RF_{Strong}}(nRF_{Strong})$
 74. $P_{RF_{Strong}}(k) = W_{RF_{Strong}}(k) / SumW$ for $k = 1, \dots, nRF_{Strong}$

75. $E_{RF_{Weak}} = RF_{Weak}(1) * P_{RF_{Weak}}(1) + \dots$
 $\quad + RF_{Weak}(nRF_{Weak}) * P_{RF_{Weak}}(nRF_{Weak})$

76. $E_{RF_{Shift}} = RF_{Shift}(1) * P_{RF_{Shift}}(1) + \dots$
 $\quad + RF_{Shift}(nRF_{Shift}) * P_{RF_{Shift}}(nRF_{Shift})$

77. $E_{RF_{Strong}} = RF_{Strong}(1) * P_{RF_{Strong}}(1) + \dots$
 $\quad + RF_{Strong}(nRF_{Strong}) * P_{RF_{Strong}}(nRF_{Strong})$

78. $RecNormFac = E_{RF_{Weak}} * P_{Weak_Years} +$
 $E_{RF_{Shift}} * P_{Weak_to_Strong_Years} + E_{RF_{Strong}} * P_{Strong_Years}$

79. $FRF_{Weak}(1) = P_{RF_{Weak}}(1)$
 80. $FRF_{Weak}(k) = FRF_{Weak}(k - 1) + P_{RF_{Weak}}(k)$
for $k = 2, \dots, nRF_{Weak}$

81. $FRF_{Shift}(1) = P_{RF_{Shift}}(1)$
 82. $FRF_{Shift}(k) = FRF_{Shift}(k - 1) + P_{RF_{Shift}}(k)$ for $k = 2, \dots, nRF_{Shift}$

```
83. FRFstrong(1) = P_RFstrong(1)
84. FRFstrong(k) = FRFstrong(k - 1) + P_RFstrong(k)
```

for k = 2,...,nRFstrong

```
85. ClimaSim = Input
```

```
86. OceanClimate(k) = 0 for k = 1 To nSIM20
```

```
87. Rnd (-1)
```

```
88. Randomize (123)
```

```
89. numb = Rnd()
```

```
90. If numb < 0.5:
```

```
91.     OceanClimate(0) = -1
```

```
92.     WeakRegime = True
```

```
93. If numb > 0.5:
```

```
94.     OceanClimate(0) = 1
```

```
95.     WeakRegime = False
```

```
*****
```

```
96. nYears = 1
```

```
97. While nYears < nSIM
```

```
98.     tU = Rnd()
```

```
99.     If WeakRegime:
```

```
100.         for k = 1, ..., 19:
```

```
101.             If tU < FWeak(k):
```

```
102.                 nWeakY = k
```

```
103.                 GoTo fCO
```

```
104.             End If-test
```

```
105.         End k-loop
```

```
106.         nWeakY = 20
```

```
107. fCO:
```

```
108.     nYearsNew = nYears + nWeakY
```

```
109.     nYearsNewM1 = nYearsNew - 1
```

```
110.     nYearsNewM2 = nYearsNew - 2
```

```
111.     If nYears < nYearsNewM1:
```

```
112.         OceanClimate(k) = -1 for k = nYears,..., nYearsNewM2
```

```
113.     End if-test
```

```
114.     OceanClimate(nYearsNewM1) = 0
```

```
115.     WeakRegime = False
```

```
116.     nYears = nYearsNew
```

```
117. If NOT WeakRegime:
```

```
118.     for k = 1, ..., 19:
```

```
119.         If tU < FStrong(k):
```

```
120.             nStrongY = k
```

```
121.             GoTo fWA
```

```
122.         End If-test
```

```
123.     End k-loop
```

```
124.     nStrongY = 20
```

```
125. fWA:
```

```
126.     nYearsNew = nYears + nStrongY
```

```
127.     nYearsNewM1 = nYearsNew - 1
```

```
128.     nYearsNewM2 = nYearsNew - 2
```

```

129.      If nYears < nYearsNewM1:
130.          OceanClimate(k) = 1   for k = nYears To nYearsNewM2
131.      End if-test

132.      OceanClimate(nYearsNewM1) = -1
133.      WeakRegime = True
134.      nYears = nYearsNew

*****

135. CritOilMort = Input / 100
' *****

136. FishMortJuv(k) = Input   for k = 100, ..., 200
137. FishMortAd(k) = Input   for k = 100, ..., 200
138. OilMort(k) = Input     for k = 100, ..., 200

139. FishMortJuv(k) = FishMortJuv(100)   for k = 0, ..., 99
140. FishMortAd(k) = FishMortAd(100)   for k = 0, ..., 99

141. FishMortJuvAV = FishMortJuv(0)
142. FishMortAdAV = FishMortAd(0)

143. NatSurvJuvFOav = (1 - NatMortJuv) * (1 - FishMortJuvAV)
144. NatSurvAdFOav = (1 - NatMortAd) * (1 - FishMortAdAV)

*****

145. AgeStrucJuvFO(t_Rec, 0) = E_Recr
146. AgeStrucJuvFO(k, 0) = AgeStrucJuvFO(k - 1, 0) *
    NatSurvJuvFOav           for k = t_RecP1, ..., t_MatM1

147. AgeStrucAdFO(t_Mat, 0) =
    AgeStrucJuvFO(t_Mat - 1, 0) * NatSurvAdFOav

148. AgeStrucAdFO(k, 0) = AgeStrucAdFO(k - 1, 0) * NatSurvAdFOav
    for k = t_MatP1, ..., t_Max

149. SpawnersFO(0) =
    AgeStrucAdFO(t_Mat,0)+...+AgeStrucAdFO(t_Max,0)
' *****

150. For kSim = 1, 2, 3, ... 100:
151.     kSimM1 = kSim - 1
152.     If kSim < 6 :   SpawnDensFO = SpawnersFO(kSimM1)
153.     If kSim ≥ 6 :   SpawnDensFO =
    [SpawnersFO(kSim - 5) +...+ SpawnersFO(kSim - 1)]/5
154.     If SpawnDensFO < SpawnCrit:
155.         RecrDD = SpawnDensFO / SpawnCrit
156.         wRF = RecNormFac
157.         RecruitsFO(kSim) = E_Recr *
    RecrDD * (wRF / RecNormFac)

158.     SurvDD_Juv_FO = NatSurvJuv * (1 - FishMortJuv(kSimM1))
159.     SurvDD_Ad_FO = NatSurvAdLowD * (1 - FishMortAd(kSimM1))

```

```

160.   AgeStrucJuvFO(t_Rec, kSim) = RecruitsFO(kSim)
161.   AgeStrucJuvFO(k, kSim) = AgeStrucJuvFO(k - 1, kSimM1) *
      SurvDD_Juv_FO   for k = t_RecP1,..., t_MatLOWD_M1

162.   AgeStrucAdFO(t_MatLowD, kSim) =
      AgeStrucJuvFO(t_MatLowD - 1, kSimM1) * SurvDD_Ad_FO
163.   AgeStrucJuvFO(t_MatLowD, kSim) = 0
164.   AgeStrucAdFO(k, kSim) = (AgeStrucAdFO(k - 1, kSimM1) +
      AgeStrucJuvFO(k - 1, kSimM1)) * SurvDD_Ad_FO
      for k = t_MatLOWD_P1,...,t_Max
165.   AgeStrucJuvFO(k, kSim) = 0
      for k = t_MatLOWD_P1,...,t_Mat
166.   SpawnersFO(kSim) = AgeStrucAdFO(t_MatLowD, kSim) +...
      + AgeStrucAdFO(t_MatLowD, kSim)

167.   If   SpawnCrit < SpawnDensFO < K_Spawn80:
168.     NatMorDD = NatMortAdLowD +
      (SpawnDensFO - SpawnCrit) * coefM
169.     NatSurvAdDD = 1 - NatMorDD
170.     SurvDD_Juv_FO = NatSurvJuv * (1 - FishMortJuv(kSimM1))
171.     SurvDD_Ad_FO = NatSurvAdDD * (1 - FishMortAd(kSimM1))
172.     hRd = (K_Spawn80 - SpawnDensFO) /
      (K_Spawn80 - SpawnCrit)

173.     wRF = RecNormFac
174.     RecruitsFO(kSim) = E_Recr * (wRF / RecNormFac)
175.     AgeStrucJuvFO(t_Rec, kSim) = RecruitsFO(kSim)
176.     AgeStrucJuvFO(k, kSim) = AgeStrucJuvFO(k - 1, kSimM1) *
      SurvDD_Juv_FO   for k = t_RecP1,..., t_MatLOWD_M1
177.     AgeStrucJuvFO(t_MatLowD, kSim) = (1 - hRd) *
      AgeStrucJuvFO(t_MatLowD - 1, kSimM1) * SurvDD_Juv_FO
178.     AgeStrucAdFO(t_MatLowD, kSim) = hRd *
      AgeStrucJuvFO(t_MatLowD - 1, kSimM1) * SurvDD_Ad_FO
179.     AgeStrucJuvFO(k, kSim) = (1 - hRd) *
      AgeStrucJuvFO(k - 1, kSimM1) * SurvDD_Juv_FO
      for k = t_MatLOWD_P1,..., t_MatM1
180.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
      SurvDD_Ad_FO   for k = t_MatLOWD_P1,..., t_MatM1
181.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k, kSim) + hRd *
      AgeStrucJuvFO(k - 1, kSimM1) * SurvDD_Ad_FO
      for k = t_MatLOWD_P1,..., t_MatM1
182.     AgeStrucAdFO(t_Mat, kSim) =
      AgeStrucAdFO(t_Mat - 1, kSimM1) * SurvDD_Ad_FO
183.     AgeStrucAdFO(t_Mat, kSim) = AgeStrucAdFO(t_Mat, kSim)
      + AgeStrucJuvFO(t_Mat - 1, kSimM1) * SurvDD_Ad_FO
184.     AgeStrucJuvFO(t_Mat, kSim) = 0
185.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
      SurvDD_Ad_FO   For k = t_MatP1 To t_Max
186.     SpawnersFO(kSim) = AgeStrucAdFO(t_MatLowD, kSim) +
      ... + AgeStrucAdFO(t_Max, kSim)

187.   If   SpawnCrit > K_Spawn80:

```

```

188.     SurvDD_Juv_FO = NatSurvJuv * (1 - FishMortJuv(kSimM1))
189.     SurvDD_Ad_FO = NatSurvAd * (1 - FishMortAd(kSimM1))
190.     wRF = RecNormFac
191.     RecruitsFO(kSim) = E_Recr * (wRF / RecNormFac)

192.     AgeStrucJuvFO(t_Rec, kSim) = RecruitsFO(kSim)
193.     AgeStrucJuvFO(k, kSim) = AgeStrucJuvFO(k - 1, kSimM1) *
        SurvDD_Juv_FO   for k = t_RecP1,..., t_MatM1

194.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
        SurvDD_Ad_FO   for k = t_MatLOWD_P1,..., t_Mat
195.     AgeStrucAdFO(t_Mat, kSim) = AgeStrucAdFO(t_Mat, kSim)
        + AgeStrucJuvFO(t_Mat - 1, kSimM1) * SurvDD_Ad_FO
196.     AgeStrucJuvFO(t_Mat, kSim) = 0
197.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
        SurvDD_Ad_FO   for k = t_MatP1,..., Max
198.     SpawnersFO(kSim) = AgeStrucAdFO(t_MatLowD, kSim) +...+
        AgeStrucAdFO(t_Max, kSim)

199. End of kSim 1,..., 100 - loop
' *****

200. For kSim = 100, 101, 102, ... 200:
201. If kSim < 106:     wRF = RecNormFac
202. If kSim ≥ 6 :
203.     tU = Rnd()
204.     Tnow = OceanClimate(kSim - 100 - t_Mat_Wait)
205. End if

206.   If Tnow = -1
207.     For k = 1,..., nRFweakM1:
208.       If tU < FRFweak(k):
209.         wRF = RFweak(k)
210.         GoTo KAL
211.       End If
212.     End k-loop
213.     wRF = RFweak(nRFweak)
214.   End if

215. KAL:

216.   If Tnow = 1:
217.     For k = 1,..., nRFstrongM1
218.       If tU < FRFstrong(k):
219.         wRF = RFstrong(k)
220.         GoTo VAR
221.       End If
222.     End k-loop
223.     wRF = RFstrong(nRFstrong)
224.   End if

225. VAR:

226.   If Tnow = 0
227.     For k = 1,..., nRFshiftM1
228.       If tU < FRFshift(k):
229.         wRF = RFshift(k)
230.         GoTo SHI
231.       End If
232.     End k-loop

```

```

233.     wRF = RFshift(nRFshift)
234.   End if
235. SHI:

236.   kSimM1 = kSim - 1
237.   If ClimaSim = 0:   wRF = RecNormFac
238.   If kSim < 106 :   SpawnDens = Spawners(kSimM1)
239.   If kSim ≥ 106 :   SpawnDens =
[Spawners(kSim - 5) +...+ Spawners(kSim - 1)]/5
'*****
240.   If   SpawnDens < SpawnCrit:
241.     NatSurvAdDD = NatSurvAdLowD
242.     RecrDD = SpawnDens / SpawnCrit
243.     If wRF > 2 Then wRF = 2
244.     Recruits(kSim) = E_Recr * RecrDD * (wRF / RecNormFac)
245.     AgeStrucJuv(t_Rec, kSim) = Recruits(kSim)
246.     AgeStrucJuv(k, kSim) = AgeStrucJuv(k - 1, kSimM1) *
NatSurvJuv   for k = t_RecP1,..., t_MatLOWD_M1
247.     AgeStrucAd(t_MatLowD, kSim) =
AgeStrucJuv(t_MatLowD - 1, kSimM1) * NatSurvAdLowD
248.     AgeStrucJuv(t_MatLowD, kSim) = 0
249.     AgeStrucAd(k, kSim) = (AgeStrucAd(k - 1, kSimM1) +
AgeStrucJuv(k - 1, kSimM1)) * NatSurvAdLowD
for k = t_MatLOWD_P1,..., t_Max
250.     AgeStrucJuv(k, kSim) = 0   for k = t_MatLOWD_P1,..., t_Max
251.     Spawners(kSim) = AgeStrucAd(t_MatLowD, kSim) +...+
AgeStrucAd(t_MatLowD, kSim)

252 If   SpawnCrit < SpawnDens < K_Spawn80:
253.     NatMorDD =
NatMortAdLowD + (SpawnDens - SpawnCrit) * coefM
254.     NatSurvAdDD = 1 - NatMorDD
255.     Recruits(kSim) = E_Recr * (wRF / RecNormFac)
256.     AgeStrucJuv(t_Rec, kSim) = Recruits(kSim)
257.     hRd = (K_Spawn80 - SpawnDens) /
(K_Spawn80 - SpawnCrit)

258.     AgeStrucJuv(k, kSim) = AgeStrucJuv(k - 1, kSimM1) *
NatSurvJuv   for k = t_RecP1,..., t_MatLOWD_M1
259.     AgeStrucJuv(t_MatLowD, kSim) =
(1 - hRd) * AgeStrucJuv(t_MatLowD - 1, kSimM1) * NatSurvJuv
260.     AgeStrucAd(t_MatLowD, kSim) =
hRd * AgeStrucJuv(t_MatLowD - 1, kSimM1) * NatSurvAdDD
261.     AgeStrucJuv(k, kSim) =
(1 - hRd) * AgeStrucJuv(k - 1, kSimM1) * NatSurvJuv
for k = t_MatLOWD_P1,..., t_MatM1
262.     AgeStrucAd(k, kSim) = AgeStrucAd(k - 1, kSimM1) *
NatSurvAdDD   for k = t_MatLOWD_P1,..., t_MatM1

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263.     AgeStrucAd(k, kSim) = AgeStrucAd(k, kSim) +
        hRd * AgeStrucJuv(k - 1, kSimM1) * NatSurvAdDD
        for k = t_MatLOWD_P1,..., t_MatM1
264.     AgeStrucAd(t_Mat, kSim) =
        AgeStrucAd(t_Mat - 1, kSimM1) * NatSurvAdDD
265.     AgeStrucAd(t_Mat, kSim) = AgeStrucAd(t_Mat, kSim) +
        AgeStrucJuv(t_Mat - 1, kSimM1) * NatSurvAdDD
266.     AgeStrucJuv(t_Mat, kSim) = 0
267.     AgeStrucAd(k, kSim) = AgeStrucAd(k - 1, kSimM1) *
        NatSurvAdDD for k = t_MatP1,..., t_Max
268.     Spawners(kSim) = AgeStrucAd(t_MatLowD, kSim) +...+
        AgeStrucAd(t_Max, kSim)

269.     If    SpawnDens > K_Spawn80:
270.         Recruits(kSim) = E_Recr * (wRF / RecNormFac)
271.         AgeStrucJuv(t_Rec, kSim) = Recruits(kSim)
272.         AgeStrucJuv(k, kSim) = AgeStrucJuv(k - 1, kSimM1) *
        NatSurvJuv for k = t_RecP1,..., t_MatM1
273.         AgeStrucAd(k, kSim) = AgeStrucAd(k - 1, kSimM1) *
        NatSurvAd for k = t_MatLOWD_P1,..., t_Mat
274.         AgeStrucAd(t_Mat, kSim) = AgeStrucAd(t_Mat, kSim) +
        AgeStrucJuv(t_Mat - 1, kSimM1) * NatSurvAd
275.         AgeStrucJuv(t_Mat, kSim) = 0
276.         AgeStrucAd(k, kSim) = AgeStrucAd(k - 1, kSimM1) *
        NatSurvAd for k = t_MatP1,..., t_Max
277.         Spawners(kSim) = AgeStrucAd(t_MatLowD, kSim) +...+
        AgeStrucAd(t_Max, kSim)

' *****
278.     OilMortality = OilMort(kSim)
279.     If kSim < 106:    SpawnDensFO = SpawnersFO(kSimM1)
280.     If kSim > 106:    SpawnDensFO =
        [SpawnersFO(kSim - 5) +...+ SpawnersFO(kSim - 1)]/5

281.     If    SpawnDensFO < SpawnCrit:
282.         RecrDD = SpawnDensFO / SpawnCrit
283.         If wRF > 2 Then wRF = 2
284.         RecruitsFO(kSim) =
        E_Recr * RecrDD * (wRF / RecNormFac)
286.         SurvDD_Juv_FO = NatSurvJuv * (1 - FishMortJuv(kSimM1))
287.         SurvDD_Ad_FO =
        NatSurvAdLowD * (1 - FishMortAd(kSimM1))

288.     If OilMortality > CritOilMort:
289.         RecruitsFO(kSim) = RecruitsFO(kSim) * (1 - OilMortality)
290.         AgeStrucJuvFO(t_Rec, kSim) = RecruitsFO(kSim)
291.         AgeStrucJuvFO(k, kSim) = AgeStrucJuvFO(k - 1, kSimM1) *
        SurvDD_Juv_FO for k = t_RecP1,..., t_MatLOWD_M1

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292.   AgeStrucAdFO(t_MatLowD, kSim) =
        AgeStrucJuvFO(t_MatLowD - 1, kSimM1) * SurvDD_Ad_FO
293.   AgeStrucJuvFO(t_MatLowD, kSim) = 0
294.   AgeStrucAdFO(k, kSim) = (AgeStrucAdFO(k - 1, kSimM1) +
        AgeStrucJuvFO(k - 1, kSimM1)) * SurvDD_Ad_FO
        for k = t_MatLOWD_P1,...,t_Max
295.   AgeStrucJuvFO(k, kSim) = 0
        for k = t_MatLOWD_P1,..., t_Max
296.   SpawnersFO(kSim) = AgeStrucAdFO(t_MatLowD, kSim)
        +...+ AgeStrucAdFO(t_Max, kSim)

297.   If   SpawnCrit < SpawnDensFO < K_Spawn80:
298.       NatMorDD =
            NatMortAdLowD + (SpawnDensFO - SpawnCrit) * coefM
299.       NatSurvAdDD = 1 - NatMorDD
300.       SurvDD_Juv_FO = NatSurvJuv * (1 - FishMortJuv(kSimM1))
301.       SurvDD_Ad_FO = NatSurvAdDD * (1 - FishMortAd(kSimM1))
302.       hRd = (K_Spawn80 - SpawnDensFO) /
                (K_Spawn80 - SpawnCrit)

303.       RecruitsFO(kSim) = E_Recr * (wRF / RecNormFac)
304.       If OilMortality > CritOilMort:
305.           RecruitsFO(kSim) = RecruitsFO(kSim) * (1 - OilMortality)
306.       AgeStrucJuvFO(t_Rec, kSim) = RecruitsFO(kSim)
307.       AgeStrucJuvFO(k, kSim) = AgeStrucJuvFO(k - 1, kSimM1) *
            SurvDD_Juv_FO      for k = t_RecP1,..., t_MatLOWD_M1
308.       AgeStrucJuvFO(t_MatLowD, kSim) = (1 - hRd) *
            AgeStrucJuvFO(t_MatLowD - 1, kSimM1) * SurvDD_Juv_FO
309.       AgeStrucAdFO(t_MatLowD, kSim) = hRd *
            AgeStrucJuvFO(t_MatLowD - 1, kSimM1) * SurvDD_Ad_FO
310.       AgeStrucJuvFO(k, kSim) =
            (1 - hRd) * AgeStrucJuvFO(k - 1, kSimM1) * SurvDD_Juv_FO
                for k = t_MatLOWD_P1,..., t_MatM1
311.       AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
            SurvDD_Ad_FO      for k = t_MatLOWD_P1,..., t_MatM1
312.       AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k, kSim) +
            hRd * AgeStrucJuvFO(k - 1, kSimM1) * SurvDD_Ad_FO
                for k = t_MatLOWD_P1,..., t_MatM1
313.       AgeStrucAdFO(t_Mat, kSim) =
            AgeStrucAdFO(t_Mat - 1, kSimM1) * SurvDD_Ad_FO
314.       AgeStrucAdFO(t_Mat, kSim) = AgeStrucAdFO(t_Mat, kSim)
            + AgeStrucJuvFO(t_Mat - 1, kSimM1) * SurvDD_Ad_FO
315.       AgeStrucJuvFO(t_Mat, kSim) = 0
316.       AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
            SurvDD_Ad_FO      for k = t_MatP1,..., t_Max
317.       SpawnersFO(kSim) = AgeStrucAdFO(t_MatLowD, kSim) +...+
            AgeStrucAdFO(t_Max, kSim)

318.   If   SpawnDensFO > K_Spawn80:

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319.     SurvDD_Juv_FO = NatSurvJuv * (1 - FishMortJuv(kSimM1))
320.     SurvDD_Ad_FO = NatSurvAd * (1 - FishMortAd(kSimM1))
321.     RecruitsFO(kSim) = E_Recr * (wRF / RecNormFac)

322.     If OilMortality > CritOilMort:
323.         RecruitsFO(kSim) = RecruitsFO(kSim) * (1 - OilMortality)
324.     AgeStrucJuvFO(t_Rec, kSim) = RecruitsFO(kSim)
325.     AgeStrucJuvFO(k, kSim) = AgeStrucJuvFO(k - 1, kSimM1) *
        SurvDD_Juv_FO           for k = t_RecP1,..., t_MatM1
326.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
        SurvDD_Ad_FO           for k = t_MatLOWD_P1, ..., t_Mat
327.     AgeStrucAdFO(t_Mat, kSim) = AgeStrucAdFO(t_Mat, kSim) +
        AgeStrucJuvFO(t_Mat - 1, kSimM1) * SurvDD_Ad_FO
328.     AgeStrucJuvFO(t_Mat, kSim) = 0
329.     AgeStrucAdFO(k, kSim) = AgeStrucAdFO(k - 1, kSimM1) *
        SurvDD_Ad_FO           for k = t_MatP1,..., t_Max
330.     SpawnersFO(kSim) = AgeStrucAdFO(t_MatLowD, kSim) + ...+
        AgeStrucAdFO(t_Max, kSim)
' *****

331. End of kSim 100,..., 200 - loop
' *****

332. Print 100 * Spawners(k) / K_Spawn for k = 0 To 200
333. Print 100 * SpawnersFO(k) / K_Spawn for k = 0 To 200

End of Program

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