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ERA Acute

Reports and other documents issued as preparation for or through the ERA Acute JIP (2009-2018) are made available through the Norsk Olje og Gass web-site, approved by JIP industry partners Equinor, Total EP Norge and Norsk Olje og Gass.

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

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

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

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

Report 6: ERA Acute – Development of Seafloor Compartment Algorithms – biological modelling

Authors: Cathrine Stephansen, Tom Sørnes, Geir Morten Skeie (Akvaplan-niva)

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

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SENSE
Sensitive Environments Decision Support

Report

ERA Acute – Development of Seafloor Compartment Algorithms

Statoil and Total

Biological Modelling –

Impact and Restoration Modelling for Resources on the Seafloor

Technical Implementation Guideline

Akvaplan-niva AS Report No. 5425.02

Akvaplan-niva

Akvaplan-niva AS
Rådgivning og forskning innen miljø og akvakultur
Org.nr: NO 937 375 158 MVA
Framsenteret
9296 Tromsø
Norway

www.akvaplan-niva.no

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Sensitive Environments Decision Support Group
Idrettsveien 6
1400 Ski
Norway
Tlf: +47 92804193/+47 91372252

Sensitive Environments Decision Support Group (SensE) is a group within Akvaplan-niva AS. SensE delivers a wide range of services related to environmental risk and oil spill preparedness for petroleum operations and activities in sensitive marine areas. SensE focuses on high quality competence when carrying out analyses and projects, and cooperates closely with the client in the process, to ensure a high degree of involvement of environmental aspects and preparation of analyses with a high quality.
Our tool www.senseweb.no is a presentation portal for viewing of full results from environmental risk assessments carried out by SensE at Akvaplan-niva AS and for other material. The service is open to all in the hearing period of analyses and continuously open for the client.

Report title:

ERA Acute – Development of Seafloor Compartment Algorithms – biological modelling

Author(s):

Cathrine Stephansen (Akvaplan-niva)

Tom Sørnes (Akvaplan-niva)

Geir Morten Skeie (Akvaplan-niva)

Contributions from:

Anders Bjørgesæter (Acona)

Torgeir Bakke (NIVA)

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Summary:

The report describes the development and theory behind the ERA Acute model for the seafloor compartment and its-sub-compartments. The model is based on Equilibrium Partitioning theory and feeding modes as the routes of exposure. Initial impact, lag-phase and restitution modelling is included in the impact model. Calculation steps for implementation are given. A flow sheet of the steps is available.

Project Manager:

Cathrine Stephansen

Quality Control:

Geir Morten Skeie

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Contents

Abbreviations and definitions

AD50 Abundance decrease 50%

APN Akvaplan-niva

BCF Bioconcentration factor

Bdepth Depth of bioturbated layer in mm. Used to derive HC concentrations in sediments from HC/m^2.

BSAF Biota to Sediment Accumulation Factor

BTEX Benzene, Toluene, Ethylbenzene and Xylene

CBR Critical Body Residue

CEDRE Centre of Documentation, Research and Experimentation on Accidental Water Pollution

C_{IW} Interstitial (pore) water concentrations

$C_{THCsed,cell}$ Concentration of THC in sediments in a cell

$C_{THC,IW,cell}$ Concentration of THC in interstitial water in sediments in a cell

$C_{THC,biota,cell}$ Concentration of THC in biota in a cell

$C_{,THC,WC,cell}$ Concentration of THC in the water column

OC Organic carbon

COC Sediment concentrations

DryDens Density of dry weight fraction of sediment.

DSHA Defined Situation of Hazard and Accident

DWH Deepwater Horizon Incident

EIF Environmental Impact Factor

EPA Environmental Protection Agency

EqP Equilibrium Partitioning Theory

ERA Environmental Risk Assessment

ERMS Environmental Risk Management System

ESB Equilibrium partitioning Sediment Benchmark

EU European Union

Fates Submodel of OSCAR

FCV Final Chronic Value

FM Feeding Mode

f-SSD Field-based SSD curve.

f_{OC} Total organic carbon content in sediment expressed as fractional mass TOC

Frap rapidly desorbing fractions

GIS Geographical Information System

GOM Gulf of Mexico

HC Hydrocarbon

HOC Hydrophobic organic compounds

IW Interstitial (pore) water

Ing Denotes relating to ingestion

Klif Climate and Pollution Control Authority, earlier name for Norwegian Environment Agency

K_{OC} Organic carbon (oc)/water partition coefficient for the chemical

K_{ow} Octanol-water coefficient

K_p Sediment – water partition coefficient

LAB Linear alkyl benzenes

LC_{50} Chemical concentration causing lethal effect in 50 % of organisms in test

LD_{50} Dose of toxicant causing lethal effect in 50 % of organisms in test

LOEC Lowest Observed Effect Concentration, the lowest concentration that caused a measureable effect in toxicity testing.

MOD Monitoring Offshore Database

MEMW Marine Environmental Modelling Workbench

N The resource unit/parameter for which an impact is calculated

NCS Norwegian Continental Shelf

NIVA Norwegian Institute of Water Research

NGU Norges Geologiske Undersøkelser

NOEC No Observed Effect Concentration, the highest concentration that did not cause a measureable effect in toxicity testing.

NPD Napthalene, Phenanthrene and Dibenzothiophene

OBM Oil Based Mud

OC organic carbon

OSCAR Oil Spill Combat And Response model

PAF Potentially Affected Fraction of species

PAH Polyaromatic hydrocarbons

PCB Polychlorinated biphenyls

pexp The probability of an individual being exposed given that the contaminant was present at a toxic/harmful level

$plet_{sed}$ Toxicity endpoint data for the seafloor sediment sub-compartment

plet Probability for death at given concentration

$plet_{LWC}$ Probability of lethal effect calculated for the lower water column compartment

$plet_{WC}$ Probability of lethal effect calculated for the water column main compartment

PNEC Predicted No Effect Concentration

QSAR Quantitative Structure-Activity Relationship

RIF Resource Impact Factor

SCV Secondary chronic value

SF Sensitivity factor

SOW Scope of work

SPM Suspended Particulate Matter

SQC Sediment Quality Criteria

SSD Species Sensitivity Distribution

TGD Technical Guidance Document

THC Total Hydrocarbon Content

THC_{IW} THC in interstitial water = $C_{THC,IW}$

THC_{OC} THC in organic carbon fraction of the sediment = $C_{THC,OC}$

THC_{sed} THC in sediments= $C_{THC,SED}$

t_{imp} Time until full impact is reached

t_{lag} Time from full impact to restitution starts

TLM Target Lipid Model

TLP Tension Leg Platform

TOC Total Organic Carbon

TOM Total Organic Matter

t_{res} Time when restitution is complete

UNEP United Nations Environment Programme

USEPA United States Environmental Protection Agency

UTM Universal Transverse Mercator

VEC Valued Ecosystem Component

WatC Water content of sediment

WSF Water Soluble Fraction

Indices used

seafl relating to seafloor compartment

sed relating to sediments (soft bottom substrates, including particles and interstitial water)

WC relating to water column ***main*** compartment.

LWC relating to ***lower*** water column ***sub***-compartment as part of the seafloor main compartment (for e.g. corals and sponges).

Ing relating to ingestion (sub-compartment

IW relating to Interstitial (pore) water

r relating to a resource, N

cell relating to one cell

sim relating to one simulation

month relating to one month

imp relating to impact (time)

lag relating to lag phase (time)

res relating to restitution (time)

Part 1 – Theory behind the model

Part 1 describes the theoretical background of the model, and consists of chapters 1 through 11.

1 Executive Summary

1.1 Introduction

This report presents the ERA Acute seafloor compartment impact and restitution model and the theory behind the model. It also includes descriptions of the individual calculation steps and the data structure required to implement computer programming of a software tool. A flow sheet of the calculation process is given as an attachment.

1.2 Background Prerequisites and Previous Decisions

ERA Acute has been developed through several multi-phase projects, beginning with EIF Acute between 2003-2006 (Clients Statoil and Norsk Hydro) and the previous development of ERA Acute level A (Clients Statoil and Total), which has been implemented in a software tool.

EIF Acute was developed between 2003-2006 and featured:

- Three compartments were included initially, shoreline, sea surface and water column.
- The initial template was other Environmental Impact Factor models, e.g. for produced water, which was based on the EU TGD for risk assessments, which makes used of a PEC/PNEC approach.
- In addition to thresholds, EIF Acute should estimates of the level of impacts above threshold levels, i.e. to make use of the whole dose-response curve. However, as several compartments had impacts for which a dose-response relationship and threshold levels could not be quantified, the approach was further modified to develop a framework that could be applied to all compartments. The grid-based EIF Acute model was therefore developed at three levels introducing the probability parameters of p_{let} and p_{exp}, as well as using a quantification of resource populations/population equivalents.
- EIF Acute included restoration modelling in the impact assessment. This was included in EIF Acute level 3, also introducing a possibility to include lag-phases where relevant.

EIF Acute was not implemented and model development was continued in 2008. The project group was given the task of deciding between currently available approaches and models as basis for developing the best approach for ERA Acute. Two levels (A and B) were to be developed, for the same three compartments.

In the scoping discussions, the project group decided to continue using the EIF Acute framework with elements from MIRA wherever relevant, and to base impact assessment on continuous functions between oil amounts and impacts where quantifiable.

Level A was finalized and implemented into a software tool in 2012 (Phase 1 and 2).

1.3 ERA Acute Development –Level B for Seafloor

Level B development was started in Phase 3 of the project. It was decided to base Level B on the framework of EIF Acute level 3, using the same probability factors for exposure and lethal effects and population fractions to calculate values for impact assessments, and the same time factors for lag-phase (if relevant) and restoration.

Project phase 3 also included developing a model for the seafloor compartment, including both sediment and hard-bottom substrates, reported herein. The seafloor compartment ERA Acute model was based on project prerequisites and a pilot project carried out in an initial part of the Phase 3 project, which concluded the following based on available scientific information:

- To use the SSD curve developed for the water column main compartment (EIF Acute 2005/2006 and 2011) for the seafloor compartment, based on lack of specific toxicity data from tests using sediment-dwelling organisms. Equilibrium Partitioning Theory (EqP) should be used to derive the pore water concentrations considered bioavailable to sediment-dwelling organisms. The theory behind this is discussed at length in the present document.

  - For hard-bottom substrates the SSD curve in water column main compartment is used directly.
  - EqP is used to derive pore water concentrations from water column SSD curves for sediment dwelling organisms
  - Through the decision, the seafloor compartment model is tied to the water column compartment SSD curve.
    - Future improvements to the ERA Acute water column (*WC*) SSD curve should be evaluated for validity for sediment-living organisms before being changed for the sediment compartment also.
    - To avoid the link, the algorithms implementing the WC SSD-curve could be duplicated into the sediment compartment model program.
- To divide the seafloor compartment into sub-compartments, based on impact mechanisms (exposure route and feeding mode) in the sub-compartment:
  - Hard-bottom substrates: Organisms living on hard substrates and exposed through the lower water column (LWC) (exemplified by corals and sponges).
  - Soft substrates (sediment)(*sed*): Organisms living completely in the sediments (*infauna*) or on the sediments (*epifauna*) or a combination. A distinction was made between organisms exposed through sub-compartments:
    - Interstitial water (pore water) (IW)
    - Sediment ingestion (in addition) (Ing)
- The OSCAR model currently does not give THC values in sediments (*sed*) in the output from stochastic simulations as is used for the other main compartments. It was thus decided to extract THC concentrations in sediment from single simulations, but allowing for continued development/updates of the ERA Acute model if improved THC input data can be retrieved from the future oil spill model or if other oil spill models are used.
- THC in sediment is the sum of the oil components that has an affinity to sediment (thus highly water soluble, rapidly biodegraded and low-molecular-weight components are excluded).
- Time until full impact is reached (t_{imp}) may be in the matter of months, for simplification it has been decided to set to 1 year as a default value as most acute impacts are assumed to be apparent after 1 reproductive year cycle. This can be set longer if information exists.
- None of the available data regarding restitution of sediments after oil exposure indicate a lag-phase (t_{lag}) between full impact and beginning of restorative re-growth. For soft-bottom substrates, a restitution time (t_{res}) calculation is suggested without a lag-phase.
- Recent information from the Macondo incident (April 2010) indicates that for several impacted corals no restitution has been observed to date (end 2014), thus a lag-phase is suggested for corals and sponges.

1.4 Brief Summary of the Model Description for the Seafloor

1.4.1 Parameters

ERA Acute Seafloor model uses the common parameters developed for ERA Acute/EIF Acute:

- p_{let} Probability of lethal effect at the given exposure
- p_{exp} Probability that the exposure will occur
- N Resource unit ("population") total
- t_{imp} Impact time. Time until full impact is seen.
- t_{lag} Lag time. Time until growth-inhibiting factors (e.g. contamination) have been reduced so much that restitution can start
  t_{res} Restitution time. Time from restitution starts until the community is assumed to be intact (pre-spill level).

1.4.2 Exposure

Following a spill, oil can reach the sediments as emulsified oil sinking to the seafloor, or by oil adhering to inorganic or organic particles. After sedimentation, partitioning between the sub-compartments sediment organic carbon (OC), interstitial water (IW) and the gut of sediment-ingesting organisms begins. The model requires input of sediment hydrocarbon concentrations in defined georeferenced grid cells ($C_{THCsed,cell,sim}$) from oil spill modelling, either by an oil drift model that provides this from statistical simulations (preferred) or by single-scenario.

For calculations related to organisms in soft substrates, ERA Acute uses EqP and user-input of Total Organic Carbon (TOC) content in the sediment and K_{OW} of the hydrocarbons to calculate $C_{THC,IW,cell,sim}$ and $C_{THC,biota,cell,sim}$ from $C_{THCsed,cell,sim}$

For organisms exposed in lower water column only, the concentration of THC in the water column is used, $C_{,THC,WC,cell,sim.}$ These calculated concentrations are used to read the corresponding *plet* values using the same dose-response curve used for the water column compartment in the already implemented in ERA Acute (Level A).

1.4.3 Basic Calculations of Initial Impact (All Seafloor Sub-Compartments)

The basic impact calculation is (Equation 1) (all compartments and sub-compartments):

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

Where:

- 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 B)

The Impact calculated above is for one resource (*r*), for one simulation (*sim*) for the seafloor main compartment (*comp=seafl*) and for one cell (*cell*). Based on feeding modes, the organisms can be exposed in the following seafloor sub-compartments: Lower water column (*LWC*), sediment interstitial water (*IW*), via ingestion of sediment (*Ing*), or combinations of these exposure routes. For organisms that actively ingest contaminated sediment particles, bioaccumulation through ingestion is accounted for. Biomagnification is considered too complex at present to incorporate into ERA Acute. For VECs that are habitats with groups representing several feeding modes, these feeding modes can be incorporated into the data set, and proportions of organisms belonging to each are used to provide an impact for the habitat VEC, based on proportional contributions from each of the impact mechanism basic equations that are relevant.

$$Imp_{r,cell,sim,seafl,month} = Imp_{r,cell,sim,seafl,month,FM1} \times (FM1) + Imp_{r,cell,sim,seafl,month,FM2} \times (FM2) + Imp_{r,cell,sim,seafl,month,FM3} \times (FM3) + Imp_{r,cell,sim,seafl,month,FM4} \times (FM4) + Imp_{r,cell,sim,seafl,month,FM5} \times (FM5) + Imp_{r,cell,sim,seafl,month,FM6} \times (FM6) + Imp_{r,cell,sim,seafl,month,FM7} \times (FM7)$$

Where FM1-7 are fractions (between 0-1) of the organisms present that belong to the respective feeding modes (denoted 1-7).

1.4.4 Calculation of Impact-, Lag- and Restitution Times.

ERA Acute at level B incorporates restitution time into the impact equation and the impact is calculated as the sum of the geometric area (Figure 1):

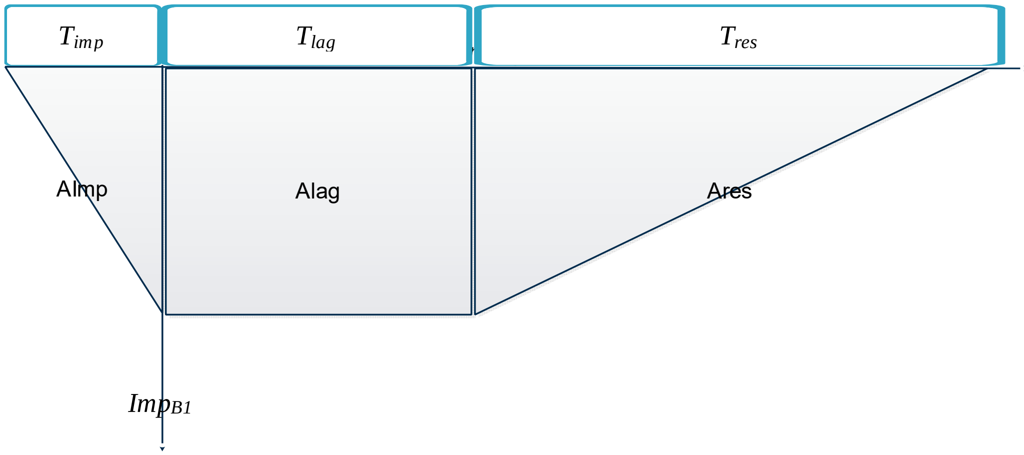

Figure 1. Linearised version of the impact function using damage and restoration values.

The data supporting exact quantifications of restitution times are scarce. Experiences from spills involve many factors and biases, and some assumptions and best estimates have been used to arrive at solutions suitable for the ERA Acute concept. For sediment-dwelling organisms, restitution times are calculated using the concentration of THC in the sediments, based on experience data from monitoring studies after the use of oil-based drilling mud on the Norwegian Shelf. Based on literature and best judgement, a linear relationship between $C_{THC,sed}$ and $T_{res,\ sed}$ is suggested.

$$T_{res,sed} \text{ (years)} = (C_{THC,sed} - C_{threshold,sed})/C_{benchmark\text{-}max,sed} \times 20 \text{ years}$$

For corals exposed in lower water column only, the data on restitution may be improved in the future when results from the Deepwater Horizon incident improve knowledge on restitution times of coral reefs and deep-sea corals impacted by oil spills. Currently, it seems that heavily impacted corals have not begun to recover. The suggested preliminary restitution times of corals presented in this work are based on limited studies of impacts, as well as growth rates of coral colonies. The table suggested is based on the impact level (p_{let}) in intervals and gives preliminary best estimate values of $T_{res,coral.}$ and $T_{lag,coral.}$ for use in ERA Acute until better data are available.

The data from offshore monitoring after use of oil based mud indicate that the lag-phase and recovery phase as they have been defined in ERA Acute are intertwined in the sediments, and lag-phase in sediments is therefore set to $T_{lag,sed} = 0$.

In the seafloor compartment, restitution times are incorporated into the impact calculations at level B, based on the linearized model in Figure 1. Impact calculations are carried out in several steps where the results can be

$$ImpB_{r,cell,sim,seafl,month} =$$

$$(Imp_{r,cell,sim,seafl,month} \times T_{imp})/2 + (Imp_{r,cell,sim,seafl,month} \times T_{lag}) + (Imp_{r,cell,sim,seafl,month} \times (T_{res} \times SF)/2$$

Where SF is a resource specific optional sensitivity factor related to the resource's restitution time that can be entered if the resource is known to have a shorter or longer restitution time than indicated in general for sediment communities (Default should be SF=1).

1.4.5 Summations and Inclusion of Frequencies for Risk Calculation

The results of the initial impact $ImpB_{r,cell,sim,seafl,month}$ are used for further calculations in a series of different steps: Average impacts in different georeferenced cells are calculated based on all simulations and can be presented in maps, and cell-based statistics can also be presented in graphs/statistics. Impacts are also summed up over all cells to provide a total impact for the resource, and these can be presented in graphs.

Results are further summed up over all simulations (if a multi-simulation oil drift model providing $C_{THC,sed}$ is used), and entering in a series of further calculation steps, the probabilities of scenarios and probabilities of defined situations of hazard and accident are entered to provide the final risk expression for the DHSA.

$$\mathrm{R}isk_{\mathrm{r,cell,DSHA,seafl,month}} = \mathrm{EImp}_{\mathrm{r,cell,DSHA,seafl,month}} \times frequency_{DSHA}$$

The model has a monthly resolution providing that input data have a monthly resolution. Every calculation step that gives a cell-based result can be visualised on a map and all summations over all cells give total impacts that can be graphed in various ways.

A suggestion is also given for suitable steps to export results before calculations with probabilities, so a risk matrix approach can be used.

1.4.6 Comparison with MIRA (OLF, 2007)

The seafloor compartment is not part of the current MIRA methodology. A comparison can therefore not be made.

1.5 Conclusions

The seafloor main compartment has not been implemented into ERA Acute previously, thus both level A and level B are developed in the current phase 3 of the project.

The seafloor compartment consists of several community types. In ERA Acute they are represented either as sediment or hard-bottom substrates. VECs may be community-based habitats consisting of several feeding modes or single species.

Organisms in the seafloor compartment are exposed either directly from the lower water column (hard-bottom living organisms and *epifauna*) or through living in the sediment. Exposure for sediment-dwelling organisms through the sub-compartments interstitial water and/or ingestion is derived from sediment THC concentrations by using Equlibrium Partitioning (EqP) to calculate THC concentration in the interstitial water, to which the organisms are exposed. Exposure for organisms that ingest sediment is calculated by including the BSAF.

THC-concentrations calculated for the exposure modes are entered into the SSD curve for the water column main compartment. The seafloor compartment is therefore closely linked to the water column compartment.

Lag-phase is difficult to separate from restitution, and these are thus combined. The exeption is corals, for which evidence suggests a lag-phase of several years. Impact-, lag- and restitution time factors are incorporated into the impact calculation of level B based on a linearised model. The time factors are reported separately. Impact calculations are carried out in several summation steps allowing for visualisations in maps, graphs and other formats. By implementing probabilities of scenarios, DSHA etc. the risks are calculated.

2 Introduction

2.1 Background

A model development approach was proposed for the seafloor compartment (June 2012) based on prerequisites, decisions and clarifications made in two net-meetings within APN and between APN and SINTEF as well as discussions between Gro H. Olsen and M. Smit, building on the meetings in February and April of 2012. However, based on comments from the Clients to the draft of 12.06.2012, and the fact that specific toxicity tests on benthic organisms were not found in the pilot study (Akvaplan-niva, 2012), a simplified approach was suggested as per June 2013 to use SSD curves and toxicity values from the water column and to extrapolate these to sediment *infauna* using EqP.

Seafloor compartment basic algorithms for Level A build on the work carried out in ERA Acute Phase 1 (2011). Phase 3 development therefore focuses on finding relevant p_{let}, and p_{exp} values and defining the resource parameter "N" for level A and B, as well as t_{res} and t_{lag} for the Level B algorithms.

The seafloor compartments include both soft and hard substrates. In earlier phases of the work, it has been decided that the intertidal zone is developed by the shoreline workgroup. The impact function for the seafloor compartment is also to be used for Level A. Oil parameters that are needed for ERA Acute calculations are discussed. It has been noted that it is necessary to distinguish between exposure in the water column and sedimentation/accumulation in seafloor soft substrates as well as exposure through pore water.

It was decided in the scoping phase of ERA Acute (early 2009) that the concepts from EIF Acute should be built on, ie. the concepts of the below given parameters, and that the basic algorithms of Level B should follow the foundation from Level 3 from EIF Acute 2005 using impact size and duration of impact as the basic concepts (then denoted resource impact factor equation, as it was resource specific, and the number of resources in each compartment may vary):

- p_{let}
- p_{exp}
- N
- t_{imp}
- t_{lag}
- t_{res}

These factors are to be developed first time for the seafloor compartment.

Numerical results of the model will depend on p_{let}, p_{exp} and N-values. "N" is the resource unit/parameter for which an impact is calculated, and its distribution in a grid cell is a fraction of the "whole" which needs to be defined for each resource group. This 100 % of the resource unit (whole population, intact community etc.) reflects the fraction of the full potential impact and needs definition for each compartment.

Damage and restoration parameters should be defined in functions or lookup tables that can be programmed or given as input/lookup tables. Inter-changeable lookup tables are recommended for non-function parameters.

To calculate *plet* in sediment, toxicity data for sediment organisms are needed. In the first phase of the Level B development project, Gro H. Olsen, PhD looked into the possibilities for obtaining specific SSD-curves for *infauna*. However, there is a lack of experiments involving sediment dwelling organisms, the typical test organisms are often aquatic. The pilot study included a literature/database search and information from previous studies, and it revealed that there were insufficient data using benthic organisms to fulfil the requirements for data quality and diversity to utilize statistical extrapolation methods to derive a toxicity endpoint *specifically* for benthic organisms. Hence, SSD curves to derive *plet* values cannot be constructed for the benthic compartment using only benthic organisms. The conclusions from that phase were that data from aquatic species would have to be used to derive one or more SSD curves for representative compounds of the groups of (pseudo)-components. However, data was already available from the work carried out by

SINTEF and Statoil (Nilsen et al., 2006) that could be used. The conclusions of the study and the discussions that followed lead to the current revised model, which utilizes the SSD curves developed for water column and equilibrium partitioning theory (EqP) to derive the necessary endpoint parameters for the sediment-dwelling organisms. The theoretical basis for this approach is well established (EPA 2003, EPA 2008) and is discussed in this document. It was also decided to use experience from toxicity testing of sediments contaminated with oil based mud from the Norwegian Continental Shelf to validate, adjust or support the theoretical approach outlined here, where relevant.

One later adaptation was the instruction in the scope of work SOW to use THC instead of single components, however – we will define THC for the sediment as the sum of components with affinity to sediment. The goal is to develop a model that is as precise and scientifically accurate as possibly ("scientifically robust") while keeping it easy to use for the user, and requiring as few input parameters as possible, whilst maintaining detail enough to distinguish between cases. Also, hydrocarbon components that are too low-molecular-weight, too water soluble or too degradable to reach the sediments will not be part of the THC that is reported as bound to sediment.

ERA Acute builds on the decision made in the EIF Acute project (2003-2006) to use threshold values instead of PNEC values (Nilsen et al. 2006) which makes the SSD approach the most preferred of the two EU Technical Guidance Document (TGD) methods (either assessment factors or statistical extrapolation (SSD) approach). ERA Acute (based on EIF Acute) aims to calculate lethality above the threshold values by calculating a fraction of the population killed/non-reproducing; therefore, the full dose-response curve must be established for a VEC in the compartment. For the seafloor compartment, it has been suggested and decided to use communities in substrates as the VEC unit, a decision which supports the use of species sensitivity distributions.

Data availability and detail, mechanisms of contamination, retention of oil and degradation issues of relevance to impact/lag/restoration functions for biota (excluding oil drift modelling issues) are discussed for the substrate types, and main route of exposure is given.

The availability of toxicity data was studied in the above mentioned pilot study. The EqP approach is based on available oil sedimentation parameters, and fate and distribution of sedimented oil, and impact depends on community composition and substrate types. Monitoring studies on the NCS gives some information on biodiversity vs. oil amounts and is used to support especially restitution calculations.

Resources are divided into functional groups of benthos organisms, which is relevant because the feeding mode has been shown to be one of the most important biological parameters that influences fate and effect of oil pollution in benthos.

The traditional procedure for evaluating effect of sediment-based compounds on benthic organisms is through sediment chemistry, benthic invertebrate community and laboratory sediment toxicity testing. The three different methodologies do not always agree. If there are data available for effects on communities they may be useful, e.g. to find threshold levels for effects on specific communities.

The suggested method requires the applied oil drift model to provide concentrations of the relevant hydrocarbon compounds in sediment and/or pore water. However, currently used oil drift models (in statistical mode) do not supply this. A work-around is shown for the OSCAR model.

2.2 Basis – Generic Model for All Compartments

The basis for ERA Acute Level A is described in Spikkerud *et al*. (2010), which describes how impact is calculated for each resource, cell, simulation and compartment. Spikkerud *et al.* (2010) also describes summations across cells, simulations and compartments, as well as inclusion of frequency of DSHAs and scenarios to provide a risk estimate.

Level A is an impact model, using ERA Acute at Level B also includes restoration modelling, including a lag-phase before restitution growth can begin, if relevant for the compartment.

The basic impact calculation is (Equation 1) (all compartments).

Equation 1 $$\mathrm{Imp}_{r,cell,sim,comp} = p_{\exp r,cell,sim,comp} \times p_{let,r,cell,sim,comp} \times N_{r,cell,comp}$$

Where:

N=1 if there are no resource data (Level A.1)

N=0 *or* 1 if presence/no presence data (e.g. polygons of areas)

N= 0-1 (if fractions of a population, fraction of a "whole" valued resource etc, (the chosen resource unit)

The above equation calculates the basic impact for one VEC (resource) in one cell, in one simulation of oil drift, in the compartment. Through a series of summations and averages, a total risk is calculated. Total risk calculation for all level A.1, A.2 and A.3 types are described in Spikkerud *et al.* (2010), in equations 1.1 to Equation 7, from impact to a single resource in a single cell and single simulation, to the risk for a VEC resource in a whole scenario (consisting of many simulations).

The parameter p_{exp} is the probability of an individual being exposed, given that the contaminant was present at a toxic/harmful level. The factor was introduced in EIF Acute to take into consideration certain factors, e.g. behavioural, that might cause the individual in a population to "escape" exposure or have a higher probability of being exposed. In the sediment compartment, this is less relevant, as within the scale of a 10x10 km grid cell, there is assumed to be no movement of the individuals to adjacent cells. It follows from the basic EIF/ERA Acute equation (equation 1) that p_{exp} therefore is *not* the concentration of contaminant in the environment, but a probability of being exposed to the toxic dose. The hydrocarbon concentration (dose) is obtained from an oil spill model and used to calculate the expected response lethal fraction, *plet*. The probability of exposure given oil contamination and presence of organism (p_{exp}) is a modifying factor and is suggested to be set to $p_{exp} = 1$ as in the water column, using the exposure concentration directly to derive lethality.

The basis for level B for the seafloor compartment is, as for the other compartments, taken from the previous work of EIF Acute (Spikkerud *et al.* 2006) and the work carried out in previous phases of the ERA acute project. These reports describe the use of impact time (denoted t_{imp}), lag-phase time (if relevant) (denoted t_{lag}) and restoration time (denoted t_{res}), to calculate a resource impact factor for each resource assigned to a compartment. This theory was introduced in Lein *et al*. (1992), and further used in Moe *et al.* (2000a, 2000b) and by Brude *et al.* (2003). All these reports describe the DamEShore concept development and implementation for shoreline oil spill impact. The concept of using a geometrical area calculated by extent of impact and time of impact was continued in the development of EIF Acute (Johansen *et al*., 2003, Østby *et al.* 2003) (Figure 2) and used in a linearized form in Spikkerud *et al.* (2005) (first linearized in Spikkerud and Brude, 2004) (Figure 3).

The theoretical process of damage and recovery is illustrated in Figure 2, and the rationale for choice of this model is further described in Østby *et al.* (2003). In this figure, the following time parameters are defined:

t_{imp}: Impact time. Time until full impact is seen. This was in the initial work (2005) set to 1 year as a preliminary value as most acute impacts are assumed to be apparent after 1 reproductive year cycle.
t_{lag}: Lag time. Time until contamination has been reduced so much that restitution can start.

t_{res}: Restitution time. Time from restitution starts until the community is assumed to be intact.

From this theory, a VEC-specific Resource Impact Factor (RIF) was introduced and calculated (Spikkerud et al., 2005) (Figure 3). However, for the present development of ERA Acute level B (2014), a simpler approach was requested in the SOW, where the risk endpoint is calculated as size of the impact and probability for a restitution time length, assuming this will lead to an easier concept to understand and use for risk management. The below figures are therefore only given as *historical reference* to EIF Acute.

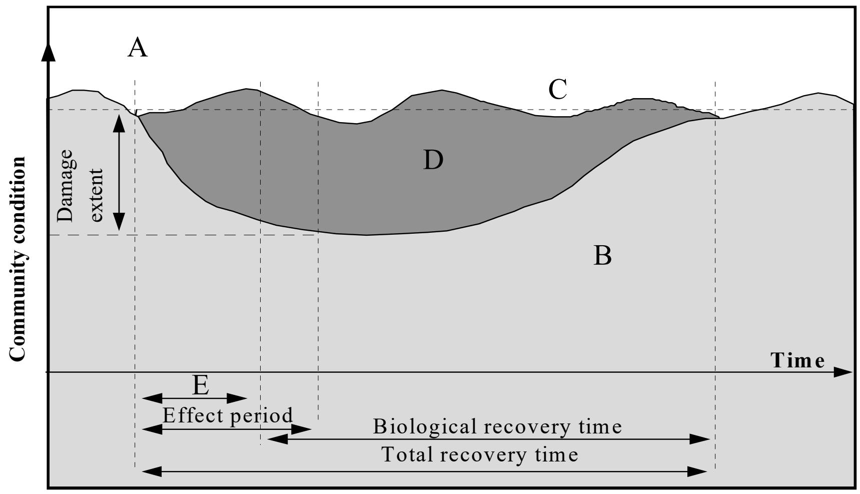

Figure 2 The impact of an oil spill on the condition of the community (or population). The sensitivity is expressed as the shaded area (D). A: the time at which the contaminant strikes the resource; B: recovery process after the initial exposure; C natural conditions, including fluctuations without contamination; E: initial impact period. Modified from Lein et al. (1992).

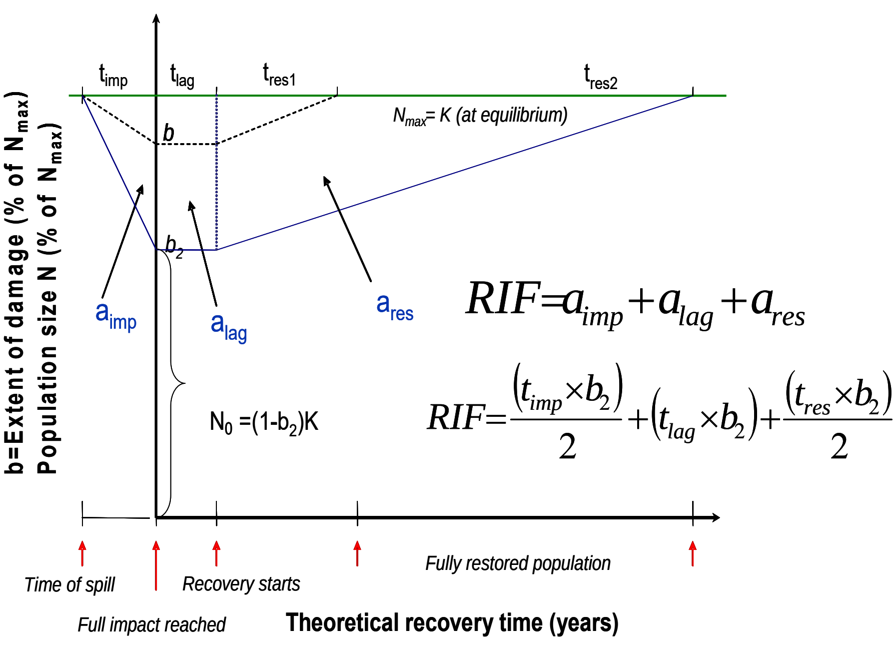

Figure 3 Resource Impact Factor (RIF) calculated from the linear functions of damage and recovery of an oil-sensitive resource. RIF is calculated for a resource as a total over all grid cells, using an average population loss b over all simulations. Here, two examples are shown, with two levels of impact. Nmax= Size of population before impact assumed to be at ecological equilibrium (denoted K), N0= Population left after full impact, b= size of impact (relative loss of population), timp = duration of impact, tlag = duration of lag-phase before restoration can begin, tres = duration of restoration time (years. (Spikkerud et al., 2005).

2.3 Pilot Study of SSD Curve from EqP for Sediment for Naphthalene

To develop sediment compartment-specific SSD curves for acute and chronic lethality calculations, ideally, one would use toxicity studies for benthic organisms. However, the pilot study undertaken as part of the ERA Acute project by Akvaplan-niva in 2012, concluded that there were insufficient data from toxicity studies on benthic organisms, and that aquatic species data would have to be used.

Instead, the EqP theory approach was chosen by the Client experts and Akvaplan-niva, to derive benthic SSD curves from aquatic ones and if possible, to use one curve for all hydrocarbons (THC). To verify feasibility of the EqP approach for obtaining an SSD, a trial was carried out. Naphthalene was chosen to construct a SSD curve for acute effects based on effect concentration in sediment calculated using the EqP theory (Table 1. the Potentially Affected Fraction of species (PAF) was shown to be used directly as p_{let} for sediment dwellers (Gro Olsen, ERA Acute 2012).

It was also originally suggested to make different SSD curves for groups of chemicals and substrates, however, this was deemed too complex by the Client expert group, given the level of input that would be needed.

The p_{let} (sediment) for naphthalene can be read from the SSD curves as PAF (Potentially Affected Fraction of species) (Figure 4).

Table 1 Aquatic LC50 values and Koc value used to calculate sediment LC_{50} ng/g oc for ***naphthalene****.*

Compound	Koc	Taxonomy	Species	Effect endpoint	water LC_{50} (µg/L)	LC50 ng/g oc = (LC_{50}ng/L)*Koc(L/kg_{00}) *1kg/1000 g_{00}
Naphthalene	1990.67	Crustacea	*Daphnia pulex*	LC_{50} (96 hours) mortality	1000	1990.67
			Eualis suckleyi	LC_{50} (96 hours) mortality	1390	2767.0313
			Neomysis americana	LC_{50} (96 hours) mortality	1065	2120.06355
			Paneaus aztecus	LC_{50} (96 hours) mortality	2500	4976.675
		Fish	*Oncorhynchus mykiss*	LC_{50} (96 hours) mortality	855	1702.02285
			Oncorhynchus gorbuscha	LC50 (96h) mortality	1200	2388.804
			Oncorhynchus kisutch	LC_{50} (96 hours), mortality	2660	5295.1822
			Micropterus salmoides	LC_{50} (96 hours), mortality	510	1015.2417
			Pimephales promelas	LC_{50} (96 hours) mortality	5650	11247.2855

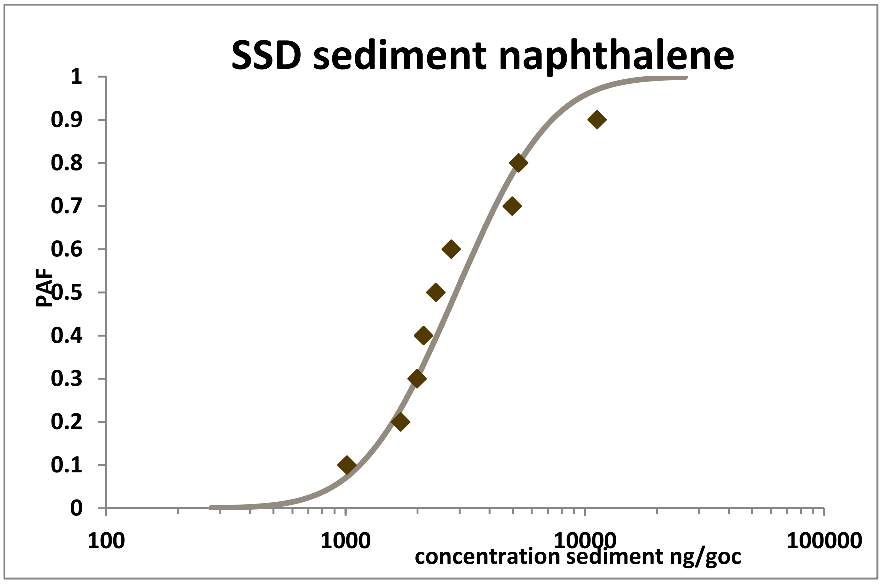

Figure 4 Species-sensitivity distribution curves showing the relation between naphthalene concentration sediment (ng/g oc) and potentially affected fraction of species (PAF). PAF is used directly as p_{let} for sediment dwelling organisms.

2.4 Starting Point for the Present Work

Since the data available are mostly for aquatic species anyway, and the SOW was revised to suggest using THC instead of single components, the suggestion was therefore made to use the same *plet* curve as in the water column. This means one can utilise the work carried out in 2003-2006 on toxicity for the water column, or implement later QSAR-based improvements for the water column in general. SINTEF have in the current project development phase, suggested an impact function for corals and sponges (seafloor organisms exposed in water, and that live on hard substrates). Using Equilibrium Partitioning Theory (EqP) and either the current or future *plet* toxicity curve (SSD function) of the water column main compartment, a *plet* value for toxicity assessment in the sediment sub-compartment (soft bottom substrates) can be calculated. Background information on the work carried out for the water column in the EIF Acute project can be found in the SINTEF/Statoil contribution from 2005/2006, available in the documentation of EIF Acute (Johansen, 2006; Nilsen et al., 2006).

3 Sedimentation of Oil Following an Oil Spill

3.1 Sedimentation of Oil from an Acute Oil Spill

3.1.1 Transport of Oil to the Sediment

Contamination of sediments/seafloor from a release of oil in the marine environment may occur along the following pathways:

1) *Sinking of emulsified oil to the seafloor*, either due to the emulsion reaching a higher density than the ambient water, or due to the emulsion incorporating sediment particles, forming globules with a higher density than the ambient water. An example of the latter is patches of emulsified oil at a sandy shore, incorporating sand particles due to wave action.

2) *Oil adhering to inorganic particles* (e.g. clay) under high energy conditions, still adhering to the particles as conditions get calmer. An example is the grounding of the tanker "Braer" on Shetland in January 1993, where 5 subsequent weeks of storm to hurricane wind conditions caused a high degree of dispersion of oil and mineral particles, which later settled far offshore in deep water.

3) *Oil adhering to organic particles*, either passively to e.g. marine snow, or through active ingestion by marine fauna and secondary deposition through fecal pellets.

Ongoing research by the College of Marine Science at the University of South Florida (USF) *(In progress*) identified three distinct transport pathways of hydrocarbons after the Deepwater Horizon (DWH) incident: Oil-contaminated marine snow, sinking of burnt-oil particles, and advective transport of dissolved oil from the deep intrusion that occurred at approximately 1000-1200 m depth. The oil was deposited through these three pathways as particulate organic matter, oil-droplets, weathered oil, weathered burned-oil and dissolved hydrocarbon compounds into the deep-sea during 2010-2011. The values were compared to pre-2010 years and it has been found that higher concentrations of PAHs were observed in 2010 (up to 525 ng/g) compared to pre-2010 years (up to 320 ng/g). The large increase of PAH concentrations and large PAH fluxes observed in 2010-2011 may indicate a potential ecological risk to deep-sea environments, although these values were lower than urbanized and industrialized areas worldwide.

Formation of marine snow is described as flocs containing oil that were formed through the interaction of three mechanisms: Through the production of mucous (exopolymer) webs formed by oil-degrading bacteria at the slick, through particulated and coagulating matter that was contaminated by oil at the surface and through phytoplankton that coagulated at the surface (Passow et al 2012). The spill occurred in spring, and algal presence may therefore be expected to vary with the amounts of particulate matter and algal activity near the slick, peaking at times with high diatom blooms. This marine snow is responsible for a major part of the downward transport of material by settling. Large particles may sink at velocities of 100 m per day, rapidly enough to avoid degradation in the upper water layers. Shortly after the onset of the DWH incident in May 2010, large particles of marine snow were observed on the sea surface near the sunken platform, suggested to have been associated with the oil spill. One month later, the marine snow was gone, indicating sedimentation of the flocs had occurred within that time period (Passow et al 2012). The research results from the DWH incident are still in progress, and the amounts of oil that reached the sediments and in which time-frame sedimentation and full impact occurred is still not clear. One recent estimate (Chanton *et al.* 2014) is that1.8 to 14.4% of the oil reached the sediment.

3.2 Partitioning Between the sub-Compartments in the Sediment compartment

Following initial sedimentation of the oil, the degree to which the hydrocarbons will continue to be adhered to the lipophilic organic carbon of the sediment is dependent on the balance between lipophilic and hydrophilic properties of the THC molecule. A partitioning between sediment organic carbon, overlaying water compartment and interstitial (pore) water will begin and continue in the direction of equilibrium. The rate of leaching from organic carbon-bound to water-phase bound HC depends on the Kow of the HC molecule. This is the basis for using Equilibrium Partitioning Theory and is further explored in the discussion of EqP in chapter 6.

4 Habitats, Feeding Modes and the Exposure of Organisms

4.1 Habitats

To prepare a robust model that requires a certain amount of VEC data to use, but is applicable without extensive research ahead of each analysis if specific data do not exist, we propose a practical approach to the definition of habitat types in the model. Proposed habitat types are (slightly modified from ISO-14688-1):

Hard substrate habitat types

- *Rock: Continuous rock cover, also including cobbles, boulders and large boulders.*
- *Gravel: Consists of inorganic particles 2 to 63 mm in size.*
- *Coral reefs*

Sensitive communities associated with hard substrates include corals, kelps and sponges.

Figure 5. Hard substrate (boulder) with coral growth (left), close-up of a sponge (right) (Photos Cathrine Stephansen)

Soft substrate habitat types

- *Sand: Consists of inorganic particles of 63 µm to 2 mm in size. Transported mainly as bedload.*
- *Mud (silt and clay): A fine, cohesive material of particles less than 63 µm in size. Potentially rich in organic matter. Transported in suspension.*
- *Sandy mud: A mixture of sand and mud.*

Sensitive communities associated with soft substrates include sea grass and sea pens.

Figure 6. Sea pen (left) and feather worm (right) on soft substrates with varying grain size (Photos Cathrine Stephansen)

Soft bottom sediments are predominant at greater depths. To discriminate between hard and soft bottom, *if detailed data do not exist*, we propose the following simplified approach:

- Assume that hard bottom environments are restricted to grid cells containing shoreline, or to cells with water depths e.g. shallower than 20 m. This could allow a level B approach even where detailed data do not exist.

4.2 Feeding Modes

Organisms' way of life, including their feeding mode(s), may control to what extent they are primarily exposed to contaminants suspended in the water column, resting at the sediment-water interface or buried in the sediments. Recognizing the need for simplification in the context of ERA Acute, feeding modes will serve to allocate exposure routes and thereby impact functions to organisms/groups of organisms included in the assessments.

In general, bottom organisms often hold one of the following five feeding strategies (Rosenberg, 2001):

Suspension feeders

Suspension feeders capture food particles from the water (i.e. removes them from suspension) using for example stinging tentacles. This strategy has been adopted by members from the Anthozoa class, including scleractinian corals and octocorals.

Filter feeders (a sub-group of suspension feeders) filter dissolved and suspended matter from the water by pumping water through filtration structures. Includes e.g., some tunicates, bivalves and sponges.

Areas with high currents tend to see more species of suspension feeders.

Figure 7. Barnacles (suspension feeders) embedded in a sponge (left), Christmas-tree worm (suspension feeder) embedded in a soft coral on a coral reef (right) (Photos Cathrine Stephansen)

Surface deposit feeders

Organisms that consume particulate, organic material deposited at seafloor sediments (e.g., some holothurians and echinoids).

Deposit feeders tend to be found in areas with finer sediments (dominant in muddy sediments).

Figure 8. A sea cucumber partly buried in the sediment, but feeding on surface deposits (Photos Cathrine Stephansen)

Sub-surface deposit feeders

Organisms that consume organic material below the surface of seafloor sediments (e.g., some bivalves and polychaetes).

Herbivores

Organisms that consume plant material in the benthic assemblage.

Carnivores

Organisms that consume other fauna (e.g., some starfish and gastropods).

Finer sediment habitats are more likely to support carnivores that primarily feed at the sediment-water interface.

Figure 9. A nudibranch (gastropod) grazing on a colony of bryozoans. (Photo Cathrine Stephansen)

For some species, morphology may reveal their primary feeding mode. For others, assigning a feeding mode is far more complex. Some species can even switch between feeding modes, such as the brittle star *Amphiura filiformis* (Rosenberg, 2001). Thus, the above classification will necessarily be a simplification, but in our view suitable for ERA Acute.

4.3 Predominant Feeding Modes

In general, one can assume that:

- areas considered sensitive due to the presence of specific species or communities, such as coral reefs (hard bottom), kelp forests (hard bottom) or sea grass beds (soft bottom) are mapped more frequently and at a higher level of detail, securing availability of more detailed data.
- potentially sensitive habitats/species are mapped more sporadically at greater depths, given the greater efforts needed to carry out site specific surveys.

Thus, for areas where biological data of sufficient detail are not available, we propose to assign predominant feeding modes (and thus primary exposure pathways) based on observations for the different substrate types. Proposed guiding principles:

Along the depth gradient

1) In shallow, euphotic benthic habitats, one can expect tight coupling between the primary production of plankton and benthic consumers. Below the photic zone, the link between plankton and benthos is less efficient.

The success of filter feeders assumes, at least temporarily, supply of sufficient particles of potential food suspended in the water. Thus, filter feeders, along with herbivores, should prefer “shallower” areas.

2) The greater the depth, the greater the proportion of organic matter that is decomposed before it arrives at the bottom. And, by then, its nutritional value for benthos has dramatically decreased (Barnes and Hughes, 1988).

Thus, being less sensitive to the benthopelagic coupling, deposit feeders should play a greater role at increasing depths.

Along the soft/hard bottom gradient

In Pearson and Rosenberg`s paper “Feast and Famine” (1987), the authors describe a habitat related depth distribution of the five feeding mode groups described above, also including mobility and modes of feeding habit (jawed, tentaculate, etc.). Some of their main conclusions are;

- carnivores were found in all habitats
- deposit feeders were to be more abundant on accumulation bottoms
- the highest diversity of functional groups could be found in offshore sandy mud

For soft substrate habitat types:

<u>Sand</u>

In areas dominated by sand, the sediment is poor in organic matter. Thus, the access to nutrients in sandy sediments will be limited and the fauna should contain a greater proportion of fauna that feed from the water masses (suspension feeders) and carnivores.

<u>Mud</u>

In areas dominated by mud (silt and clay), the greater access to sedimented organic matter will secure a greater proportion of burrowing animals (deposit feeders). The activity of the deposit feeders would contribute to somewhat unstable substrates, reducing the suitability of muddy sediments as prime habitats for suspension feeders.

<u>Sandy mud</u>

In areas dominated by sandy mud, one should expect a more even distribution of suspension feeders, deposit feeders and carnivores.

<u>For hard substrate habitat types:</u>

For natural reasons, suspension feeders dominate most hard bottom habitats. Other suspension feeders, such as molluscs and sponges, are also most associated with coral reefs

As always, there are many exceptions to such general trends. However, the above principles should serve as a suitable proxy if detailed data do not exist.

4.4 Exposure Routes for Organisms

Seafloor habitats and biota may be exposed to oil contamination via either 1) oil in the water column, 2) oil in interstitial water, 3) oil bound to sediment, or a combination of these. Separate impact functions are developed for these three exposure routes.

4.5 Sensitivity of Benthic Organisms

Oil spills may affect benthic communities in many ways; suffocation and/or toxification, modification of their habitat, removal of key habitat forming species, etc. (Baker, 2001). Earlier studies have demonstrated complete breakdown of communities following spills, others have indicated negligible impacts to marine life. In fact, Kotta *et al.* (2006) found deposit and suspension feeders to respond positively to the spill, most probably due to increasing loads of organic matter in the system.

Reviewing some of the field studies conducted following real spill incidents, the trend seems to be that crustaceans (Rostron, 1997; Kingston, 1999), and especially amphipods (Schwartz et al., 1990; Jewett et al., 1999; Kotta et al., 2006), suffered the most severe species and population declines from oil pollution. Some of the studies are however not conclusive, because of lack of detailed pre-spill data.

Benthic invertebrate species are often small, and thus more difficult to monitor than larger species. Also, sampling watery animals (including many suspension feeders) is rather difficult, at least using traditional techniques, and pre-spill studies are quite seldom performed. Thus, information on organism group sensitivity must be read in this context.

A more comprehensive review of organism sensitivity, in the context of restitution following spills, is described in chapter 11.

4.6 Habitats, Feeding Modes and Exposure

The two tables below attempt to summarize the information on habitats, feeding modes and exposure routes provided in the above chapters. Lack of an "X" in a cell does not necessarily mean that the group is not present. Biomagnification is not considered in ERA Acute.

Table 2 Overview of ***expected dominant*** *feeding modes per substrate habitat type. Assumption; the distribution of substrate habitat types (first column) follows a depth gradient; shallow at the top, deep at the bottom.*

	Carnivores	*Herbivores*	*Suspension feeders*	*Surface deposit feeders*	*Sub-surface deposit feeders*
Hard substrate habitat types					
Rock	X	X	X		
Gravel	X	X	X		
Coral reefs	X		X		
Soft substrate habitat types					
Sand	X		X		
Sandy mud	X		X	X	X
Mud	X			X	X

Table 3 Overview of ***primary*** *route of exposure for the different feeding modes.*

	Carnivores	*Herbivores*	*Suspension feeders*	*Surface deposit feeders*	*Sub-surface deposit feeders*
Exp. Water Column (WC)	X	X	X	X	
Exp. Interstitial Water (IW)	X		(X)		X
Exp. Ingestion (ING)				X	X

5 Model outline

5.1 Suggested outline of model and development of elements for seafloor compartment

From the discussion in the preceding section, the impact, lag-phase and restitution model theory can be outlined as follows for the seafloor compartment.

Impact is estimated as the fraction of the VEC that is impacted, in ERA Acute denoted as $plet_{sed}$.

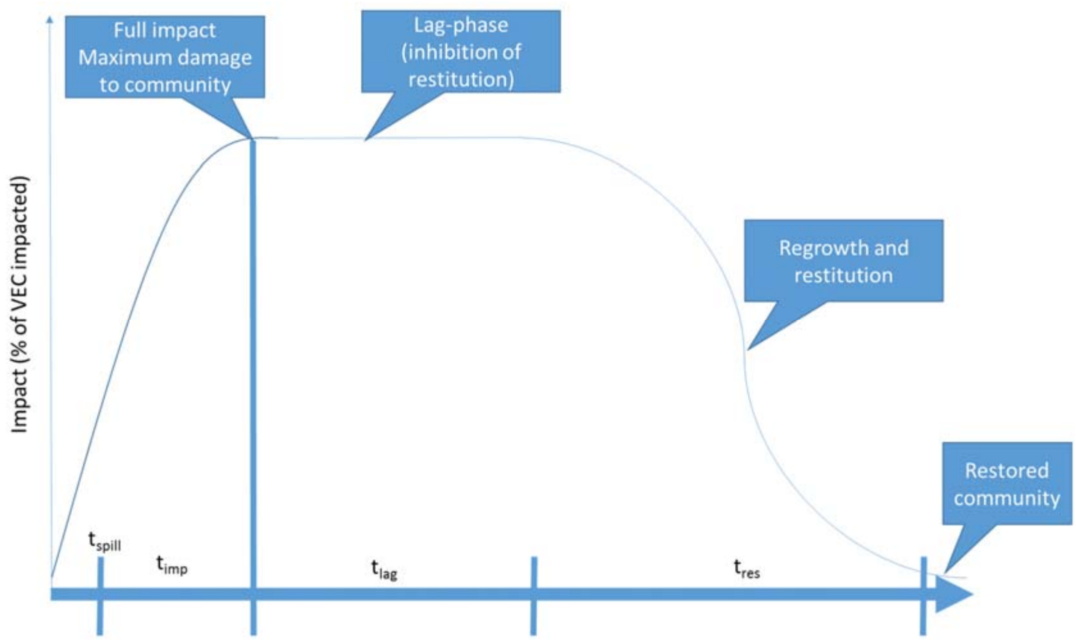

Figure 10 Impact and restoration modelling theory in the seafloor compartment.

The model uses input parameters:

- Input estimate of oil amounts in sediment from oil drift modelling to calculate the concentration of oil in the sediments $C_{THC,sed}$ (see chapter 7)
- VEC data sets: GIS data with descriptive parameters relating to the communities and substrate containing parameters relating to the resources including the resource distribution unit *N* (See chapter 9)
- Physical-chemical parameters relating to the chemical components in the hydrocarbon fraction in sediments

Given the decision to use SSD-curves developed for the water column impact function ($plet_{WC}$), the impact functions developed for sediment compartment organisms are connected to the water column compartment functions through the Equilibrium Partitioning Theory (EqP, Chapter 6).

Exposure, and thereby the choice of impact function is tied to the feeding mode of the VEC. (See chapter 4 and Table 3).

The full model including calculations, as it is to be implemented, is described in chapters 12 through 15. A flow sheet of the entire process is given in chapter 15 and is available as a separate, larger PDF file for details.

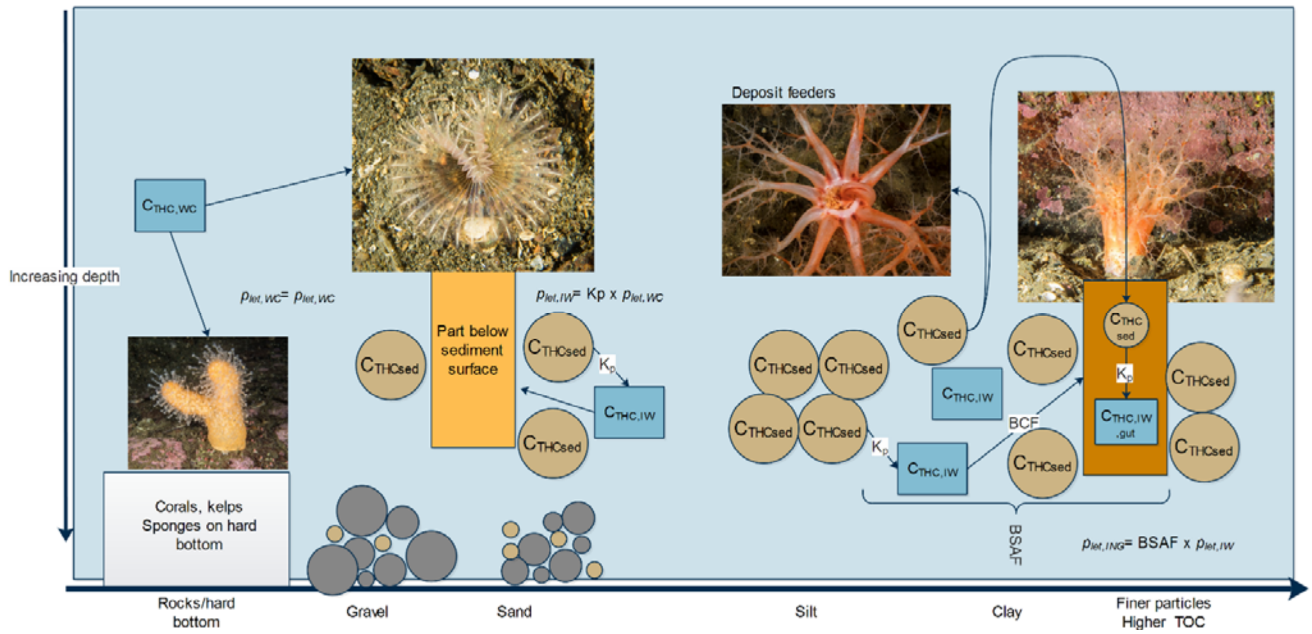

Figure 11. Overview of the three exposure routes, with examples of feeding modes and habitat types.

5.2 Relationships between exposure and impact

p_{let}-curves based on the methodology described in detail in Chapter 6, for each of the epifaunal or infaunal feeding modes described in 4.6, are suggested developed for both hard and soft substrate seafloor organisms.

The soft substrate habitat dwelling organisms are either *epifaunal* or *infaunal*.

- For organisms that are primarily exposed in the lower water column above the seafloor, the water column THC concentration $C_{THC,WC}$ is used to derive lethality from the same *plet* curve that is used in in the water column main compartment, or for corals and sponges (Brönner & Nortug, 2014)
- For organisms that are primarily exposed in the pore water/interstitial water in the sediment, partitioning theory is used to calculate $C_{THC,IW}$ from $C_{THC,sed}$, and $C_{THC,IW}$ is used to derive lethality from the *plet* curve in the water column.
- For organisms that are primarily exposed through ingestion of sediment particles, a BSAF is calculated and partitioning theory is used to calculate $C_{THC,ING}$ from $C_{THC,sed}$, and $C_{THC,IW}$ is used to derive lethality from the *plet* curve implemented in the water column main compartment.

Hard substrate habitat organisms (corals, sponges and kelps) (one p_{let}-curve for all in this group), see Brönner & Nortug, 2014) and chapter 5.3.

The basic impact function calculates the probability for a unit of the resource N to be exposed to oil, and the probability for it to be lethally impacted by the concentration/oil amount to which it is exposed.

The time it takes before the full impact is reached is denoted T_{imp}, if relevant, the model includes a possibility to enter a time factor that reflects a possible lag phase, denoted T_{lag}: where the level of HC in the sediment is too high to allow for restitution growth to occur. The time it takes from restitution starts until the resource/population is fully restored is denoted T_{res}. See Figure 3. At level 2, the impact calculation uses the time factors.

5.3 A QSAR-based ERA Acute Approach for exposure in Water Column for Seafloor Compartment

A QSAR-based approach for the water column is under development by SINTEF in the current phase of the project. A separate activity has been carried out to develop an impact function for the seafloor compartment organisms that are exposed solely in water column (i.e. corals and sponges) (Brönner & Nortug, 2014).

Until this approach is finalised for seafloor water column-exposed organisms and implemented in the oil drift simulations, the existing ERA Acute methodology for the water column, developed by SINTEF and Statoil in 2003-2005 (EIF Acute) Statoil (Nilsen et al. 2006) can be used in its place. The seafloor compartment soft substrate impact functions for calculating $plet_{IW}$ or $plet_{Ing}$ are functions of the *plet* functions in the water column main compartment using equilibrium partitioning theory, an approach that will also allow for other oil drift models to be used that provide a THC value for the sediments.

6 Theoretical Discussions for Use of EqP

6.1 The EqP Theory

The EqP theory is used to predict toxicity of contaminants to sediment-dwelling organisms (Di Toro *et al.*, 1991). In this widely quoted article, it is stated in the introduction that: *"It has been found that if the different sediments in each toxicity experiment are compared, there is essentially no relationship between sediment chemical concentrations on a dry weight basis and the biological effects. However, if the chemical concentrations in the pore water of the sediment are used (for chemicals that are not highly hydrophobic) or if the sediment chemical concentration on an organic carbon basis are used, then the biological effects occur at similar concentrations (within a factor of two) for the different sediments"*. Key insight to quantifying bioavailability of chemicals in sediments was that the concentration – response curve of the chemical was correlated with the pore water (interstitial water) concentration, and that the effects concentrations found for pore water was essentially equal to that found in water-only exposures. Also, the use of total sediment chemical concentration as a measure of the bioavailable chemical is not supported by data, as the toxicity may be different in different sediments with the same total concentration (Di Toro *et al.* 1991). For non-ionic organic chemicals, the concentration-response curves correlate equally well with the sediment-chemical concentration on an organic carbon basis. This suggested that the pore water and sediment concentrations were at equilibrium and that the concentrations are related by a partition coefficient between organic carbon in the sediment and pore water, K_{oc}. Figure 12 shows the rationale behind the theory. The system is an approximation and has inherent uncertainty, but is nevertheless widely used, e.g. by the US EPA to establish water quality criteria (EPA 2008).

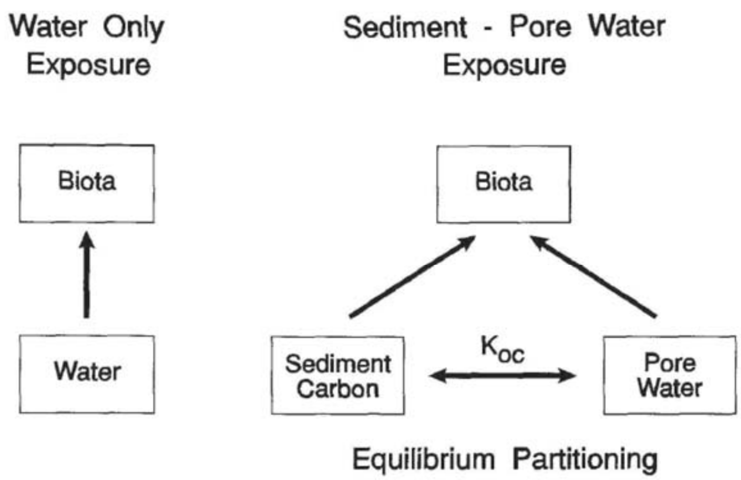

Fig. 1. Diagram of the organism exposure routes for a water-only exposure (left) and a sediment exposure (right). *Equilibrium partitioning* refers to the assumption that an equilibrium exists between the chemical sorbed to the particulate sediment organic carbon and the pore water. The partition coefficient is K_{oc}.

Figure 12. (From Di Toro et al 1991): The rationale behind the EqP theory that water-only and sediment-exposure effects are equal ***on a pore water concentration basis****, is that the two systems shown left (water-biota) and right (sediment-pore water-biota) provide the same exposure. At equilibrium, the chemical activity is the same in each system. Koc is the organic carbon-pore water partition coefficient.*

This approach is based on the premise that the distribution of contaminants among different sub-compartments in the sediment matrix (i.e. sediment solids and pore water) is predictable based on their physical and chemical properties. The binding of contaminants to sediment particles is a function of their solubility and amount of organic matter present in the sediment. The K_{oc} value is thereby dependent on both the chemical's hydrophobicity and the organic carbon content of the sediment. K_{oc} of the chemical must be

>2 for EqP to be valid (EPA, 2008). This is true for the components of crude oils that are of concern. The model assumes that continuous equilibrium exchange between sediment and pore water occurs (EPA 2008, di Toro *et al.* 1991), hence toxicity to sediment organisms is directly proportional to the amount of unbound hydrocarbon that is dissolved in sediment pore water and is bioavailable to the organism in sediment. It follows that if we can predict how much of the bulk sediment HC is bound to the organic carbon on sediment particles (and, therefore, by difference calculate how much is in the pore water), then toxicity prediction can be done solely on the basis of LC_{50} values derived from water-only studies, using the estimated concentration of toxicant in the pore water (interstitial water). Di Toro *et al.* (1991) claim that sediment organisms are as sensitive as water column organisms, and that the equality between the effects concentration measured in pore water and the water-only exposures support the use of effects concentrations derived from water-only exposure (in ERA Acute: $plet_{WC}$). Under equilibrium conditions, the relative distribution of HCs between pore water and sediment organic carbon can be predicted on the basis of organic carbon-water partition coefficients (Koc).

Additionally, biota-sediment accumulation factors (BSAF) are a function of the sediment type (organic carbon amount in the sediment and the particle size) and the HC mixture. Therefore, values derived by the EqP method also must account for differences in relative bioavailability, when calculating *plet*. This is discussed further in section 6.3.5.

In sediments, EqP theory is applicable only for those sediments with >0.2% organic carbon (dry weight OC). Nearly all sediments meet this criterion. Areas that deposit fine, carbon-rich particles with a high surface area to volume ratio will tend to accumulate more contaminants (EPA, 2008). A lower f_{OC} value gives a more conservative result (less THC in the interstitial water and hence, lower bioavailability).

6.2 Basic Equations

Interstitial (pore) water concentrations (C_{IW}) of a substance can be calculated according to the equilibrium partitioning model. Schwartz *et al.* (1990) concluded that LC_{50} values based on fluoranthene concentrations in interstitial water (C_{IW}) were constant over the three levels of organic carbon concentrations in the sediments used in their experiments. They concluded that the concentration of fluoroanthene in the interstitial water was essentially constant at equitoxic concentrations. Schwartz calculated the concentration in the interstitial water using the partitioning coefficient and the fraction of organic carbon in the sediment, this is the basic EqP equation:

Equation 2 $C_{IW} = C_{OC} / (K_{OC} \times f_{OC})$

Where:
C_{IW} = concentration of chemical in interstitial water (mg/L),
C_{OC} = concentration of chemical in the organic carbon fraction of the sediment (mg/dry kg),
K_{OC} = organic carbon (oc)/water partition coefficient for the chemical (L/kg organic carbon)
f_{OC} = total organic carbon content in sediment expressed as fractional mass (kg OC/kg dry kg sediment)

Schwartz et al. (1990) found that their results supported the conclusion of other investigations with a variety of sediment contaminants and test species that toxicity is much better correlated with the concentration of chemical in the interstitial water (C_{IW}) than with the concentration in the sediment.

According to EPA (2008), the EqP theory can be used to calculate effect concentrations in sediment for *any toxicity endpoint* for which there are water-only toxicity data. For example, in the EPA guideline for non-polar organic contaminants they call the endpoint threshold value the "Equilibrium partitioning sediment benchmark" – ESB. For ERA Acute this will imply that for sediment-living organisms, any endpoint in the water column can be used to predict the impact in the sediment compartment. The endpoint can be based on estimations of toxicity using the target-lipid model (as in Di Toro *et al.*, 2007) or from experimental LC_{50} values, SSD curves etc. The benefit for the ERA Acute project is that any updates on the methodology in the water column main compartment may (given validity) be used for the calculations for seafloor compartment as well.

The guideline document (EPA, 2008) further states that for narcotic chemicals, the ESBs can be used in a framework to evaluate the toxicity of mixtures. A narcotic effect is a non-specific disruption of membrane function due to the lipophilicity of the chemical and causing decreased biological activity. Based on this assumption, when toxicity endpoint data are calculated for the water compartment, ($plet_{wc}$), it is possible to calculate $plet_{sed}$ in sediment sub-compartment directly using the EqP theory.

From the EPA guideline (EPA 2008) (page 2-3), the fundamental equation is presented on how to calculate the corresponding Equilibrium partitioning Sediment Benchmark (ESB) for an acceptable chronic toxic value (an example of an endpoint) such as the endpoints used in ESB: the Secondary chronic value (SCV) or the Final Chronic Value (FCV) (in µg/L) to generate an ESBTier2. Di Toro et al. (1991) present the same formula calculating another toxicological endpoint, the SQC (Sediment quality criteria) from the Final Chronic value (FCV). As the endpoint can be any toxicological endpoint, it follows that we can use this calculation to calculate a *plet*-value for the sediment, using toxicity values from the water column. Keep in mind that in Figure 12, both systems (biota-water and biota-pore (interstitial) water-sediment carbon) give the same exposure at equilibrium.

Generalised, we then have:

$\text{Effect-endpoint}_{sed} = K_{OC} \times f_{OC} \times \text{Effect-endpoint}_{WC}$

It follows that for the ERA Acute lethality endpoint *plet* we have:

Equation 3 $Plet_{sed} = K_{OC} \times f_{OC} \times Plet_{WC}$

In most reference articles, a *sediment-pore water coefficient* (K_p) is used to denote the partitioning of a chemical between the sediment compartment (as both interstitial water and sediment particles) and the interstitial water. However, the K_p is a function of that chemical's K_{OC} and the weight fraction of organic carbon (f_{OC}) in the sediment ($K_{OC} \times f_{OC}$). This can be used to calculate the $C_{THC,IW}$ from the $C_{THC,sed}$ measured or modelled in the sediment.

The relationship is as follows: $K_p = C_{sed}/C_{IW} = f_{OC} \times K_{OC}$ (EPA 2008, Equ. 3-2, Di Toro et al 1991, Equ. 3; Klif 2011)).

Where:
C_{sed}: sediment concentration of chemical
C_{IW}: Interstitial (Porewater) concentration of chemical
K_p: Sediment – water partition coefficient (as above)
f_{oc}: Fraction of organic carbon in the sediment
K_{oc}: Organic carbon–water partition coefficient

From the above equations it follows that a chemical's toxicity in sediments can be calculated from its water toxicity, the K_{oc} value and the fraction of organic carbon in the sediment, and since the value of Kp needs to be calculated from the f_{OC} and K_{OC} values, we do not use it further.

Equation 4 $C_{IW} = C_{sed} / (K_{OC} \times f_{OC})$

Where C_{sed}: Concentration in sediment

To calculate the chemical's K_{OC} we use the equation by Di Toro et al. (1991), an empirical relationship between K_{OC} and K_{OW}. The relationship is also used by Klif in the Norwegian guideline for sediment criteria (Klif, 2011).

Equation 5 $\log_{10} K_{OC} = 0.00028 + 0.983 \times (\log_{10} K_{OW})$ *(Di Toro et al., 1991, EPA 2008, equ. 3-4)*

If there are no direct measurements of K_{OC}, Equation 5 may be used to calculate it.

6.3 Validation of the Use of EqP Theory

6.3.1 Partitioning Between Water, Sediment and Pore Water

EqP theory holds that a nonionic chemical, such as a hydrocarbon in sediment, partitions between sediment organic carbon, interstitial (pore) water and benthic organisms. It is well established that partitioning models can relate sediment concentrations for non-ionic organic compounds to freely dissolved concentrations in interstitial water, on basis of organic carbon. At equilibrium, if the concentration in any one phase is known, then the concentrations in the others can be predicted. This is confirmed by observations of correlation between observed biological effects on sediment dwelling organisms across a range of sediment types and the concentrations of non-ionic chemicals in those sediments (expressed on an organic carbon basis) and the concentrations in the interstitial (pore) water. Also, as the sensitivity distributions of benthic species are similar to water column organisms, the effect concentrations established for water column may be used to derive corresponding values for benthos (EPA 2008).

The ratio of the concentration in water to the concentration in organic carbon is termed the organic carbon-water partition coefficient (K_{OC}) for the chemical (EPA 2008). The Technical Basis Document (EPA 2003a) further demonstrates that if the effect concentration in water is known, the effect concentration in sediments on a µg/gOC basis can be accurately predicted by multiplying the effect concentration in water by the chemical's K_{OC}. This forms the basic assumption for calculating effect concentrations in the sediment based on water column effect concentrations, as demonstrated in 6.2.

Values of toxicity derived by using EqP are only applicable to sediments permanently inundated with water, or for intertidal sediments and sediments that are inundated with water long enough for there to be established a development of benthic assemblages (EPA 2008).

6.3.2 Can we Disregard Pore Water?

As previously stated, the EqP method can be used to derive any toxicological endpoint necessary (EPA, 2008) assuming equilibrium between water column THC, sediment-OC-bound THC and interstitial water THC. It may therefore be considered unnecessary to disregard pore water/interstitial water, as the bioavailable fraction of THC is in interstitial water (with the exception of filter feeders). Toxicity thereby decreases (by reduced bioavailability) with increasing content of organic carbon in the sediment. Schwarz et al (1990) found that the epibenthic, tube-dwelling *Corophium* was less sensitive to test sediments than the infaunal, free-burrowing *Rhepoxynius*, possibly because of different routes of exposure to fluoranthene. As mentioned (Section 6.2), Schwartz et al. found that the concentration in interstitial water, C_{iw} was essentially constant at equitoxic concentrations. The magnitude of the range in LC50s based on C_{iw} (30% of the lowest value) was much less than that for LC50s based on the concentration in sediment, C_{sed} (230% of the lowest value). Their results support the conclusion of other investigations with a variety of sediment contaminants and test species that toxicity is much better correlated with C_{iw} than C_{sed} (Schwarz *et al.*,1990). Schwartz *et al.* also concluded that *Corophium* was less sensitive to the test sediment, but that the difference may be attributable to possible differences in exposure, not lower sensitivity to fluoranthene. *Rhepoxynius* is a subsurface burrower and therefore directly exposed to interstitial water. *Corophium* was exposed to overlying water as it pumped through its tube or frequently crawled on the sediment surface. The close similarity of the interstitial water LC50 for *Rhepoxynius* (23.8 µg/L) and the seawater LC50 for *Corophium* (23.9 µg/L) indicates that the fluoranthene sensitivity of the two species may be closer than indicated by comparisons of LC50s based on the same medium. This, we find to be supportive of dividing the organisms by feeding modes.

We suggest that the pore water is not disregarded in the equations, with the above given arguments and the following reference to the EPA guideline on development of Equilibrium Partitioning Sediment Benchmarks (ESBs) (EPA 2008).

The EPA further states that this does not mean that all of the exposure is from the interstitial waters. From a purely practical point of view, this correlation suggests that if it were possible to measure the interstitial water chemical concentration, or predict it from the total sediment concentration and the relevant sediment properties, then that concentration could be used to quantify the exposure concentration for an organism. Knowing the partitioning of chemicals between the solid and liquid phases in a sediment is a necessary component for establishing the benchmark values. In the EPA guideline, the ESB values presented are expressed as µg chemical/g sediment organic carbon (µg/gOC) and not on an interstitial water basis. The reasoning behind this is that (1) interstitial water is difficult to sample and (2) significant amounts of the dissolved chemical may be associated with dissolved organic carbon; leading to an overestimation of the total concentrations in interstitial water (EPA 2008).

6.3.3 Assumption of Equilibrium

An essential assumption of the EqP is that it assumes equilibrium between the phases in order to predict the relative distribution of contaminant between the pore water phase and the organic carbon in sediment. Thereby, EqP theory is only applicable for situations where there is equilibrium; it has therefore be questioned whether this will be reached in acute oil spills, even in the post-spill recovery phase when oil is degraded. If so, EqP would be more valid in chronic exposure situations than in acute oil spills.

Fairbrother (2006) states that since use of the EqP model requires equilibrium between the compartments it is not valid for acute spills. Although Fairbrother discusses the use of EqP method that was developed for sediments on soils, the claim that equilibrium is not reached in acute spills is valid and is a concern in ERA Acute. The EPA guideline primarily discusses protective levels and the use of chronic toxicity values meant for chronic exposure situations.

If there are particles of undissolved chemical in the sediments, there will be disequilibrium and the benchmarks may be over-protective (chemical concentrations in interstitial water may in reality be lower than EqP theory would predict based on chemical concentrations in sediment and f_{OC})). However, the EPA (2008) also states that it is also true that in this situation, basing an assessment solely on chemical concentrations in the interstitial water might under-represent the degree of contamination. The undissolved chemical has a potential to contaminate a larger mass of sediment if the sediment containing as yet undissolved chemical is later mixed with other, less contaminated sediments. Even so, the EqP method seems to be the best founded method for estimating toxicity in sediments, the EPA further state that disequilibrium should not be used as an excuse to dismiss ESB values without developing an alternate conceptual model on which to base the assessment (EPA, 2008). Toxicity tests are useful for predicting the toxicity of mixtures, but only give results for the species and toxicological end point tested. In cases where results using both EqP and field validations agree (either both positive or both negative), the interpretation is clear. If the two methods give different results, the interpretation is more complex and requires further evaluation (EPA 2008).

Immediately after a spill, we do not expect equilibrium. We expect that the overlying water has a higher concentration than at equilibrium with the sediment, and that the sediment is not at equilibrium with the interstitial water. The potential is high for a calculated ESB to be under-protective (EPA 2008), before equilibrium is reached. The time that is required for there to be equilibrium is dependent on the characteristics and concentration of the chemical/chemical mixture. The literature differs in the time frames expected for equilibrium to be reached. The EPA Guideline states that sediment spiking experiments suggest that the time to reach equilibrium is typically in the range of weeks, and that even high K_{ow} nonionic organic compounds come to equilibrium in clean sediment in a period of days, weeks or months. However, the time-to-equilibrium is different for different chemicals and sediment. The Norwegian guideline document (Klif, 2011) states that equilibrium is usually reached in a matter of hours. We assume that this is after the spill situation is stopped and that distribution of the components have evened out on a large scale. For ERA Acute purposes, where there is no continuous influx of contaminants after the spill is stopped, we suggest to use the concentrations of THC in sediment at some time after the spill has stopped, while the concentrations in sediment are at the peak, and to disregard re-distribution of hydrocarbons between different sediments.

6.3.4 Sensitivity and Using The plet SSD Curve from Water Column for Sediment

As mentioned in 2.4, it was decided in the revision of the seafloor compartment approach to use p_{let}-curves from previous work for the water column (SINTEF and Statoil work in 2005; Nilsen *et al.,* 2006) and to use Equilibrium Partitioning Theory to derive a sediment p_{let}-curve from water column *plet* values. This is due to there being few data from sediment-dwelling organisms available to derive an SSD curve (Spikkerud *et al.*, 2013).

Practically, this can either be done by deriving specific SSD curves for the sediment compartment, or more simply for the user, as suggested (Chapter 12) to calculate the concentration in interstitial water and to use this concentration to read the water column *plet* curve directly. By using this approach, it is easy to improve modelling by utilising improvements in the water column algorithms also for the sediment compartment. The approach will also allow for possible implementation of future approaches for water column main compartment and for the lower water column sub-compartment of the sea floor (Brönner & Nortug, 2014).

It is believed that there is little difference in sensitivity between freshwater and marine organisms for chemicals having a narcotic mode of action. Organic carbon appears to be the dominant sorption phase for most nonionic organic chemicals in naturally occurring sediments and, thus, controls the bioavailability of these compounds in sediments. (EPA 2008). Note that the EPA document states any *effect concentration*, meaning that the whole continuous *plet* curve can be calculated, and the *plet* curves for sediment and pore water can be stated as a function of water column *plet*-curves in ERA Acute calculations.

By using species-sensitivity distributions, a range of toxicity data are used, encompassing several species. However, it is important to remember that the species for which there are toxicity data available from quality experiments are species that can be kept in laboratory conditions. These may not be the most sensitive species, nor may they cover the rarer species. Considering that most species in sediments occur at very low numbers, approximately half of them could be considered to be rare (Bjørgesæter *et al.,* 2009a, (published in doctoral thesis). Most experiments are also carried out on macrofauna (defined in Bjørgesæter and Gray (2008) as organisms retained on a 1 mm sieve), further contributing to bias in the estimation of SSD curves.

Also, since it is inherent in the SSD concept that the species have different sensitivities, a medium or high potentially affected fraction (PAF) would mean that the most sensitive species could be expected to be very heavily affected. This can be expected to influence restitution. Some species may be eliminated more or less, and may not restore their populations, even if the diversity indexes are restored to former diversity as different and opportunistic species. Bjørgesæter and co-workers used Abundance Decrease 50 % (AD50) values to construct field-based-SSD curves (f-SSD) for several contaminants in sediments, using the data from the MOD database (Bjørgesæter *et al.* 2009a), to better understand how threshold toxicity values (HC5) would be influenced by rare benthic species. They found that f-SSD using AD50-values indeed protected 95 % of the species including the rarer ones.

Designed for protection of species using thresholds for toxicity, the EqP methodology can be used to derive a benchmark with any desired level of protection, so long as the water-only concentration affording that level of protection is known. Therefore, it is expected that a water-column curve of lethal values at various concentrations can be used to derive the *plet* values in the sediment using the method. The use of EqP to arrive at ESBs for nonionic substances in sediments is denoted as a "Tier 2" approach in the EPA document (EPA, 2008). Tier2 ESBs are likely to have a higher degree of uncertainty than Tier 1, which was developed for specific pesticide substances (specific mode of toxic action), whereas the toxic action of non-ionic substances is non-specific narcotic (disruption of biological membranes due to lipophilicity). The document (EPA, 2008) discusses uncertainty at length.

Using EqP can lead to an under-protective ESB if the organic carbon has a low sorptive affinity, if the chemicals are additive with an ESB chemical or if there are species present with an unusually high sensitivity at the site.

In this phase of the ERA Acute project, SINTEF have a task to outline a QSAR-based approach for corals and sponges valid for organisms of the seafloor that are exposed through the lower water column. This methodology is described in Brönner & Nortug (2014). The methodology outlined in SINTEFs present work will to provide an improvement of the initial impact when it becomes available for corals and sponges, by giving a *potential* impact that gives a *plet* value directly from the oil drift simulations. Combined with the *pexp* and *N*-values, the initial impact will be calculated in ERA Acute, keeping the VEC-files in ERA Acute, but making the initial calculations of *plet* superfluous for corals and sponges (Skip steps up to Step 2BWC.1. (see section 12.4.1). For the other exposure routes, the methodology will not change. Utilisation of the method lies in the future, within the current scope of work, we propose a methodology using currently available oil drift simulations.

Our suggestion for the sediment sub-compartment of the seafloor therefore bases its calculations on whichever impact function is current in the water column main compartment, however preferring one developed specifically for corals and sponges for these organisms should one become available.

6.3.5 Sequestration, Active Ingestion of Contaminated Particles and Bioaccumulation

Accumulation of hydrophobic organic contaminants by benthic organisms can occur either from the aqueous phase or via dietary exposure. E.g. bivalves filter water, and deposit feeders actively ingest particles of sediment, and are therefore not primarily exposed through water column. Toxicity to these organisms cannot be predicted based on bioassays in water only. This statement needs to be discussed for the use in ERA Acute, as active ingestion of organic substances will be a very relevant route of exposure for many organisms.

Sequestration, hydrophobicity and sediment type

As the affinity of chemicals to sediment increases with increasing hydrophobicity (increasing octanol–water partition coefficient) (K_{ow}), the importance of aqueous exposure pathways through pore water or overlying water decreases relative to the increasing importance of ingestion of organically bound hydrocarbon via sediment ingestion. For several species of deposit feeding organisms exposed to hydrophobic chemicals with log K_{ow} values ≥5.5, sediment ingestion has been shown to be a significant or even primary route of uptake (Lamoureux & Brownawell, 1999). The assumption of benthic organisms being exposed only through sediment pore water is considered to be valid only for a subset of species (Kraaij et al., 2002a). Lamoureux & Brownawell (1999) summarize that the equilibrium partitioning model proposed for the protection of benthic organisms, which predicts bioaccumulation levels that are independent of the route of uptake, diverges from field and laboratory studies that have shown that organism body burdens sometimes depart significantly from equilibrium conditions. Accumulation of polycyclic aromatic hydrocarbons (PAHs) have been reported at levels *lower* than predicted by equilibrium partitioning calculations, whereas accumulation of polychlorinated biphenyl (PCB) congener mixtures by deposit feeders are often *higher* than equilibrium partitioning predictions. PCBs are not relevant for ERA Acute, whereas use of EqP theory for establishing a PAH *plet* value for filter feeders may overestimate impact.

Sequestration of hydrophobic organic compounds (HOC) is the presence of relatively slowly desorbing fractions of HOC in sediment, which can account for up to 98% of the total. Evidence has been provided that the bioavailability of HOC to microorganisms and benthic deposit-feeders is inversely related to sequestration (Kraaij *et al.,* 2002a). Most PAHs and components relevant to petroleum oils are more bound to the particle fraction of sediment than they are soluble in the pore water (Torgeir Bakke, NIVA, *pers. comm.*). The rate of desorption to water phase varies between chemicals with different K_{ow} values, and also depends on the sediment organic content, f_{OC}, and the type of organic carbon present. To complicate the use of estimated values of Koc, it is not irrelevant what type of organic carbon is in the sediment. Especially PAHs are more bound to organic carbon from combustion than to biogenic carbon (Klif 2011). Especially in near coastal areas, near industry etc, there may be a higher content of combustion-generated OC in the sediments, that binds PAH more. Also, the degree of oxygenation of the sediment plays a role. As an example, PAHs adsorb to soot particles with a higher affinity than to biogenic organic carbon, such particles in the sediment matrix may decrease desorption to interstitial water. However, with increasing combustion-generated organic carbon (OC) in the sediment, less PAH is found in the pore water, resulting in a lower toxicity than the estimated value should suggest, resulting in a conservative result.

In aquatic environments, the fraction of solids and organic carbon are often inversely related. The Norwegian Guideline (Klif, 2012) for setting of quality criteria for coastal marine sediments and background document (Klif, 2011) use a general concentration of sediment organic carbon f_{OC} of 1 % This is based on the average K_{oc} in marine offshore sediments in the EU area. In monitoring studies of some fields in the North Sea in 2008, Akvaplan-niva found background f_{OC} concentrations varying between 0.6 and 1% (Cochrane *et al.*, 2009). The 1 % value is considered to be too low for Norwegian coastal waters (Torgeir Bakke *pers. comm*). Near the coast it would therefore seem relevant to use a higher K_{OC} for areas with a high influx of organic matter from rivers etc. Using site-specific fraction of organic carbon in the sediment (f_{OC}) values will reduce uncertainty of the ERA Acute EqP calculations. It is suggested that this is included as a parameter in the information on data sets for Valued Ecosystem Components (VEC), allowing for regional differences. Subject to future updates or local changes, a value of f_{OC}=1% is suggested as a "default" value for shallower sediments if local values are not available, as low as 0.6 % for deeper sediments based on the above references.

Bioaccumulation and sequestration

Kraaij *et al.*, (2003) concluded that there was an increasing body of evidence that the bioaccumulation of sediment-associated HOCs is strongly influenced by *sequestration* in the sediments (formation of relatively slowly desorbing fractions). Bioavailability is suggested to be related to the extent of sequestration of the components in the sediment carbon fraction, a chemical process that is also affected by contact time.

Lamoureux and Brownawell (1999) compared the rate and extent of desorption of HOC into seawater with the extent to which these contaminants are accumulated by a deposit-feeding bivalve. Three HOC classes, which differ in structure and in matrix associations, were measured: PCBs, linear alkylbenzenes (LABs), and PAHs. They found that the PAHs, LABs, and the highest molecular weight PCBs exhibit nearly first-order desorption kinetics, whereas the majority of the PCBs conform to a two-compartment model, with initially fast and then slow desorbing components. The findings regarding LABs and PAHs are considered most relevant for ERA Acute.

Kraaij *et al.* (2002a) discuss how the bioavailability of a hydrophobic organic compound seems to decrease more rapidly than the total concentration in the sediments, with increasing contact time between sediment and HOCs indicating reduced toxicity with longer contact time due to sequestration. In Kraaij and co-workers' research in 2003, it was not known how EqP could be applied to sediments with sequestered contaminants. In their work, they investigated freely dissolved pore-water concentrations of HOCs, and used the data to interpret sediment bioaccumulation and sequestration data in order to evaluate EqP in light of the sequestering processes and time. The data analysis suggested that sediment bioaccumulation of compounds up to log K_{OW} 7.5 in *Tubificidae* could be described as bioconcentration from pore-water. In addition, the pore-water concentrations of HOCs with a log K_{OW} between 4.5 and 7.5 were established by equilibrium partitioning between the rapidly desorbing HOCs fraction in the sediment and the pore-water. They concluded that their findings indicate that EqP is a conceptually correct representation of sediment bioaccumulation, provided that sequestration is accounted for. Kraaij et al. (2002a) also observed that sequestration seems to take place quickly, as they found that significant fractions of slowly and very slowly desorbing fractions are measured within a few weeks after addition of the test HOC compounds to the sediment. They further found that the sequestration process then moves on at a much slower pace with increasing contact time, a small shift toward very slowly desorbing fractions is observed. For ERA Acute purposes it could therefore be concluded that the equilibrium processes happen within the time frame of the immediate follow-up time of an acute oil spill, providing oil spill simulations include sufficient simulation time after the spill is stopped.

Kraaij et al (2003) also implied that risk assessment of sediment-associated HOCs could be simplified if the concentration of freely dissolved HOC in the pore water can be measured, and HOC body residues in sediment dwelling organisms can be estimated on the basis of concentrations in pore-water and bioconcentration factors. However, for ERA Acute the concentration of hydrocarbon (a HOC) in pore water is not reported from oil drift simulations in OSCAR "stochastic mode", which runs several simulations of the same scenario. HOC can easily be calculated from the results of one simulation in the "single-scenario"-mode (which we for the sake of avoiding confusion with the ERA Acute definition of "scenario" call "single-simulation mode"), which reports $C_{THC,sed}$ in sediments (after transformation), and using EqP (See 16.2.2.) to calculate the concentration in interstitial (pore) water. As mentioned, the estimated $C_{THC,IW}$ can be expected to be somewhat conservative for PAHs.

Biota-sediment accumulation factors (BSAF) are the ratio between the concentration of the component in the lipids of organisms and the concentration of the component in the sediment organic carbon, reflecting differences in bioavailability (Kraaij *et al.*, 2002a). In their experiments, the BSAFs were calculated by dividing the average of the lipid-normalized concentration in the oligochaetes by the organic carbon-normalized concentration in the sediment. Bioaccumulation is in the work by Kraaij et al. (2002b) defined as the steady-state accumulation into the organism divided by the concentration in the sediment, normalized to lipid and organic carbon content. In contrast to equilibrium partitioning model (EqP) calculations, the BSAF values of hydrophobic organic compounds for deposit-feeders are highly variable both with regard to components and sediment types, further complicating the picture for use in ERA Acute.

However, bioaccumulation cannot be disregarded. Kraij *et al.* (2002a) cite Lamoureux & Brownawell (1999) whose work suggests that this variability in BCAF can be attributed to differences in sequestration or the presence of slowly desorbing fractions of the HC mixture in the sediment. Kraaij *et al.* (2002a) investigated whether the observed relationship between bioavailability and sequestration is causal. They determined BSAF values and sequestration status, measured as the distribution over rapidly desorbing fractions (F_{rap}) and slowly desorbing fractions, of polycyclic aromatic hydrocarbons (PAHs) in a manipulated sediment (where F_{rap} was removed from the aqueous phase after rapid desorption) as well as in the original, unmanipulated sediment. Contrary to expectations based on EqP, BSAF (g/kg OCsediment / g/kg *Corophium* body lipid) values did not remain constant in their study, but were reduced by a factor proportional to the reduction in rapidly desorbing fractions. Figure 13 from Kraaij et al (2002a) shows that the higher the content of rapidly desorbing fractions (F_{rap}) in the initial sediment, the higher the BSAF for deposit-feeding *Corophium*. This indicates that there is a causal relationship between sequestration in sediment and lower bioavailability to deposit-feeders. With increasing contact time between sediment and HOCs, the bioavailability of a hydrophobic organic compound seems to decrease at a higher pace than the total concentration (Kraaij et al, 2002b). Sequestering of HOCs to sediment organic carbon lowers the bioavailability of the chemical.

For deposit feeders, Kraaij and co-workers (2002a, b) concluded that there is a need to modify traditional use of the equilibrium partitioning model to account for variation in the sequestration status of HOC in sediments.

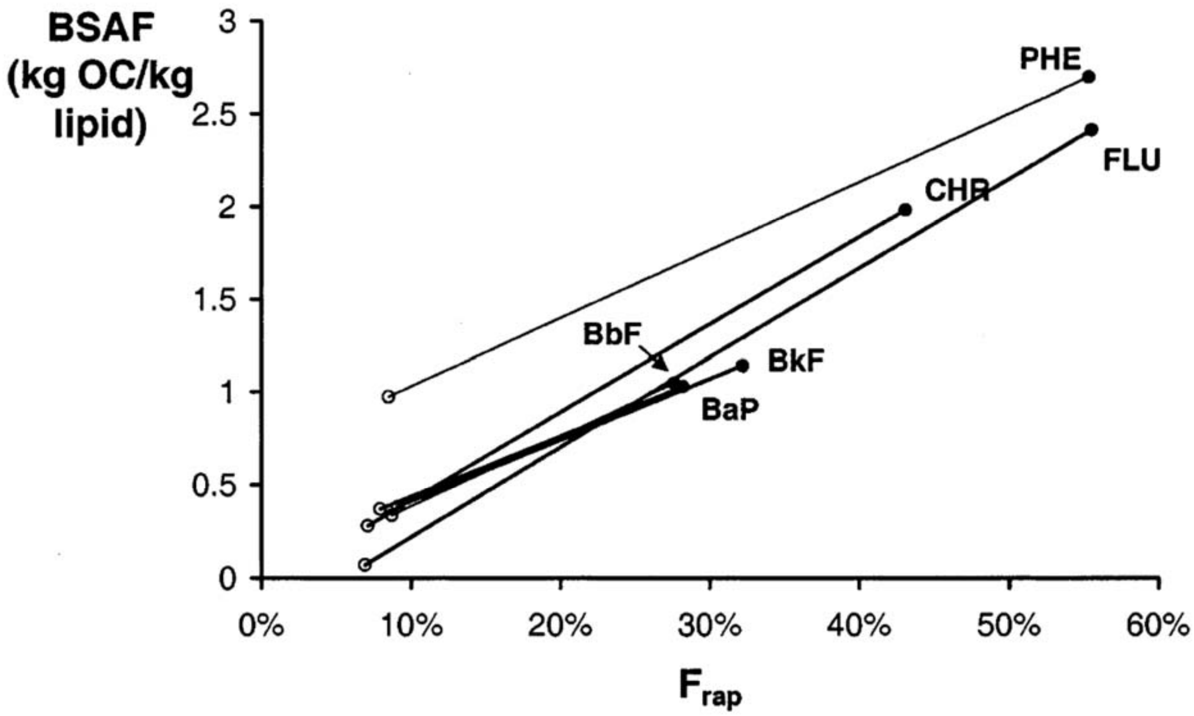

Figure 13. Figure from Kraaij et al 2002a: Biota-sediment accumulation factor (BSAF) (in kg of organic carbon/kg of lipid) of PAHs in treated (48 h shaking of aqueous suspension with Tenax, void circles) and untreated (filled circles) lab-contaminated sediment vs rapidly desorbing fractions (Frap). The data points for individual PAHs (in untreated and treated sediment) are connected by a line.

The bioavailability of hydrophobic organic compounds (HOC) to benthic organisms is determined by a complex interaction of biological and ecological factors such as habitat, feeding behaviour, and digestion mechanisms on one hand, and sorption/desorption processes in the sediment on the other hand As a result, bioavailability might vary between sediments and organism species. A literature review carried out by Kraaij and co-workers on BSAF values revealed a variability of about 2-3 orders of magnitude, contrary to traditional equilibrium partitioning theory (EqP) estimations of a relatively constant BSAF value (Kraaij, 2002a).

For the bioconcentration of HOCs in biota following exposure in water only, the Norwegian sediment quality criteria guideline quotes the EU TGD for the following relationship between K_{OW} and the Bioconcentration Factor BCF (Klif, 2011):

Equation 6 $\text{Log BCF} = 0.85 \log K_{OW} - 0.70.$

Both biota-sediment accumulation factors (BSAF) (accumulation from sediment to organisms) and Bioconcentration Factors (BCF) (from water to organisms) values generally depend on the conditions that the experiments were carried out under. In line with the above mentioned challenges of using EqP as is for all organisms, the Klif Guideline recommends using equilibrium based estimates between sediment and organisms for sediment-dwelling organisms only. For other organisms it is recommended (Klif, 2011) to use the following parameters:

- Estimate of flux of the contaminant between sediment and above water column
- Dilution effects in the water column.
- BCF values to estimate the transport between water concentrations and tissue concentration.

For non-polar contaminants, BSAF is inversely proportional with the organic content of the sediment (as fraction or weight-%). The variability of BSAF values for the components can be reduced if the concentration of contaminant is normalised to TOC, and this is done in the Norwegian Guideline.

Accumulation from sediment to organisms is expressed by the bioconcentration factor from water to organisms and the partitioning coefficient between sediment concentration and pore water concentration:

BSAF=BCF/Kp (Klif, 2011)

(Where $K_p = K_{oc} \times f_{oc} = C_{sed}/C_{IW}$)

For ERA Acute we can use the mean Log K_{OW} values for the hydrocarbon pseudo-component groups (

Table 4, from Batelle 2007). to calculate K_{oc} from Equation 5 ($\text{Log } 10K_{OC} = 0.00028 + 0.983 \times (\text{Log}10\ K_{OW})$ and using a local or typical value for f_{oc} for the sediment. We thereby have:

$BSAF = BCF/(K_{oc} \times f_{oc})$

Division of sediment types into groups depending on grain size and depth categories can be seen in Table 1 of Bjørgesæter & Gray (2008), where total organic matter (TOM) values are given where available/relevant. The values typically lie around 0.8-0.9 % (not the same as TOC) for sandy/coarser grain types at depths shallower than 100 m, whereas at greater depths the particles are finer (silt and clay) with TOM values up to approx. 11%. Bjørgesæter & Gray found high correlation between grain size, depth and TOM. All these factors are related to bioavailability.

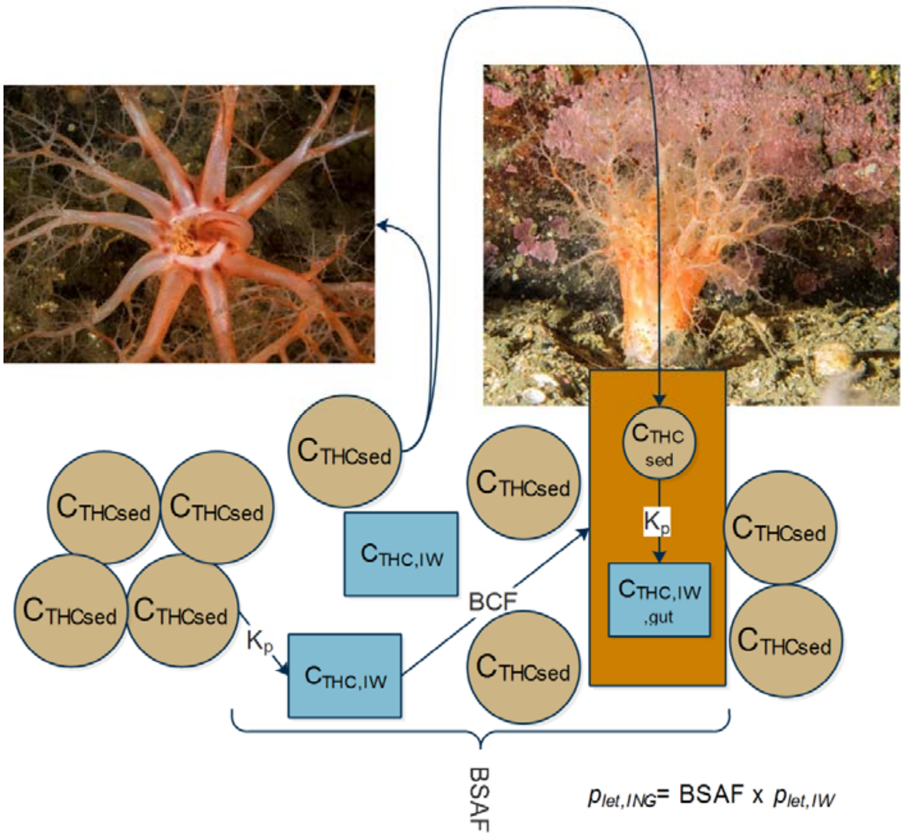

Figure 14 Relationship between organism, interstitial (pore) water and sediment particles, Kp, BCF and BSAF (adapted from Klif 2011). It is assumed that partitioning from THC_{sed} to THC in gut juices can be represented by the Kp partitioning coefficient.

6.4 THC or Component Groups?

Two options have been evaluated in this present project; either to use total hydrocarbon concentration (THC) estimated to be present in the sediment sub-compartment, or to use relevant groups of hydrocarbons with similar properties, represented by pseudo-components from oil spill fate and trajectory modelling. Following an oil spill, where oil surfaces and then is dispersed into the water column by droplet formation and dissolving of water soluble components, it can reasonably be expected that it is the higher molecular-weight hydrocarbons that will degrade slowly enough to reach the seafloor. This can occur either by sedimentation of the lipophilic substances bound to organic carbon in particulate matter, or as dissolved PAH and/or NPD in the water column near the seafloor. An exception could be application of *in situ* chemical dispersion near the seafloor, which may need to be addressed separately.

Hydrocarbons fall into major groups that may be represented by "pseudocomponents" (as in OSCAR) Saturated and unsaturated aliphatic hydrocarbons, saturated and unsaturated cyclic and polycyclic hydrocarbons and polycyclic aromatic hydrocarbons.

Water solubility is a major factor in toxicity, as described extensively in previous sections. Compounds with low water solubility have low bioavailability and high affinity to organic matter, e.g. in sediments, however lipophilicity contributes to the narcotic effects of hydrocarbons. Molecular size and polarity determine water solubility, volatility and affinity to organic carbon in sediment. It has been observed that saturated aqueous solutions of aromatic hydrocarbons larger than fluoranthene (C16) have such low aqueous solubilities that they may not be acutely toxic to aquatic organisms (Di Toro *et al.*, 2007).

Aliphatic molecules are non-polar, and tend to be lipophilic – more so with increasing molecular weight; lower molecular-weight aliphatics (octane (C8) and below) tend to be volatile (Bjørgesæter, 2009), and will not usually constitute a problem in sediments following acute oil spills. Relatively volatile, and in general more water soluble aromatic compounds (e.g. BTEX) are quite mobile in aquatic environments and are not expected to accumulate in sediments to concentrations that would pose a significant ecological risk (Batelle 2007), confirmed by OSCAR simulations (16.2.2). Aliphatic hydrocarbons in the C5-C8 aliphatic fraction have higher K_{ow} values (i.e are less soluble) than aromatic hydrocarbons in the C6-C9 fraction, but are also more biodegradable, which makes them less persistent in sediments. For fresh spills with unweathered oil, it may be relevant that the light aliphatic hydrocarbons in the C5-C8 and C9-C12 fractions are sufficiently soluble that they probably contribute to the toxicity of sediments contaminated with light and middle distillate fuels (Batelle, 2007).

The high molecular weight aliphatic hydrocarbons (aliphatic fractions C13-C18 and C19-C36) have such low solubilities and high log Kow values (7.2 – 13.07) that they have a high affinity for the sediment organic carbon phase or oil phase in the sediments. These substances have a lower bioavailability by general diffusion over biological membranes and low partitioning into the water phase reducing bioconcentration by aquatic organisms. Thus, the high molecular weight aliphatic hydrocarbons probably do not contribute significantly to the chemical toxicity of oil-contaminated sediments. SINTEF estimate initially that components with solubility greater than about 30 or 40 ppm will only appear in trace amounts in the sediments, and will also degrade rapidly (Mark Reed *pers comm.* E-mail 14.10.2014). Solubilities for the different groups in OSCAR are given in Table 5.

The components of major concern with regards to seafloor exposure are the PAHs, the NPDs (Naphtalenes, phenanthrenes and dibenzothiophenes) and decalines (well summarized in Bjørgesæter, 2009a). Modelling with an oil drift model that gives fractions will confirm or reject their presence in sediments in specific cases.

It is therefore mainly the PAHs and NPD components that are expected to be bioavailable and cause toxicity. The larger and more persistent PAHs have been linked to long-term effects on growth and reproduction of organisms, well after evaporation of the narcosis inducing compounds. To study the more long-term effects from acute exposures to the more persistent high molecular weight PAHs and NPDs are relevant.

Partitioning coefficients will vary with hydrocarbon composition of the oil type. When assessing the toxicity of mixtures of chemicals, such as for crude oil spills, the potential of effects working together to increase toxicity (either synergistically or additively) must be considered. This is of particular concern for chemicals with primarily a narcotic mode of action for which the literature in general provides a convincing argument for additive toxicity (EPA 2008). However, this issue will inherently be taken care of by using EqP to derive sediment $plet_{sed}$ values for THC from the water column $plet_{WC}$ value (Nilsen et al. 2006), where the additive effects were taken into consideration.

THC was suggested as the exposure parameter of choice if it could be modelled reliably, as it is thought to be easier for the ERA Acute user to obtain from oil drift modelling. THC is the parameter commonly reported in monitoring programs, and by oil spill simulation models. However, as stated, the THC in sediment will consist of certain fractions, and the average K_{OW} values from the relevant fractions should be used. A compilation of fractions as recommended by Batelle (2007) is given in

Table 4. It is assumed that the pseudo-component groups marked in blue in Figure 39 are the relevant groups for calculating the exposure in pore water for sediment exposure. THC in sediment is the sum of organic carbon-bound fractions and pore water fractions.

EqP is valid for mixtures of THC. However a precise calculation of an endpoint would imply the need for all components to be reported in the sediment compartment with fractions of each. The individual components and composition of the sedimented oil are presently not available in the output file from the single simulation. It is therefore proposed to use the concentrations of the C_{THC} that is reported in the sediment, mean K_{ow}-values of the chemical/chemical groups and f_{OC} of the sediment to calculate the interstitial water and/or ingested concentrations to which the organisms are exposed. From these values, by using the SSD lethality curve for the water column main compartment that has been implemented in ERA Acute (currently Level A), the *plet* value for the sub-compartment can be calculated.

Differences in crude oil contents of heavy-molecular weight/slowly degradable substances will be reflected in the actual amount of THC that is reported as entering the sediment and it is believed that for ERA Acute purposes this will be detailed enough to predict an impact.

For *epifauna*, to enhance precision, a separate exposure value from oil drift modelling for the lower water column is much preferred for calculation of impact. The same HC fractions (pseudo-component groups) are expected to be relevant for both the lower water column and the sediment sub-compartments of the seafloor.

Table 4 Sediment benchmarks for recommended petroleum hydrocarbon fractions (from Batelle 2007).

Hydrocarbon Fraction	**Geometric Mean Log K_{ow}**	**K_{oc}**	**Final ChronicValue (µg/L)**	**Sediment Benchmark (mg/kg oc)**	**Sediment Benchmark (f_{oc} = 0.001) (mg/kg)**
Aliphatic Hydrocarbons					
$C_5 – C_8$	4.12	7.24×10^3	218	1591	1.59
$C_9 – C_{12}$	6.01	4.37×10^5	6.3	2722	2.72
$C_{13} – C_{18}$	8.57	1.10×10^8	0.05 a	5543	5.54
$C_{19} – C_{36}$	11.64	8.32×10^{10}	0.0001a	9883	9.88

Aromatic Hydrocarbons					
$C_6 – C_8$	2.82	4.47×10^2	1191	531	0.53
$C_9 – C_{12}$	3.94	4.90×10^3	46.2	228	0.23
$C_{13} – C_{15}$	4.67	2.40×10^4	5.2	125	0.13
$C_{16} – C_{24}$	5.9	3.39×10^5	0.12[a]	40	0.04

[a] The fraction is not likely toxic because mean LC_{50} exceeds mean aqueous solubility.

6.5 Droplets and Dispersed Oil

Droplets may affect physically, by coating vital organs etc. and impair uptake of oxygen and food (esp. filtrating organisms). Such obstruction of important biological functions may be expected to lead to impact.

Actively filtering organisms may filter and ingest droplets of oil, as such or attached to particulate matter. There are, however a series of challenges related to assessing the toxicity of droplets, a.o. that the results of toxicity studies are not described relating to the characteristics of the resulting dispersion, making it difficult to relate toxicity results to the exposure in the water column. Nortug and Johansen (2007) conclude that the toxicity must be related to the total concentration (THC) and the composition of oil, the ratio between dispersed and dissolved oil and the droplet size distribution. They further raise the issue whether the dispersed oil contributes to acute effects during an oil spill, by enhancing bioaccumulation and increasing acute narcotic toxicity, what the significance of mechanical adsorption of oil droplets to organs such as gills are and whether these effects are significant in relation to the toxic effects of the single components. Nortug & Johansen (2007) also discuss toxicity of narcosis, and the use of QSAR to assess the toxicity of a hydrocarbon mixture based on the knowledge of the composition of the individual components in the THC (using the toxic unit model). They also assume additive effects (a well "proven" theory), based on regressions between the octanol/water partitioning coefficient (Kow) and (pseudo)component groups with similar physical-chemical properties. The method has been tested on the water-soluble fraction with a known composition of pseudocomponents from 12 different crude oils. The model predicts a higher sensitivity of "average pelagic crustacean". The critical factor is the bioavailability of the toxic components in the droplets.

The profiles of the PAHs strongly suggested that mussels accumulate PAHs from both dissolved PAH and oil droplets on suspended material (SPM), and that the suspended matter route dominated clearly. Crabs accumulate PAH from the dissolved fraction, resulting in a body burden 500 times higher in mussels than in crabs, this indicates that ingestion of droplets through particulate matter increases internal exposure. Nortug and Johansen (2007) make a reasonable assumption that regarding droplets, there are larger differences between life stages and/or species than for the WSF. There is a major challenge in that a PNEC cannot be established for dispersed oil, impact depends on droplet size and there is no distinct relationship between concentrations and lethality.

Nortug & Johansen (2007) conclude that effect studies reported in literature do not provide the parameters necessary to predict toxicity by modelling on a generalised basis, as the exposure parameters have not been characterised well enough, e.g. regarding the partitioning between dissolved and particulate phase, and the size distribution of the particulate phase. OSCAR reports both THC and dissolved HC fraction, which corresponds to the dissolved oil/dispersed oil-distribution. OSCAR also gives the composition of the two phases as compositions (pseudocomponents) based on oil type, as well as droplet size distribution.

For the sediment (soft substrate) sub-compartment, the value (Sdmas_g_m2) given by OSCAR in single simulations is the total THC in the compartment. This is therefore used for the sediment EqP calculations of hydrocarbon exposure.

7 Exposure Input Data from Oil Drift Modelling

7.1 Current OSCAR model capabilities

HC concentrations in the lower layer of the water column are considered to be most relevant for corals, kelp, sponges etc. on hard bottom substrates, whereas sedimented oil particles and their potential partitioning to pore water are most relevant for sediment *infauna*.

In the ERA Acute project development phase of 2012, SINTEF provided the following overview of the modelling capabilities of OSCAR in relation to ERA Acute modelling (Brönner & Reed, 2012).

Lagrangian oil drift models track oil concentrations of dissolved and droplet oil mass as particles during the simulation. The following is described relating to OSCAR. OSCAR can be run either in deterministic (single-scenario) mode or a statistical mode, where several simulations are run and statistical results are given as output in a UTM Grid format for ERA Acute for that one re-run simulation. The output grid can be chosen by the user, and it is crucial that the UTM output from oil spill modelling matches the grid used for resource data. This is a part of the user definitions.

Two different versions of Fates are used in the two modes of OSCAR: In deterministic modelling (single scenarios (in ERA acute terminology – "single simulations"), particles reaching the sea bottom are accounted for and stored in the sedimented fraction. However, sedimented oil particles are not tracked in stochastic runs (statistical mode) and are accounted for as being outside the modelling area. This was implemented to reduce computational time when running the model in statistical mode.

As these processes are already available in OSCAR, however, they can be included again in the statistical mode, or an alternative use of the deterministic model can be studied, in order to supply the necessary parameters without increasing calculation time too much. This would, however, need to be included in a future version of OSCAR.

The advanced sediment model in Fates that can be included when running single simulations in deterministic mode includes 3-dimensional modelling of hydrocarbon concentrations in the water column and sediments. This model is not applicable for statistical modelling as the computational time increases significantly.

For long-term effects (sub-lethal and re-growth-inhibiting properties) it was initially suggested to use degradation data (half-lives) of typical HC components in the sediments, either using THC or concentrations of HC in four defined groups. These are in the current version of OSCAR modelled today in simple sediment model (part of the stochastic OSCAR-model), but is reported as “outside” the grid in the reporting format for stochastic simulations. A separate memo has been prepared describing oil drift modelling and options for providing the relevant oil drift input parameters for ERA Acute (Brönner & Reed, 2012). Since the original suggestion to use half-lives for degradation, the project team has been asked to use data from field studies and spills to estimate a restitution time based on the oil concentrations in sediments. (See chapter 11.4 and 11.4).

In deterministic mode oil mass per area can be computed from sediment deposition of an oil spill, and is included in the mass balance. As per today, the sediment grid is post-processed from the general oil spill result and is not available as a dedicated file, yet. Current enhancements of the model output and post-processing of results may be available in future releases of OSCAR (Brönner & Reed, 2012). It is further stated that “as sedimentation is not included in stochastic simulations, there are no statistical computations and data exports available in the present version of the model software. These need to be defined and could be included in future versions.” This statement is still valid in 2014. SINTEFs conclusion of the sediment modelling capability is further that the mass of the deposited oil per sediment area can be computed by oil spill models, but that in the current version of OSCAR the parameters would need to be included in the stochastic simulations also if they were to be used as direct input for the ERA Acute Oil Spill Risk Assessment Tool.

SINTEF concluded in the ERA Acute development of 2012 that a model that is to give input directly to ERA Acute sediment compartment needs to include the following:

1. Include sedimentation processes in stochastic simulations reporting
2. Implement statistics for the sedimented fraction of the oil mass.
3. Implement the generation of defined output files which can be further processed by ERA Acute Oil Spill Risk Assessment Tool

7.2 Alternatives for Input Parameters (Example from OSCAR)

This chapter relates to the use of OSCAR as an example of an oil drift model. It is stressed that any model providing the same or equivalent results and parameters may be used.

Early in the re-scoped development of ERA Acute for the seafloor compartment, a clarification meeting between APN, SINTEF and the Client steering committee representative was held in order to go through the current capabilities of OSCAR and arrive at an approach for using input parameters from OSCAR or equivalent models as input to ERA Acute.

To maintain the integrity of the main architecture of ERA Acute, the impact and restoration modelling is to be carried out in ERA Acute, based on oil drift and weathering modelling input from a separate model (e.g. OSCAR). To accomplish the goal of the project to describe and develop calculation steps that can be programmed by software developers after the current phase of the project, it is necessary to build this version of the model on existing or soon available parameters from oil drift modelling. Three alternative approaches were put forward by APN and discussed in the meeting.

7.2.1 Alternative 1 – Use average THC in the Water Column

The background for this option is the Client decision to use total hydrocarbon concentration as the parameter for the seafloor impact modelling, and there is currently no reporting of sedimented hydrocarbons in OSCAR output files in statistical mode. This alternative has been assumed to be a simpler approach for the user, and data is currently available in oil drift models, with output as:

a. Average THC in the water column representing the total of dissolved HC and droplets. In statistical mode the THC is averaged over the entire water column and reported in the exported file.

The advantages of this approach is that it may be applied now as suggested in the approach suggested June 2013, further modelling of impact would use the approach for modelling impact using the toxicity curves from ERA Acute 2006 in the water column, using EqP to obtain a lethality curve for the sediments. This approach also maintains the ERA Acute architecture where oil drift simulations are kept separate from resource results, i.e. the model uses oil drift/weathering input from a suitable model and calculates impact and restoration based on calculation steps given in ERA Acute and resource data available in ERA Acute. This approach also means the model can be formulated as algorithms to program after this phase of the project.

Disadvantages of this approach is over-simplification. In the kick-off meeting (September 2014) it was stated that improvements and sophistications available should be considered to avoid over-simplification. THC averaged over the entire water column is not representative for near seafloor water column, as it is the heavier and less degradable components that will adsorb to particles and sink. Also, toxicity data on THC are limited, most data available are on individual toxic components.

7.2.2 Alternative 2 – Use Hydrocarbon Components and THC from Fates modelling in OSCAR

7.2.2.1 Oil reported in the sediments

Model simulation time is a critical issue. The Fates model that is currently used in statistical ("stochastic") mode does not calculate oil in sediment, but sends it out of the model when it reaches sediments and there is no further recording. According to SINTEF (Brönner & Reed, 2012) this may be included in future versions. If the future version of the single-simulations Fates model is included in statistical mode, it is important to consider implications on simulation time. In OSCAR, the version running one simulation at a time is called "single-scenario", to avoid confusion with the ERA Acute definition of a scenario, the following text will call this mode "single simulation" mode.

An alternative approach for a work-around at present is running Fates in single-simulation mode on a few representative scenarios to provide the necessary additional parameters for ERA Acute. The background for this option is that running OSCAR in single-simulation mode presently contains more data than are reported on a grid basis from the statistical output of the multi- simulation-"stochastic mode" (see section 7.1). The version of Fates that runs in single-simulation mode calculates THC (dissolved oil and droplet particles) and also calculates oil that sinks to the seafloor by a simple partitioning function, "sedimented particles" in SINTEF memo (Brönner & Reed, 2012). The version of Fates that is used in single-simulation mode ("advanced sediment model") also gives the concentrations of the individual components (as pseudo-component groups, aka "OSCAR groups") in the prt-file that is generated during the simulation.

From single-simulation mode simulations it is therefore possible to get concentrations of pseudo-components and sedimented particles with oil (THC and components), reported as mass per area.

7.2.2.2 THC in the Upper/Lower Water Column

For the seafloor compartment, organisms that are exposed in the water column (hard-bottom organisms and organisms largely exposed through water, will be exposed to HC in the lower part of the water column. To obtain as accurate estimate of THC and/or components for seafloor organisms, output data should be reported on THC and pseudo-components for water column segments, so that the lowest part of the water column can be reported separately. This was confirmed to be available in Fates modelling that is used in statistical mode, but like the sediment HC it is not reported in the output UTM file.

The concentrations in the lower water column may be reported from single simulation runs of the model. (E.g. choose the simulation that leads to the highest concentrations in the water column.

From Figure 15, at a time-step in the simulation where there is more HC in the lower water column, there is also more oil in the sediments.

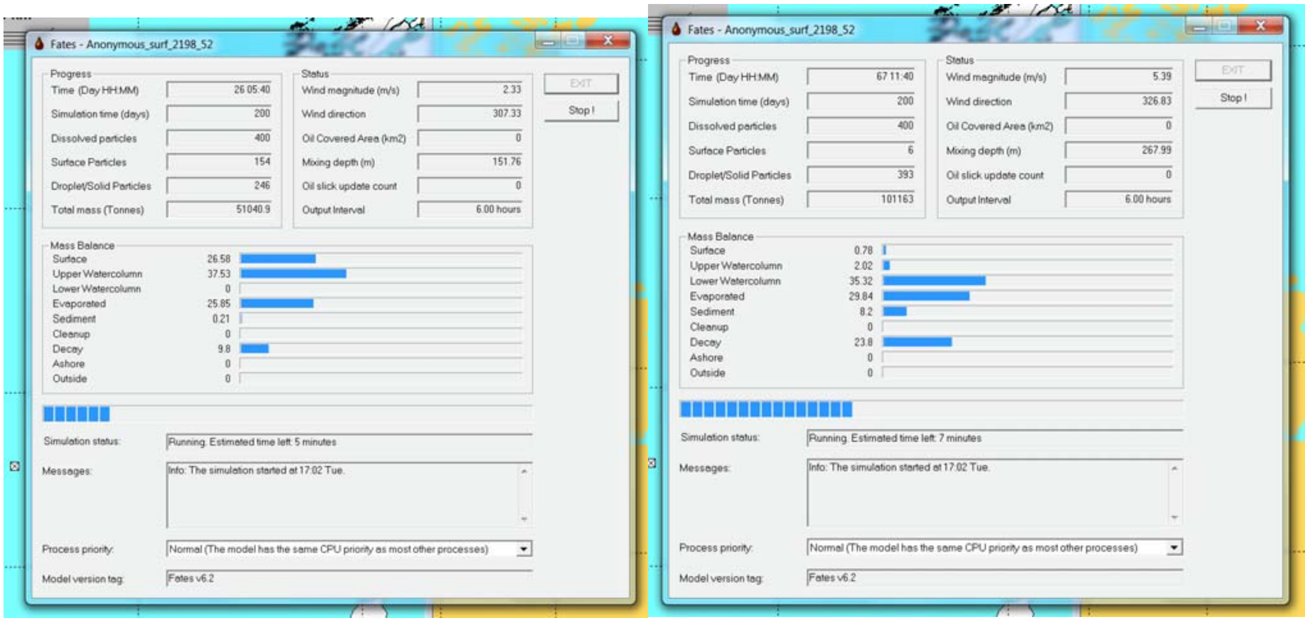

Figure 15 (left) There is little sedimentation at the beginning of the release, there is more oil in the upper water column. As the spill proceeds (right) there is more oil in the lower water column and more oil reaches the sediments.

A similar approach as for sediment HC is used (See 16): Until the relevant parameters distinguishing between upper and lower water column can be obtained directly for each cell in the OSCAR statistical output, a manual work-around is suggested for users using OSCAR. The advantages of this approach is that – although all outputs are not currently available in the output from OSCAR statistical mode (Brönner & Reed, 2012). – simulations that are assumed to be representative of a given level of conservatism may be used to derive information In the example given in this report, the simulation leading to the highest concentration in the water column is assumed to also give the highest concentration in the sediments. Other simulations may be chosen as representative at user's discretion. The approach retains the ERA Acute architecture of keeping oil drift simulations separate from resource data and ERA Acute results. It also means that although the oil drift modelling output for sediments in stochastic mode from OSCAR will not be ready to use yet without this preliminary work-around after this project phase, the calculation steps of ERA Acute can be programmed after this project period and ERA Acute can be used with the preliminary work-around. This also means there will be some more user steps until the parameters can be given as direct output. Currently, we suggest this is carried out manually by the user, to avoid programming of preliminary steps. Changes in OSCAR providing $C_{THC,sed}$ values as needed may be available in the near future, and other models may be available.

The approach outlined here does not address impacts to the same level of detail as Alternative 3 in areas where high resolution data (temporal and spatial) are available, such as time-dependent toxicity. It is, however, a significant improvement over alternative 1.

7.2.3 Alternative 3 – Future Possibilities for Higher Level of Detail in the Output from Oil Drift Modelling

The motivation for this approach is that where high resolution (temporal and spatial) resource data are available, impacts may be calculated with a higher precision. SINTEF are developing OSCAR to give a direct impact calculation based on Quantitative Structure-Activity Relationships of the (pseudo)components in OSCAR and LC50 and BCF values. Toxicity is time-dependent and internal exposure depends on uptake and depuration kinetics leading to a critical body burden for the organisms, and thereby toxic effects (lethal/sublethal, acute/chronic). SINTEF have recently looked into three approaches relevant for OSCAR – the Critical Body Residue (CBR) (already in OSCAR for water column, Target Lipid Model (TLM) and the

OMEGA model. This is described in more detail in a memo discussing the models and their potential use in OSCAR (Brönner et al., 2014).

SINTEF have a task in ERA Acute to develop a similar approach for the seafloor organisms that are exposed to HC through the water column (i.e. corals and sponges). However, the approach is under development (Brönner & Nortug, 2014) and the output from OSCAR will not be available within the time-frame of the ERA Acute development project. It was therefore decided in the clarification meeting that SINTEF were to continue developing this approach as planned, and that APN would develop the calculation steps for implementing all types of organisms in the seafloor compartment allowing for this refinement of the water column *plet* value to be entered at a later stage.

If adopted, this approach will deviate from the original ERA Acute architecture, i.e. that some of the impact calculations will be carried out in OSCAR for the water column-exposed organisms giving direct *plet*-values of potential toxicity. The grid-cell based resource data defining whether the potential toxicity is relevant or not for that cell should be part of ERA Acute, and entering a value for N (>0) will give a calculation of the impact . For the sediment-dwelling organisms, the refined toxicological endpoint can be adjusted to *infauna* directly using EqP, as demonstrated previously.

Otherwise, resource data will need to be added to OSCAR, which is expected to increase simulation time per OSCAR-simulation. It would also require re-runs of oil drift simulations if resource data distribution changes.

It was decided to develop ERA Acute for the sediment compartment using preliminary values/work-arounds from Alternative 2, whilst allowing for the refinements of a more detailed OSCAR modelling to be entered at a later stage. The advantage of this is that there will be algorithms for the sediment compartment for programming following this phase of the project. How and if the results from alternative 3 is included in a future version of ERA acute is outside the current phase of the project. However, the full potential is future.

8 Discussions for Exposure Estimation

8.1 *Infauna* Exposure

To calculate *infauna* impact, oil concentration values in the sediment are needed to be either modelled in an oil drift model (alternative 2) or calculated based on partitioning theory in the calculations of ERA Acute using THC_{WC} (alternative 1 and 2).

$C_{THC,sed}$ and the concentration for each of OSCAR's pseudo-components can be calculated using the OSCAR model single-simulation mode and can be exported for use in ERA Acute as described in 7.2.2.1. Other models can be used that give the same output parameters.

For sediment-dwelling organisms, it was requested by the clients to use THC instead of single components in the calculations As discussed earlier in this report, not all components of an oil will reach the sediments. Physical-chemical properties will decide whether the component evaporates, dissolves, degrades quickly or slowly etc. based on the size and molecular structure of the hydrocarbon. Oil drift and weathering models that take the composition of the crude into account, will calculate the concentrations of various components reaching the seafloor based on the physicochemical properties of the individual (pseudo) component groups.

Summarised from the discussion in section 6.4, pseudo-components from C13-C14 and larger are the most relevant for sediments, and these fractions are the components that are included when exporting the THC concentration from the sediment compartment in the export routine described in section 0. We therefore know that the value reported as THC will be the heavier components.

Remembering that a certain degree of water solubility is necessary for the hydrocarbons to be toxic and bioavailable and for EqP theory to be valid as an approach to estimating the toxicity for benthic *infauna*. The least water-soluble components have a high affinity to particles with high organic carbon content, however, they will be less acutely toxic. This further supports the assumption that "medium" soluble (pseudo)components are the most relevant, i.e the lighter of the groups that enter the sediment. Figure 16 to Figure 19 show the components that are relevant for the sediment compartment (using Tau crude oil as an example for a North Sea release. Selecting the THC pseudocomponents found to be relevant by the user, the selection may be exported to a shape file and converted for use in ERA Acute (See chapter 16 for a detailed description using ArcView as an example).

Table 5. Solubilities of hydrocarbon component groups (from OSCAR).

PK	CHEM_NAME	SLBLTY
24	Phenols (C0-C4 alkylated)	51000
7	Benzene	1780
8	C1-Benzene (Toluene) et. B	515
9	C2-Benzene (xylenes; using O-xylene)	175
2	C5-saturates (n-/iso-/cyclo)	95
10	C3-Benzene	57.5
1	C1-C4 gasses (dissolved in oil)	40
3	C6-saturates (n-/iso-/cyclo)	32.5
20	Naphthalenes 1 (C0-C1-alkylated)	27.5
11	C4 and C4 Benzenes	12.5
21	Naphthalenes 2 (C2-C3-alkylated)	5.5
4	C7-saturates (n-/iso-/cyclo)	4
22	PAH 1 (Medium soluble polyaromatic hydrocrbns (3 rings-non-alkyltd;<4 rings)	3.65
5	C8-saturates (n-/iso-/cyclo)	1
6	C9-saturates (n-/iso-/cyclo)	0.205
23	PAH 2 (Low soluble polyaromatic hydrocarbons (3 rings-alkylated; 4-5+ rings)	0.101
25	Unresolved Chromatographic Materials (UCM: C10 to C36)	0.001
12	C10-saturates (n-/iso-/cyclo)	0.0001
13	C11-C12 (total sat + aro)	0.00001
14	C13-C14 (total sat + aro)	0.000005
15	C15-C16 (total sat + aro)	0.000001
16	C17-C18 (total sat + aro)	0.000001
17	C19-C20 (total sat + aro)	0.000001
18	C21-C25 (total sat + aro)	0.000001
19	C25+ (total)	1E-07

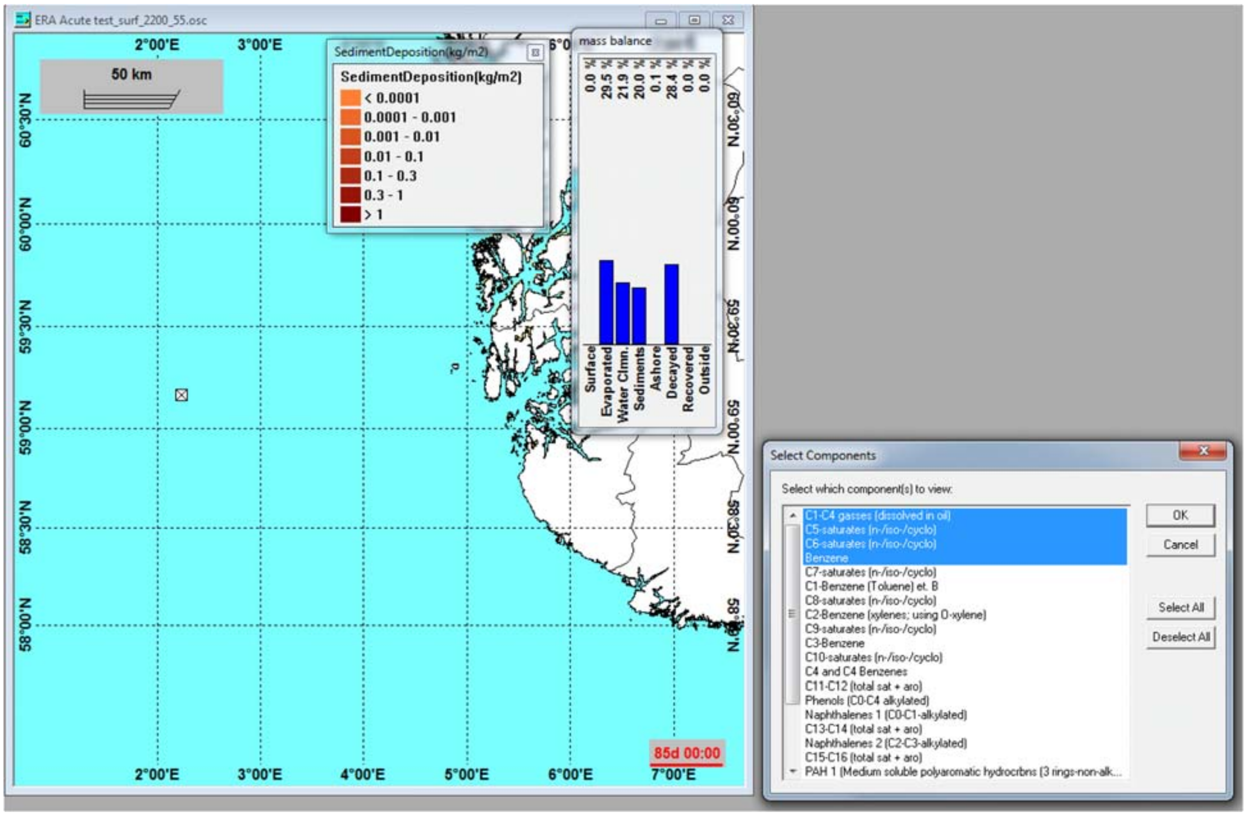

Figure 16. Selecting the sediment, the components that are present in that layer are presented as total hydrocarbon concentration. (C1-C4 gases to benzene).

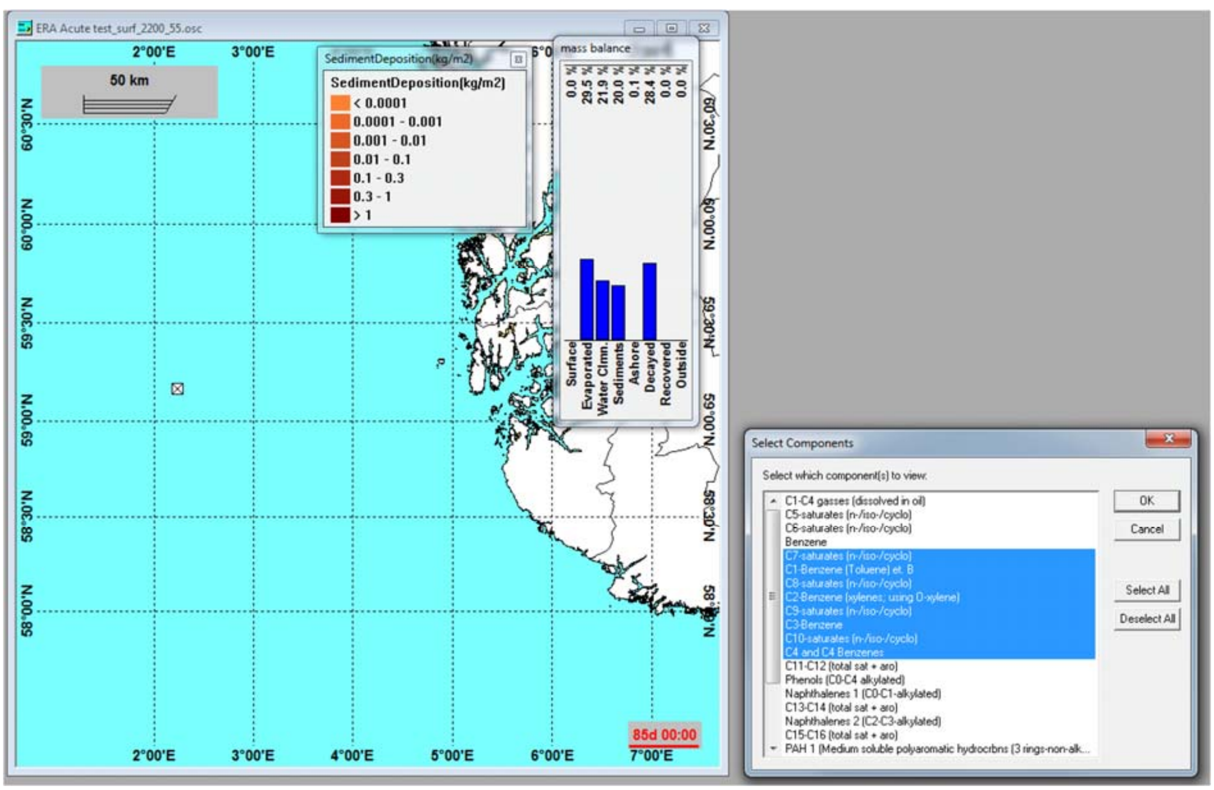

Figure 17. Selecting the sediment, the components that are present in that layer are presented as total hydrocarbon concentration. (C7 saturates-to C4 benzenes).

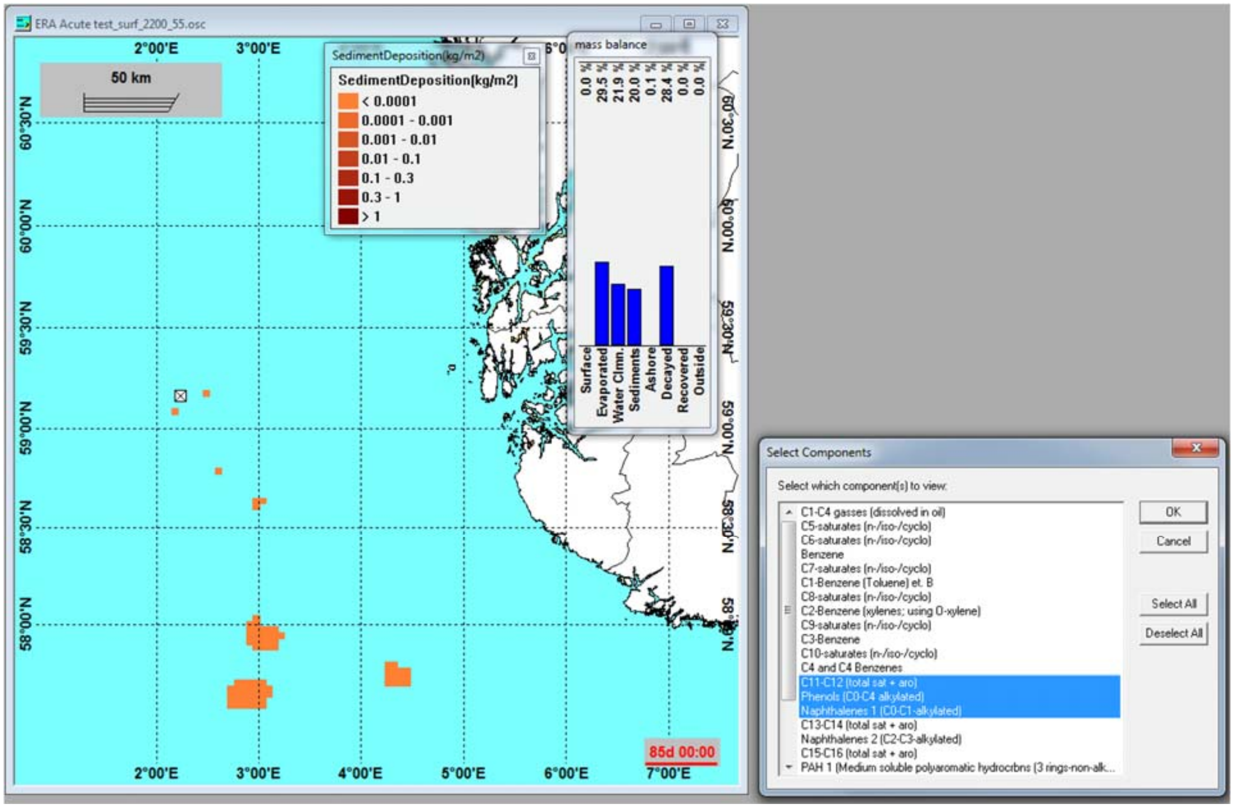

Figure 18. Selecting the sediment, the components that are present in that layer are presented as total hydrocarbon concentration. (C11 saturates-to C1-alkyl naphthalenes).

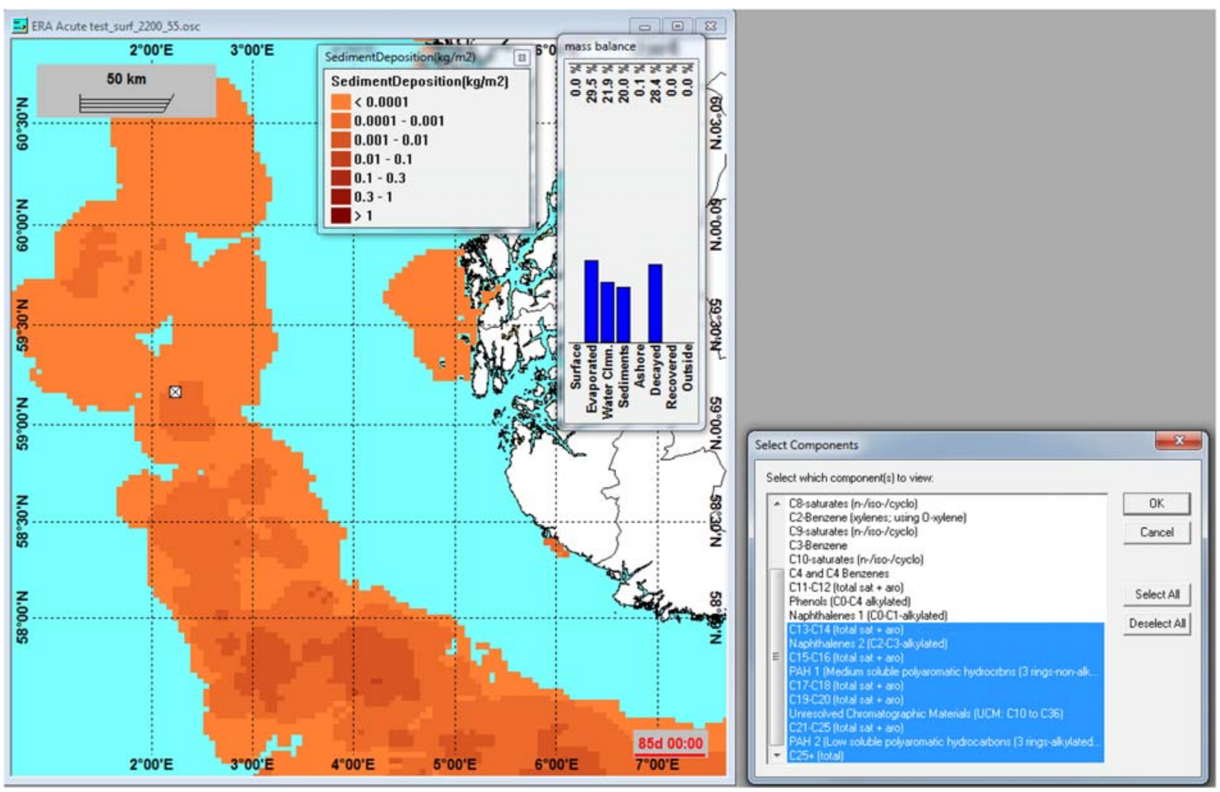

*Figure 19. Selecting the sediment, the components that are present in that layer are presented as total hydrocarbon concentration. (heaviest components (from C13-PAH 1). These are the same components that relevant as for **lower** water column.*

8.2 *Epifauna* Exposure

In OSCAR statistical mode today, only time-averaged maximum THC and time-averaged maximum dissolved HC is reported for the whole water column. As can be seen from Figure 23, apart from phenols, roughly the same components are present in the lower (bottom) water column layer that are present in the sediments. C0-C1-naphthalenes play a minor role in the case study. Due to the chemical-physical properties, it is assumed that this is generic.

The HC concentrations in the lower section of the water column are the most relevant for accurate seafloor impact calculations. Therefore, if the THC concentrations in the lower water column can be used, this is preferable. Lacking this division in the oil drift simulation statistical output, the general water column concentration can be used. In OSCAR, (MEMW 6.2) the lower water column results are available in single-simulation mode, however not in stochastic mode, but the results from the single-simulation mode can be obtained in the same way through export to a shape file for standard conversion to the specified projection and chosen model grid.

Figure 20 to Figure 23 show the concentrations of THC in the water column in different groups, with only the bottom water column layer selected.

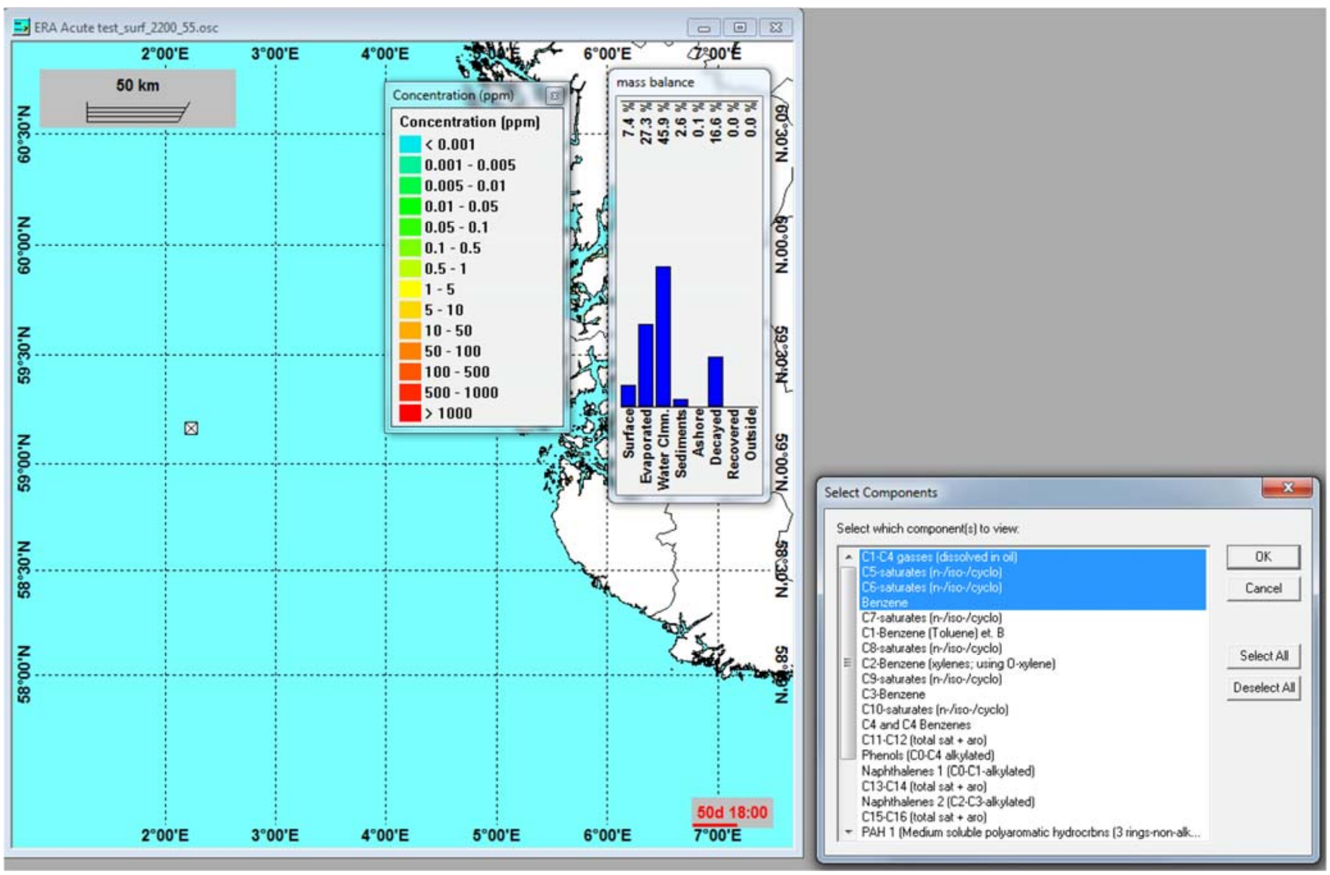

Figure 20. Selecting the lower water column layer, the components that are present in that layer are presented as total concentration of droplets and dissolved particles. (C1-C4 gases to benzene).

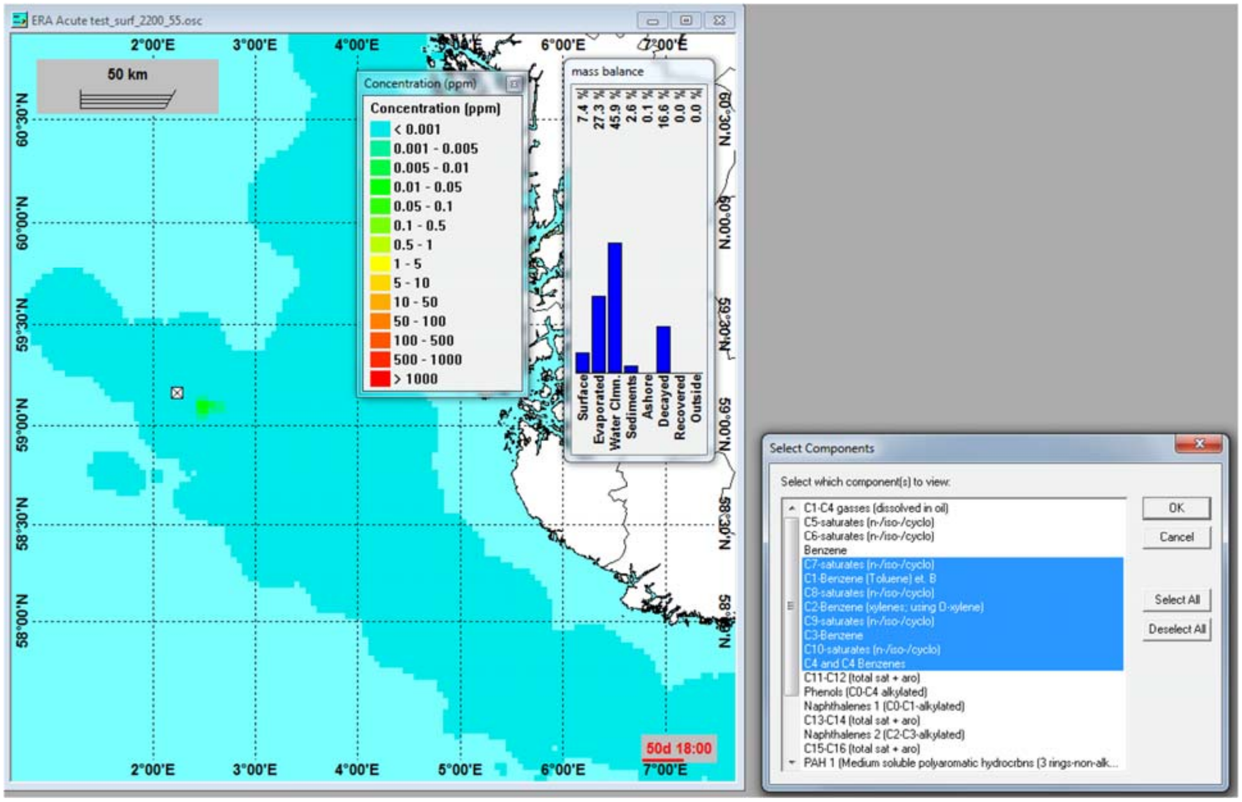

Figure 21. Selecting the lower water column layer, the components that are present in that layer are presented as total concentration of droplets and dissolved particles. (C7 saturates-to C4 benzenes).

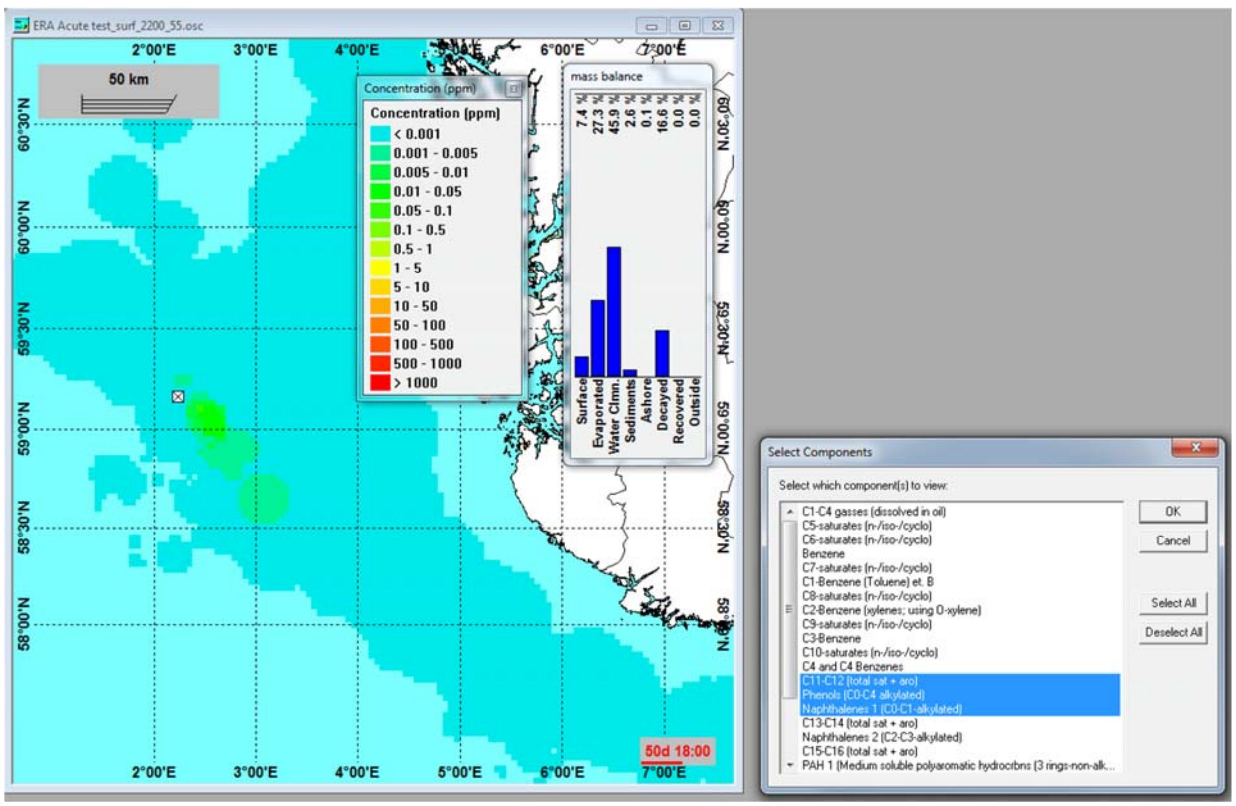

Figure 22. Selecting the lower water column layer, the components that are present in that layer are presented as total concentration of droplets and dissolved particles. (C11 saturates-to C1-alkyl naphthalenes).

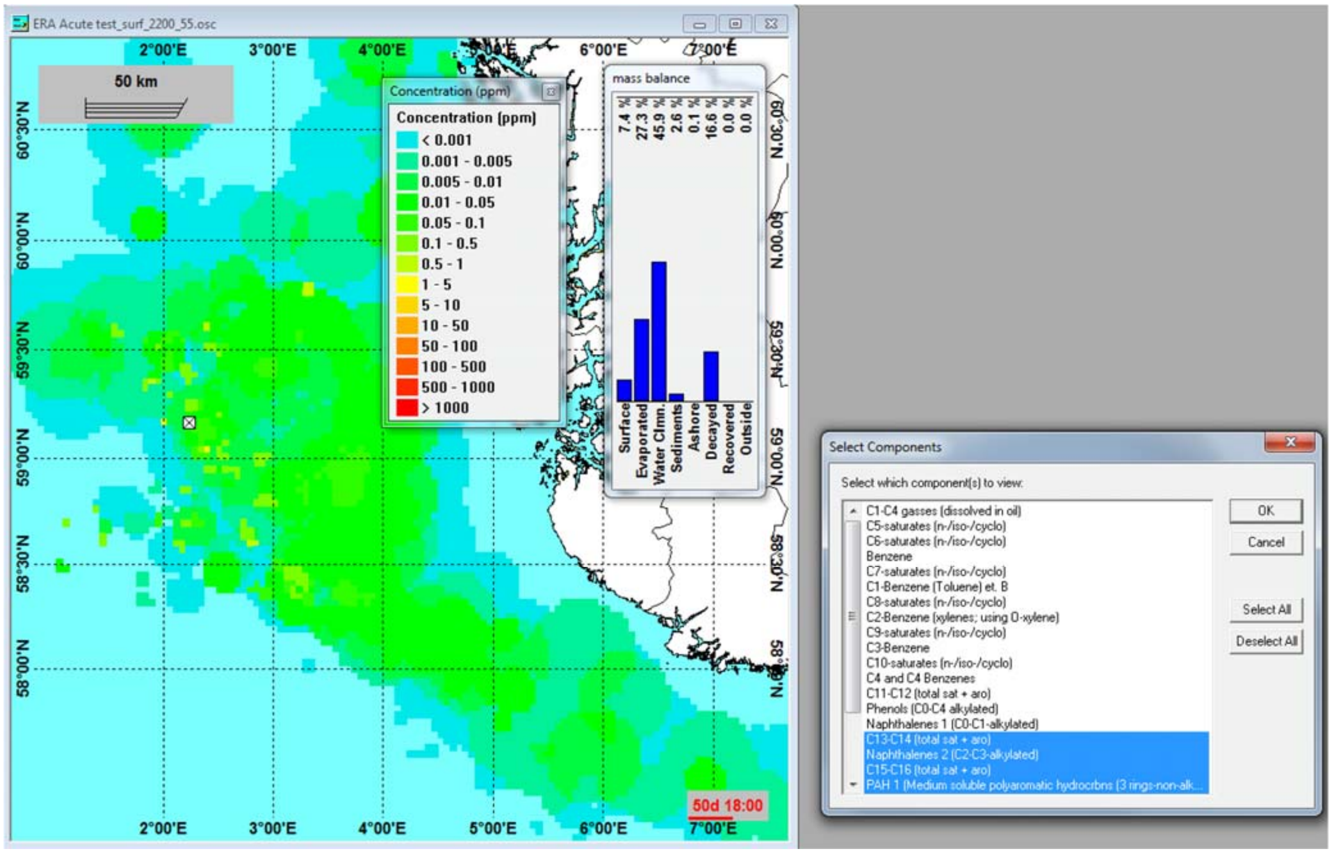

Figure 23. Selecting the lower water column layer the components that are present in that layer are presented as total concentration of droplets and dissolved particles (heaviest components (from C13-PAH 1). These are the same components that relevant as for sediment.

9 Resource (VEC) Data

9.1 Introduction

For undertaking assessments using the ERA Acute model, data sets on vulnerable resources (Valued Ecosystem Components – VECs) need to be available in a format specifying a fraction of the overall distribution of the data set within grid cells on a common grid definition. This grid definition needs to be used by the oil drift model as well as resource data sets in other compartments of the ERA Acute model.

To calculate impact, the resource data sets need to be accompanied by additional information in an overall data structure. This is outlined in section below.

Format, availability and structure of resource data sets may vary from region to region. While the ERA Acute tool does not require spatial references except for the grid cell format, data sets will most often need to be derived through the use of GIS. An outline on how to construct resource data sets from various starting points are given in section 15.2.2. This outline assumes a basic knowledge of GIS functionality.

Development of actual data sets is not part of the project SOW.

9.2 Scaling of the model

9.2.1 N_{total}

The basic impact calculation uses the value "N" to denote the resource. The number for *N* for a specific resource *r* in a cell in a compartment is the fraction of the "whole" resource that is present in that cell. It can be a fraction of a population, as e.g. for sea birds at the sea surface, or another equivalent of a population fraction for resources where the use of the term "population" would be misleading. This definition raises the question of the model scale and the analysis area.

For the model to work across compartments, the scale used in each compartment needs to be comparable with that used in another, i.e. the analysis for each compartment measures the impact relative to an N_{total} that relates to the same analysis area for all compartments. If the resource data sets in one compartment are different from another compartment, the impact may be measured *within* the compartment relative to the *unimpacted* resource in the same compartment, but a direct numerical comparison between impacts on fractions of N in two or more different compartments becomes difficult.

A proposed solution could be to report “N” in two ways in the data sets. In a multi-compartment project workshop it was decided to allow for the reporting of impact along two axes, one "absolute" (geographical) and one "population equivalent"/fraction of the resource, which relates to the most biologically appropriate definition of the population:

a. As an (absolute) area with resource present (which could be comparable across compartments), used for reporting an impacted geographical area that can be georeferenced and shown in a map as well as summed up and graphed as geometrical areas (in km^2) above impact thresholds/within levels etc.
b. As a fraction of a community (equ. to population)/area distribution in the grid cells. This latter data adaptation will then need to be harmonized across compartments if the user is to be able to compare impacts in different compartments, alternatively accept the difference in scale between compartments (e.g. allow for a regional/colony-data based sea bird population and a North-East Atlantic resource fraction for e.g. corals (North Sea, Norwegian Sea, Barents Sea)).

9.2.2 Resource Unit "N" for the Seafloor

The suggested resource unit for the seafloor is fraction of the total area of the resource (at the chosen scale, e.g. nationally) that is present in the individual grid cell. Sensitive habitats with patchy occurrences (such as coral reefs) should have data sets where N_{total} is the sum of the area of reefs within the defined scale. In the seafloor compartment, both above given N-values (absolute area fraction) and total resource fraction need to be defined for each cell.

Care needs to be given by the user when adapting the N-values for a data set for use in ERA Acute, as the value and approach chosen will affect the calculations directly. A higher-resolution in the grid cell size will give a higher level of detail for areas of particular importance, e.g. for corals.

9.2.3 Comparing compartments for different uses of ERA Acute

ERA Acute is to be used for risk assessments of individual activities, and may also be used for net environmental benefit assessments. In the latter methodology, comparison of the environmental benefit and impact is measured for different oil spill combat options. For example, a comparison can be made between the benefits of mechanical recovery, which removes oil from the surface and thereby the environment; and the use of dispersants which moves the oil from the slick on the surface to droplets in the water column. Dispersion thereby reduces the risk to surface and shoreline, but increases the risk to water column resources, and also makes the oil available for sedimentation through the formation of "marine snow" (Passow *et al.* 2012).

This use of the ERA Acute model requires that it is possible to make a comparison between the numerical values of risk reduction vs. increases in the different compartments.

9.2.4 Risk Scaling

Model development and implementation in a software tool should be followed by a familiarisation process including comparisons with other methods for risk assessment to the same VECs, as well as between large and small spills. The purpose of such a post-development benchmarking process is to establish consensus about risk values from a scientific point of view for various oil spill cases that are relevant. A familiarisation process will allow for expert users to define what is a large, small or significant risk to the resources in question, and will allow for testing of various resource unit scales.

Within an analysis area, the resource data should be harmonised between the compartments before using them in ERA Acute. There are different ways of scaling the analysis area before an analysis is carried out; however, national data sets may be the easiest available, and a national scale is assumed to be the most relevant use of the model. As risk assessments may be part of a National application scheme for oil related activities, a national scale is also relevant in this context, and use of national data sets are proposed as default. Resource data are then adapted to the national scale, meaning that everything is measured against the 100 per cent national total resource amount, i.e. a national sea bird population, national area of sensitive habitat/spawning area, national area of sensitive sea bed etc. This allows for the data sets to be prepared with the same outer boundaries, the national territory. The sum of all cell resource fractions are thereby 1 (100 %).

However, for smaller spills, the numerical value of the impact may be very small, and the familiarisation process should be followed by a risk acceptance process discussion involving users of the model. A separate risk acceptance process needs to be undertaken by the individual owners of the activity causing risk (e.g. operating companies), depending on company policies and legislative risk assessment practices in the country where the model is used.

9.3 Digital data sets – global

On a global basis, data applicable for ERA Acute are available for resource types identified as important for biodiversity and thereby a focus for protection. In addition, data on bathymetry and seafloor conditions are available, and may be used as a basis for deriving data sets on habitat types. Some key data sources are given below.

9.3.1 Coral reefs

Digital global data sets on coral reefs are available for download at the UNEP Ocean Data Viewer web site, for:

- Global distribution of Coral Reefs: http://data.unep-wcmc.org/datasets/1
- Global Distribution of Cold Water Corals: http://data.unep-wcmc.org/datasets/3

9.3.2 Seagrasses

Digital global data sets on seagrasses are available for download at the UNEP Ocean Data Viewer web site, at the address: http://data.unep-wcmc.org/datasets/8

9.3.3 Sea turtle feeding areas

Although depending on feeding mode, these data sets may be relevant for shoreline and sea surface compartments, a link is provided here: http://data.unep-wcmc.org/datasets/21

9.3.4 Marine protected Areas

Digital global data sets on protected areas are available for download following the link provided at the UNEP Ocean Data Viewer web site page for World Database on Protected Areas: http://data.unep-wcmc.org/datasets/12.

9.3.5 Water depth

Data sets on water depth are globally available. Nearshore they are available in high resolution, as such data are important for safety at sea, and a range of suppliers and data sources may be found.

On a global scale, data are available in a GIS format with a 1 arc minute resolution (approx. 2 km). See: http://comlmaps.org/how-to/layers-and-resources/physical-environment/etopo1-global-relief-model.

9.3.6 Sediment type

Mapping of sediment types on a global scale is mainly related to fisheries (e.g. trawling grounds) and marine transportation in general (anchoring conditions). An international standard for designating seafloor types and sediment types has been developed (S-57 - The IHO Transfer Standard for Digital Hydrographic Data). The extent to which data is available differs widely.

9.4 Digital data sets – regional and national

On a regional and national level, data cited in the previous section are in many instances available at a higher level of detail, on a temporal as well as spatial scale. Some examples of data sets are given below, and similar data sets may be available for other regions and nations, in a variety of formats. An exhaustive list for individual regions and countries may be developed according to need, but is beyond the scope of the current project.

9.4.1 Sediment type

Marine geological data sets for the Norwegian Continental Shelf are available as GIS layers provided by NGU, through: http://www.ngu.no/en-gb/hm/Maps-and-data2/Maringeologiske-kart/.

Seafloor type is among the GIS layers obtainable from the Norwegian Mapping Society, although with a fragmented coverage. For further information, see: http://www.statkart.no/en/Kart/Kartdata/Marine-Geospatial-Data/.

9.4.2 Corals

Cold water coral observations on the NCS are available as downloadable GIS layers from the Norwegian Institute of Marine Research, see: http://maps.imr.no/geoserver/web/;jsessionid=1gd6cavh3twgu?wicket:bookmarkablePage=:org.geoserver.web.demo.MapPreviewPage.

9.4.3 Seagrasses and kelp forests

High resolution data sets on seagrasses and kelp forests in the Norwegian coastal regions are available at The Norwegian Directorate of Nature Management "Naturbase", see: http://www.miljodirektoratet.no/no/Tjenester-og-verktoy/Database/Naturbase/.

9.4.4 Species distribution/observations

The US National Benthic Infaunal Database (NBID) (http://nbi.noaa.gov/) provides an interface for searching the database on observations of infaunal species, listed by stations with coordinates.

The Norwegian Directorate of Nature Management "Naturbase" contains information on a range of nature types and species observations, see: http://www.miljodirektoratet.no/no/Tjenester-og-verktoy/Database/Naturbase/.

9.4.5 Various

Antarctic Biodiversity: http://data.biodiversity.aq/spatio_temporal/maps? (example: http://data.biodiversity.aq/taxonomy/show/24822)

South Georgia sponge distribution: http://www.antarctica.ac.uk//bas_research/data/collections/sgmarbase/sponges.php

9.5 Digital data sets - locally

At a local level, detailed mappings are carried out related to activities and management plans. Examples will include environmental monitoring studies offshore and nearshore, as well as initiatives like the MAREANO programme in Norway (http://www.mareano.no/en).

9.6 Constructing resource data sets

Below is a step by step outline of how to proceed to construct resource data sets, based on the structure specified in section 15.2.2. In addition, information must be provided for the tables specified in the same section, if different from the generic resource data groups described.

9.6.1 Digital data sets with resource distribution (polygon)

1. If in other geographical projection, reproject as required
2. Intersect with GIS layer containing grid cells to be used in assessment
3. Expand GIS layer attribute table to columns and column names given in format
4. Assign distribution within individual months as fraction of total, using identical values for all months if no monthly variations are given
5. Export text file from GIS layer attribute layer comprising column names given in format

9.6.2 Digital data sets with boundary definitions only

1. If in other geographical projection, reproject as required (e.g. from decimal degrees to UTM33)
2. Intersect with GIS layer containing grid cells to be used in assessment In ERA acute
3. Calculate areal fractions for individual grid cells from total area
4. Expand GIS layer attribute table to columns and column names given in format
5. Assign distribution within individual months as fraction of total area, using identical values for all months if no monthly variations are given
6. Export text file from GIS layer attribute layer comprising column names given in format

9.6.3 Digital data sets – points only

1. If in tabular format, import in GIS
2. If in other geographical projection, reproject as required
3. Intersect with GIS layer containing grid cells to be used in assessment
4. Calculate statistics for individual grid cells (no. of points in each grid cell divided by total number of points) and apply as fraction
5. Expand GIS layer attribute table to columns and column names given in format
6. Assign distribution within individual months as fraction of total, using identical values for all months if no monthly variations are given
7. Export text file from GIS layer attribute layer comprising column names given in format

9.6.4 On paper data sets (maps)

1. Digitize polygons in the projection used for the paper map
2. If in other geographical projection, reproject as required
3. Intersect with GIS layer containing grid cells to be used in assessment
4. Expand GIS layer attribute table to columns and column names given in format
5. Assign distribution within individual months as fraction of total, using identical values for all months if no monthly variations are given
6. Export text file from GIS layer attribute layer comprising column names given in format

10 Level A and Level B for the Seafloor Compartment

10.1 Concept of Level A as a Simplified Approach

ERA Acute is developed at two levels. For the other three compartments, level A, the simplest level, was developed in 2010 (Spikkerud *et al.* 2010). The idea behind the two-level model is to allow for a simpler, but conservative screening analysis to be available, which also allows for the use of fewer or less detailed resource data. Without any data, level A assumes that the most sensitive organism is present in all grid cells analysed, but it also allows for the use of presence/no presence data as well as screening utilising the more refined data containing fractions of the resource. The seafloor compartment was not a part of ERA Acute in the first phase of the model development, but is therefore included in the present scope of work. The model as it was presented in 2010 is shown in Figure 24 (from Spikkerud *et al.* 2010).

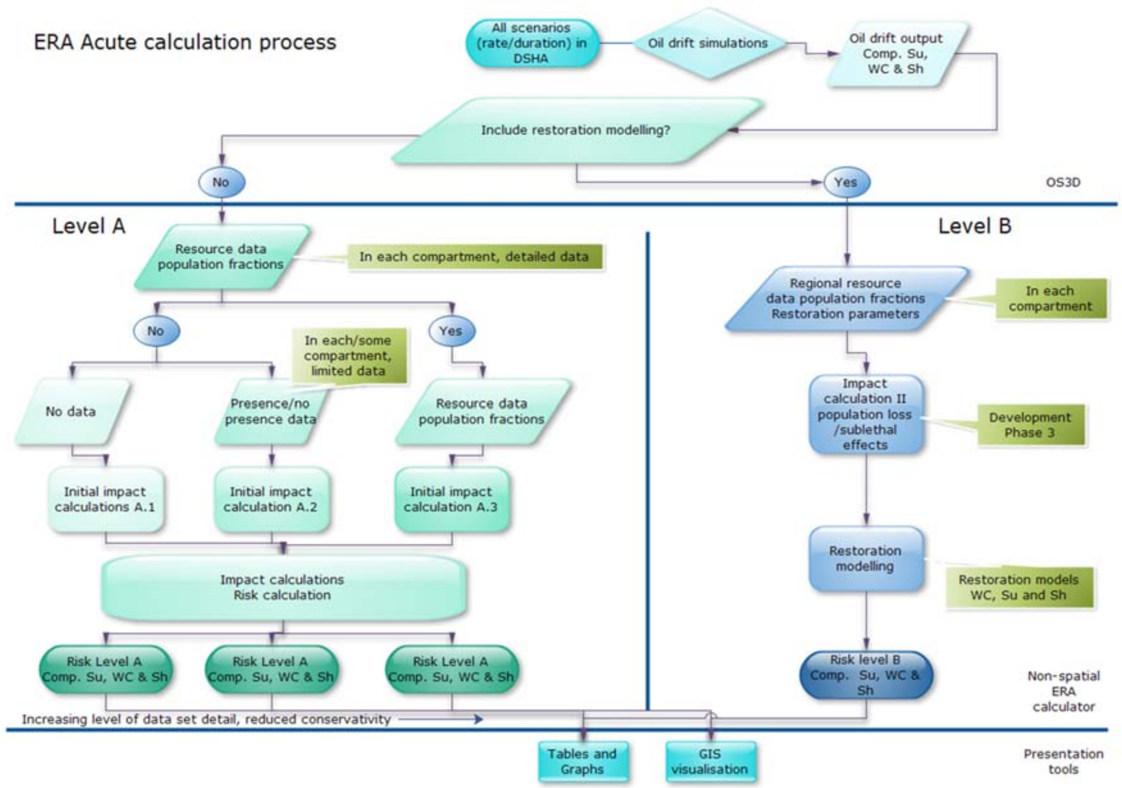

Figure 24 Outline of risk assessment in two levels A and B, allowing for several types of resource data to be used at level A, providing flexibility with respect to data adaptation needs (From Spikkerud et al 2010).

10.2 Level A for Seafloor into the Level A Tool.

10.2.1 Implementation

The implementation of level A into the existing ERA Acute tool requires that the user is able to prepare the data for $C_{THC,sed}$ from the oil spill simulations. It is therefore not as straight forward as running level A for the other compartments.

10.2.2 Level A.1 – Sensitive resources assumed to be everywhere

Level A.1 can be used when only oil drift simulations are available. Currently, to run Level A, the user needs to aquire the THC concentration in the sediment manually from a single simulation considered relevant

(Chapter 7). Corals have patchy presence and it is therefore recommended not to model these as generally present, but to obtain specific data sets and carry out a level B assessment.

The level assumes presence of the most sensitive resources within the entire oiled area in all compartments and sub-compartments, and is therefore considered to be the highest level of conservatism in the model. For each sub-compartment, presence of the most sensitive resource is assumed within the area affected by oil. $N_{cell,comp}$ is set to 1, giving the following formula for initial impact calculation (Spikkerud *et al.* 2010). At level A.1, the general principle is to use the most/medium sensitive species as conservative (at some decided level of conservativism) giving the highest impact value. The first-step impact equation at level A.1 is (Equation 7) (following the calculation of the THC concentration in the sediment sub-compartment THC_{sed} (See 12.1.1).

Equation 7 $$\mathrm{Imp}_{r,cell,sim,sed} = p_{\exp r,cell,sim,sed} \times p_{let,r,cell,sim,sed}$$

For the seafloor compartment, $p_{exp} = 1$ (Section 0)

One should use the $p_{let,sed}$ values for the most sensitive species for the seafloor as the representative values when no resource data are available, using the p_{let} function for organisms exposed through interstitial water Among most sensitive resources are amphipods and isopods, but other, more poorly studied organisms could have a higher sensitivity. However, as in the sediment compartment, the impact function assumes the same sensitivity as that used for the other resources (using the same WC main compartment dose-response curve), the different sensitivity lies in the longer restitution time, and being less competitive.

As sensitivity is differentiated by restitution time, the scientifically most robust suggestion is to apply a sensitivity factor to the p_{let} for level A.1 corresponding to the factor of difference in restitution time between the most sensitive resource and the average sensitive resource. Negative values are not recommended for resources less sensitive than average. (Could also use the difference between the resource and the least sensitive, not the average).

The potential impact in each cell is presented as values between 0 and 1, representing a potential mortality in the cell/compartment for this simulation.

The equation for the initial impact calculation in a cell is therefore in A.1:

Equation 8 $$\mathrm{Imp}_{r,cell,sim,sed} = p_{\exp r,cell,sim,sed} \times p_{let,r,cell,sim,sed} \times SF_{A,sens}$$

Where $SF_{A,sens}$ is the sensitivity factor for level A for the most sensitive organism. At Level A.1 there are no VEC data sets and the value is therefore entered manually. Currently the value of such a sensitivity factor is unknown, it is therefore suggested to be used if such data exist.

10.2.3 Level A.2 – Sensitive resources in presence/absence form data sets

Georeferenced resource data at the presence/no presence level (P/A) are expected to be the most prevailing form of data for the seafloor, for e.g. coral reefs, particularly valuable seafloor types etc. Such data can be used in level A.2 to reduce the area of potential impact compared to level A.1. As mentioned in Spikkerud *et al.* 2010) a premise for using level A.2 to reduce the area of concern is to use *reliable* data on the non-presence of vulnerable resources outside the data set. High coverage is necessary to make sure that a reduced area of concern is not simply the result of lack of data. Use of this option therefore needs careful consideration of the dataset completeness.

The data will be present as simple polygons. Impact algorithms are similar as for the situation with no data (Level A.1), but are now related to the individual data sets.

Presentation formats are as for the situation with no data available. However, for these resources, their presence is derived from the data sets on distribution, giving a less conservative impact prediction. Depending on the questions asked, the impact can be calculated for the most sensitive resource, or for several resources to provide comparison.

Equation 9 $$\mathrm{Imp}_{r,cell,sim,sed} = p_{\mathrm{exp}r,cell,sim,sed} \times p_{let,r,cell,sim,sed} \times N_{r,cell,sed} \times SF_{A,r}$$

Where:

$N_{r,cell,seafl}$ is either 0 or 1 in each grid cell depending on presence or absence of resources.

$SF_{A,r}$ is the sensitivity factor for level A, which is defined as the magnitude of the difference in restitution sensitivity between the resource and the average resource restitution time. At level A.2 it can read from the VEC data set file (VEC_list) which is also used for level B, (see section 15.2.2.1), but can also be entered manually or via a lookup file (section 15.3.2) for the benefit of using Level A.1.

As the $p_{let,sed}$ values are derived from the $C_{THC,sed}$ using the same toxicity curve that is used in the water column, there is, as mentioned above, no difference in sensitivity between the resources, and the suggested factor of difference in restitution time between the resource (if known). Thereby, average restitution time is used to modify the risk at level A which does not otherwise include incorporating the restitution time into calculations. However the impact function assumes the same sensitivity as that used for the other resources, the different sensitivity lies in the longer restitution time, and the resource being less competitive during re-growth.

A sensitivity factor is suggested to be used as for level A.1.

A lookup-table should be prepared by the user for entering $SF_{A,sens}$ and VEC-specific SF_A values. The sensitivity factors Table (simple factors based on information (if any) on different sensitivities, e.g. relative to average restoration. The table may be set to factor = 1, pending more information, thus allowing for user improvement if knowledge exists. If THC_{LWC} is used to read the toxicity curve, the estimate will relate to hard-bottom substrate VECs.

10.2.4 Level A.3 – Sensitive resources in fraction in a grid cell of total

When data sets including fractions of a resource are available, it would be equally relevant to run level B, as restitution time is calculated based on the same concentration of THC in the sediment that is calculated for impact modelling. However – for comparisons and in some instances – convenience – the level is described as being equivalent to calculation steps 1 to 3B.1, and can be implemented as level A.3 if so desired.

11 Chronic Effects and Restitution of Resources

11.1 Definition of Time Factors in ERA Acute in the Sediment Compartment

11.1.1 Impact time – T_{imp}

The impact time period is defined as the period from the start of the spill until the deposition of oil and maximum impact is reached. In the sediment compartment the impact phase includes the time until equilibrium is reached between the sediment organic carbon-bound HC and the pore water HC as per equilibrium theory, as well as moderately delayed responses to the acute phase of the spill. As defined in ERA Acute, the impact phase does not include impacts due to chronic exposure or chronic effects.

However, if an oil drift model is used that necessitates the use of a single simulation re-run (as described in chapter 7) the output has to be exported for a certain time-step within the simulation time. Depending on the available knowledge of time-to-equilibrium, the C_{THC} calculated from a certain time-step may not be exactly the C_{THC} at the time of equilibrium and the time of full impact. Therefore, by choosing the time at which the THC concentration is at its highest in sediment, the results should be conservative, and thereby it is considered to be sufficient for ERA Acute use.

In lack of specific data on the time it takes for the full impact of the sedimentation of oil to exhibit itself, it is suggested to use a default value of T_{imp} = 1 year. This is chosen in order to include the sedimentation process (weeks) and a full reproductive year-cycle of the species that are present in the seafloor sediments. During a year, different species may exhibit various life stages of the reproductive cycle, and using one year as a default is assumed to cover all impacts exhibited throughout that cycle. For corals, some preliminary research following the Macondo incident may indicate that there is a time frame of a year before impact is seen in full (see section 11.4.2). There is very little information available on sponges, and they are for the time being treated as corals.

11.1.2 Lag Time before Restoration Commences – T_{lag}

Lag phase is defined in ERA Acute as the time phase from full impact until restoration can begin. In this phase there is inhibition of re-growth, but no further increase in the impact. Chronic toxicity due to residual THC in the environment that leads to growth inhibition may contribute to a lag-time before restitution of a resource can begin.

In the sediment compartment, we find reason to believe that there will be lag-phases with impact before restorative re-growth will occur.

Based on mass balance estimates and initial results from running single simulations in OSCAR, reported elsewhere in this report, it is in an ERA Acute context assumed that deposition rates and amounts of sedimented oil will not lead to anoxic conditions. Given these assumptions hold, no lag phase before recovery starts is expected for sediments in general. For corals, the preliminary research following the Macondo incident indicates that there is indeed a lag-time before corals begin to recover after impact (see section 11.4.2), as no recovery has been detected per 2015 for the most heavily impacted corals (see section 11.4.2).

11.1.3 Restitution time After Re-growth starts T_{res}

Restitution time is defined as the time from the level of contamination is low enough for the restitution to begin and until the resource is back to pre-spill levels. There may still be contamination of the compartment, but re-growth exceeds further loss.

A challenge for the sediment compartment is the end-point for measurements of habitat quality/ restoration. It is not known whether the same species are present when the same level of diversity has been re-established.

11.1.4 Overlapping Time Phases

It is evident that some restoration begins while there still are species being impacted and other species being inhibited in their restorative growth. The division into separate phases when using a habitat as a resource is therefore a simplification for model purposes and the most robust solution for general sediment habitats was to treat lag- and restitution phase as one and thereby set $T_{lag} = 0$ (see sections 11.1.2 and 11.5.1.)

11.2 Degradation Processes of Hydrocarbons in the Sediments

The most important degradation processes in sediments are microbial, also anoxic conditions may have bacterial degradation involved. Bioturbation by organisms in the sediment contributes to oxygenation of the sediments, increasing the biodegradation rates.

11.3 Restitution of Impacted Populations

11.3.1 The term "recovery"

The benthic communities' ability to withstand or absorb the impact of a stressor before it changes may be termed *resistance*. Its ability to return to a previous state following removal of the stressor, may be regarded as *resilience* (Gray and Elliot, 2009). The rate of recovery of species or habitats impacted by an oil spill will, to a large extent, determine our view on how serious the spill was.

Recovery is often loosely defined as "returning to pre-spill conditions". However, knowing the exact pre-spill conditions is inherently difficult. Also, distinguishing spill impacts from natural fluctuations and trends requires not only pre-spill data, but a thorough understanding of the ecosystem dynamics. Several definitions of recovery have been developed to account for the above issues, including (ITOPF, 1998):

"Recovery is marked by the re-establishment of a healthy biological community in which the plants and animals characteristic of that community are present and functioning normally. It may not have the same composition or age structure as that which was present before the damage, and will continue to show further change and development. It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have persisted in the absence of the spill".

Although such definitions attempt to resolve some of the challenges of defining recovery, it introduces other challenges (i.e. defining a healthy biological community). The inconsistent use and definition of the term "recovery" complicates the interpretation of available scientific information on the subject and requires that restitution time estimates be interpreted with some care.

11.3.2 Estimating recovery

Assessing changes to species diversity is widely used to determine the impact of a disturbance (such as an oil spill). Alpha diversity is the number of species and their proportion within one sampling site. Some commonly used indices to describe alpha diversity include Shannon' index (H), Simpson's index (D) and Renyi entropy. Beta diversity means the dissimilarity between communities of two sites (or two samples). The higher beta diversity means the two communities are more dissimilar. Some commonly used beta diversity indices include Bray-Curtis' dissimilarity, percent similarity index (PSI) and Jaccard's index (qualitative index).

Numerous studies exist discussing the pros and cons of the various indices, both from a conceptual and statistical point of view (see e.g. Barrantes and Sandoval, 2009). Multivariate methods, analyzing the changes in abundance of many species, is now widely recognized as a robust alternative to biodiversity indices. Again, the measures of ecosystem change and estimates of recovery are not unambiguous, further complicating any synthesis of results.

11.3.3 Recovery potential

Despite the uncertainties in defining and estimating time of recovery, certain trends emerge in assessments of the recovery potential of different organism groups:

- When the more toxic fractions of the oil are lost (after the initial degradation and weathering), oil pollution may be considered merely another form of organic enrichment (Gray and Elliot, 2009). Thus; the organic input may raise the biomass levels of less sensitive species, while decreasing the biomass of sensitive species due to toxicity.
- Benthic species that produce large numbers of egg and larvae, a strategy to overcome high rates of natural mortality, have a distinct advantage over long-lived species at colonising new areas and replacing adults that were killed from the impact. Long-lived species, that are slow breeders and produce few offspring, may require many years to recover.

While mobile species have the ability to escape unfavourable conditions, sessile species are more susceptible to disturbances.

11.4 Experience from Oil Spills

11.4.1 General Effects and Their Duration on the Seafloor

Kotta *et al.* (2008), when examining the impacts of an oil spill on nearshore benthic communities in the Baltic Sea, found that the extent of the impact varied among benthic invertebrate feeding groups. More specifically;

- Deposit feeders, especially those tolerant to oil pollution, would gain from the increase of organic matter in the system
- Oil pollution may reduce the number of pelagic grazers, leading to increased productivity of phytoplankton, which again would benefit tolerant suspension feeders (or possibly shade negative impacts)
- Mobile herbivores, such as amphipods and isopods, were severely decimated. Declining amphipod populations is the most consistent pattern of previous oil spills (see Schwartz *et al.,* 1990; Jewett *et al.,* 1999; Kotta *et al.,* 2006).

Below are further, relevant highlights from some previous well known spills;

Amoco Cadiz (1978)

Dauvin (1998), who studied a bivalve community in the protected Bay of Morlaix following the Amoco Cadiz oil spill (Brittany, April 1978, 223 000 t of oil), found that the dominant amphipod *Ampelisca* took >10 years to recover to pre-spill levels.

Exxon Valdez (1989)

Indications that several benthic organisms showed trends towards recovery within 5 years after the spill. However, consistent and systematic surveys have not been conducted for many species. See the Exxon Valdez website for details; http://www.evostc.state.ak.us/index.cfm?FA=status.subtidal

Braer (1993)

Following the grounding of Braer (off Shetland, January 1993, 85 000 t of oil), the Norway lobster *(Nephrops norvegicus)* was most severely affected and a ban on fishing the species was imposed. The Exclusion Order was lifted in March 2000, >7 years after the event. For details, see; http://www.scotland.gov.uk/Uploads/Documents/AE17Braer.pdf

Sea Empress (1996)

The cushion star *Asterina phylactica*, a herbivore grazer, almost became extinct in West Angle Bay in Pembrokeshire due to severe oil pollution from the Sea Empress (Wales, February 1996, 73 000 t of oil). The population took 5-10 years to recover. For details, see; http://www.theseashore.org.uk/theseashore/SpeciesPages/Cushion%20Star.jpg.html

Deepwater Horizon (2010)

The Deepwater Horizon oil spill (DWH/Macondo)(GOM, April 2010, 780 000 m^3 of oil) provides a first opportunity to understand the impacts of an oil spill on deep-sea fauna. Impacts to both hard-ground and soft sediment ecosystems in the deeper parts of the Gulf of Mexico have been documented and numerous studies are ongoing. It appears somewhat early to draw conclusions with respect to recovery times for impacted species at this point.

From the available literature on previous oil spills, one can conclude that;

- Impacts to benthic species and habitats have, for most major spills, not been systematically studied and documented. Thus, the information available on potential rates of recovery is scarce
- From available data, it is not feasible to establish expected rates of recovery for the separate feeding modes described earlier in this document
- Crustaceans, in particular amphipods and isopods, seem consistently sensitive to pollution
- In general, estimates of time for recovery seldom exceeds 10 years. However, in cases of significant sediment contamination (see next section), restitution may be longer.

11.4.2 Restitution of Corals after Oil Spill Impact

Impact to e.g. corals on the sea bed is assumed to be a function of the size of the impact ("population loss") and not the concentration of THC in a sediment in which they are not exposed. A separate restitution time algorithm therefore needs to be implemented for corals, sponges and other hard-bottom epifauna exposed to water-column concentrations only.

Most of the literature on oils spills causing impact to corals is from grounding of vessels on coral reefs where the physical impact of the actual grounding seems to damage the reef more than the oil Coral communities may recover more rapidly from oil exposure alone than from mechanical damage. Recovery of shallow tropical coral reefs after oil exposure may depend partly on the recovery of associated communities that serve as nursery habitats for coral larvae (such as mangroves and seagrasses). These associated habitats may be more seriously affected than the reef itself (NOAA factsheet (accessed February 2015)). Recovery time depends on the type and intensity of the disturbance and can range from several years to decades.

Following the impacts that were found on deep-sea corals after the Deepwater Horizon incident (Fisher *et al.* 2014, White *et al.,* 2012)), it could be expected that there will be extensive follow-up in the coming years that will provide more knowledge on the recovery times of deep-sea corals after a blowout-type oil spill. As could be expected, recovery times are longer the larger the impact, and corals grow back at different rates.

Corals reproduce by releasing (broadcasting) gametes to the water or in some cases fertilised in the polyp and "brooded". By releasing the spawning products into the water masses, corals may recolonize by receiving larvae from other locations that settle. Reproduction can also be asexual, and broken-off fragments of colonies or buds produced by individual polyps may re-cement and survive independently on the reef. Several colonies on a reef may actually be clones of single individuals (NOAA 2010). Corals grow at different rates depending on the morphology of the colony and the environmental conditions. Water quality may play a part in growth rate. Branching species that can have a linear extension rate of up to 20 cm/year grow faster than massive coral colonies, which can grow approximately 1 cm/year. Species with dense skeletons grow slower than more fragile species. Branching corals thereby have a higher re-growth rate than massive, but are also more prone to breaking (NOAA, 2010). Colonies living in areas where high wave energy abrades and breaks coral show more compact or encrusting growth forms than their relatives living in calmer locations. Some species of corals are extremely long-lived as a colony, whereas the individual polyps themselves have life spans that may be less than a decade. Deep water corals have a slow growth rate, and can be several hundred years old. (Smithsonian factsheet accessed Feb. 2015).

Following the DWH oil spill, deep water corals were found to have been covered by brown, hydrocarbon-containing floc, and showed signs of tissue damage (Fisher, 2014; White 2012). Experiments with Macondo crude oil and the dispersant Corexit® 9500 on the settlement and survival of two coral species, indicate that exposure of coral larvae to oil spill related contaminants, particularly the dispersant, has the potential to negatively impact coral resilience and recovery following exposure to oil and dispersants (Goodbody-Gringley et al, 2013).

A scientific challenge increasing the uncertainty of results from the DWH incident is that at least one of the coral reefs that were found to be in an impacted state, was discovered for the first time after the spill, and had not been surveyed earlier. However, scientists agree that there is evidence that the impacts were caused by the incident ((Fisher, 2014; White 2012). White and co-workers assessed the potential impact of the DWH oil spill on 11 sites that contain deep-water coral communities. These sites were examined 3 to 4 months after the well was capped (November 2010). Healthy coral communities were observed at all sites >20 km from the Macondo well, these sites included seven sites previously visited in September 2009, providing background data that the corals and communities there appeared unchanged. Closer to the well head, at one site 11 km southwest of the Macondo well, coral colonies showed widespread signs of stress, including varying degrees of tissue loss, sclerite enlargement, excess mucous production, bleached commensal ophiuroids (associated brittle stars), and covering by brown flocculent material ("floc")(White et al. 2012).

Underneath the covering floc, the coral tissue was dead (Hsing *et al.* 2013), although on some corals and part of impacted corals that were covered with floc, showed little sign of initial visual damage. Individual colonies were ranked according to the level of impacts, ranging from 0 (least impact) to 4 (greatest impact). Of the 43 corals imaged at the site 11 km from the well, 46% exhibited evidence of impact on more than half of the colony, whereas nearly 25 % of all of the corals showed impact to >90% of the colony (White *et al.* 2012). Additionally, 53% of these corals' ophiuroid (brittle star species) associates displayed abnormal colour and/or attachment posture behaviour. Analysis of the floc provided evidence that it contained oil from the Macondo well. Also, the site with the impacted corals was in the path of of a previously documented plume emanating from the Macondo well.

The colonies were followed up during five visits (November and December 2010, March and October 2011 and March 2012) (White *et al.* 2012; Hsing *et al,* 2013), and the changes in the confirmed impacted corals from 2010 were documented.. The flocculent material was no longer present by March 2011, however, octocorals that had originally been impacted to over 20% of their colony were a year later (by October 2011) often patchily colonized by hydroids, a feature which was not not seen on deep-water octocorals at unimpacted sites distant from the Macondo wellhead. The hydroids were only seen on parts of the coral that had been impacted (Fisher *et al.* 2014), and hydroid growth correlated positively with the degree of initial impact (Hsing *et al.* 2013). There were also corals that were free of floc, and that were healthy. The degrees of impacts are minimum estimates as the researchers would classify a coral portion as "not visually impacted" if there was doubt. Statistical analysis and imaging during the five visits, showed that there was a reverse correlation between the degree of initial impact and the percentage of the visibly impacted portions of the colony that moved into the "no visible impact" category between visits (Hsing *et al.*, 2013). The authors indicate that given the longevity of the slow-growing deep sea gorgonian corals (hundreds of years or longer), they may not be able to recover quickly from impacts to significant portions of the colony.

The coral hosting sites round Macondo have thus been surveyed and the degree (in %) of impact has been registered, the follow-up of recovery over the next years should give valuable input to the development of an improved restitution function for corals. Almost five years after the spill, these coral colonies still show signs of impacts.

Interpretation of these very preliminary results (within the time frame since the incident and the time frame of expected recovery times for corals) for ERA Acute purposes could be that there seems to be full impact within the first year after the spill (Timp = 1) and a lag phase (Tlag) of at least 5 years for some impact levels. It seems likely from the data available so far that there could at least be a 2-5 year lag time before restorative growth begins in an impacted colony (See 11.4.3).

11.4.3 Recovery Function for Corals and Sponges– Preliminary Results

A specific function between the degree of impact (equivalent to cell "population" loss) and the restoration time in a cell cannot be determined at this point, due to lack of data. It is expected that the ongoing research after DWH will reveal more knowledge about restitution of corals that have been impacted from an oil spill that did not include mechanical impact from the grounding of a vessel. The degree of impacts to the corals have been registered at the various sites that are being investigated (Fisher et al, 2014; White et al, 2012, Hsing *et al.* 2013)), and in the future it should be possible to expect information that can be used to derive a (probably linear) function between the impact size and restitution time that can be implemented in ERA Acute in the future.

Generally the literature so far supports developing a recovery function where restitution time of corals within the cell is a function of the impact to the corals within that cell. Although corals can receive larvae from other colonies, corals are considered sessile also in reproduction terms, and like organisms exposed in the soft substrates, where restitution is suggested to be derived from the THC concentration in the cell, the restitution time of corals in a cell is a function of the impact in that cell. This is in contrast to other, moving resources, e.g. sea birds, where the total population loss is summed up over all cells before a restitution time is calculated.

However, it is not scientifically sound at this point to generate a restitution function based on impact. It is therefore suggested to use preliminary values as given in table Table 6: These values should ideally be exchanged as soon as there are better results, but given the indicated time frames for recovery, this might not be relevant within the life-time of ERA Acute. Our suggestion is therefore to implement the below table as a changeable lookup-file or a user-input table containing default values but user-changeable and user expandable as more data come in.

Very little information on the sensitivity and restitution potential of sponges is available. Sponges are therefore treated as corals until more knowledge is available.

Table 6 Suggested preliminary values for lag- and restitution time for corals, based on lethality level in a cell. Should be implemented as a user-changeable and user-expandable table for flexibility and entry of new results and more detail

Coral/sponge habitat (group) VEC (Res_func in VEC_list)	p_{let}	Suggested preliminary lag-time values (best guess) $T_{lag,coral}$	Suggested preliminary restitution values (best guess) $T_{res,coral}$
Shallow coral/sponge	<20 %	1	10 years
Shallow coral/sponge	20-30 %	1	20 years
Shallow coral/sponge	30-50 %	1	50 years
Shallow coral/sponge	> 50 %	2	100 years
Deep sea coral/sponge	<20 %	2	20 years
Deep sea coral/sponge	20-30 %	2	40 years
Deep Sea coral/sponge	30-50 %	5	100 years

Deep Sea coral/sponge	> 50 %	5 (minimum)	200 years

11.5 Restitution Times after Use of Oil-Based Drilling Muds

11.5.1 Mechanisms/rationale

Oil based drilling muds were used extensively in the North Sea until their use on the Norwegian Continental Shelf was banned in 1993. After use, drill cuttings and mud with adhered oil was discharged to sea, normally near the sea surface. For a comprehensive description, see e.g. Engelhardt et al. (1989).

After discharge, particles with adhered oil sedimented to the seafloor, at a distance from the point of discharge dependent on particle size, density, water depth and current speed. This fate has several characteristics with what would be expected from oil reaching the seafloor after an accidental discharge.

The discharges after use of oil based muds resulted in increased concentrations of hydrocarbons in surface sediments, and also biological effects in the form of changes in the seafloor faunal communities. As a result, mandatory monitoring programmes were established, which provide us with a comprehensive data set on relevant parameters, as well as long times series, the latter usually lacking in post-spill surveys.

In limited areas near some installations, deposition rates of oil based cuttings were very high, resulting in piles of several metres thickness. At these contaminant levels, degradation rates are slow, leading to long lag time before recovery and long recovery times. However, such deposition patterns are not expected from an accidental oil spill, and are not addressed further in the context of ERA Acute. Also, the results indicate that there is no separate lag-phase without recovery. The two phases overlap significantly, and T_{lag} is therefore set $T_{lag} = 0$, using only T_{res} based on $C_{THC, sed}$.

11.5.2 Data from literature

There is a wealth of references reporting results from monitoring studies as well as peer reviewed papers from scientific studies related to these discharges. A number of studies have looked into the relationship between contaminant levels, focusing on THC, and biological effect, focusing on changes in seafloor faunal communities.

In their review paper, Davies *et al.* (1984) summarized contaminant levels and effects in their definition of four zones, as presented inTable 7. Their definition of zone III is extensively used today as the range of contamination related to background concentration where there are no discernible biological effects, as measured with the standard faunal community indices.

Table 7 Zones of effect of oil based drilling mud cuttings. From Davies et al., 1984.

TABLE 2

The zones of effect of oil-based drilling mud cuttings based upon a wide range of surveys around North Sea oilfields.

Zone	Maximum extent within range	Biology	Chemistry
I	0–500 m	Impoverished and highly modified benthic community (beneath and very close to the platform the seabed can consist of cuttings with no benthic fauna)	Hydrocarbon levels high Sediments largely anaerobic HC's 1000 plus×background
II	200–2000 m	Transition zone in benthic diversity and community structure	Hydrocarbon levels above background HC's 10–700×background
III	800–4000 m	No benthic effects detected	Hydrocarbon levels return to background HC's 1–10×background
IV		No benthic effects	No elevation of hydrocarbons

Olsgård & Gray (1995) discuss the results from a comprehensive analysis of data from the Norwegian continental Shelf, and arrives at a correlation between THC and diversity that is statistically significant. They state restitution times of several years, but at the time of writing, the discharge of cuttings from the use of oil based drilling muds were recently banned, so no definitive conclusions regarding restitution times could be drawn.

In 2008, Renaud *et al.* summarized the results from offshore sediment monitoring on the NCS in the period 1996 to 2006. Their main focus is on the extent of areas with elevated hydrocarbon levels, and with biological effects. However, recovery times of 3-6 years after a change from oil based to water based drilling muds are indicated. Their study also reviews data from three fields (Ekofisk, Statfjord A., Snorre TLP). Interpretation is somewhat limited as they are focused on mean values, but data from Statfjord A dropped below the 50 ppm concentration (referenced as an agreed threshold value for damage), 12 years after the ban on discharge of oil based muds.

Renaud et al. (2008) also provides a comprehensive discussion on factors affecting variation over time, including remobilisation, resuspension and spreading of contaminated sediments, even after several years. Additional factors affecting results are also discussed, including sampling techniques. The paper also briefly addresses alternative/supplementing faunal indicators of environmental impact, including the polychaete/amphipod ratio applied by Peterson et al. (1996) in the GOM.

11.5.3 Excerpts from the MOD database

Based on the findings from the literature, and discussions with Torgeir Bakke (NIVA member of the Norwegian expert group evaluating the results from the monitoring studies), it was decided to attempt an excerpt of data directly from the database holding the results from offshore sediment surveys on the Norwegian Shelf (MOD). The objective was to by querying data from individual stations to:

a) identify trends in degradation of hydrocarbons
b) identify restitution times where there has been an environmental impact

In consultations with Bakke and Anders Bjørgesæter of Acona, it was decided to select data from the following fields:

- Ekofisk
- Gyda
- Gullfaks C
- Statfjord C
- Valhall

Criteria for selection included long time series, defined discharge histories and minimum variations in sediment composition, the latter a factor that strongly structures faunal communities.

An open copy of the MOD database was obtained, allowing queries across tables, stations and parameters, for subsequent analysis. Location of the stations is shown in Figure 25. For these, data on the following parameters were extracted:

- Percentage sand
- Total Organic Matter
- THC in the 0-1cm sediment interval
- Diversity
- Evenness
- ES100
- No. of species
- Density of individuals

For each sampling point (one station – one year), THC values were available from replicate core samples, while faunal indices were available as on value per parameter.

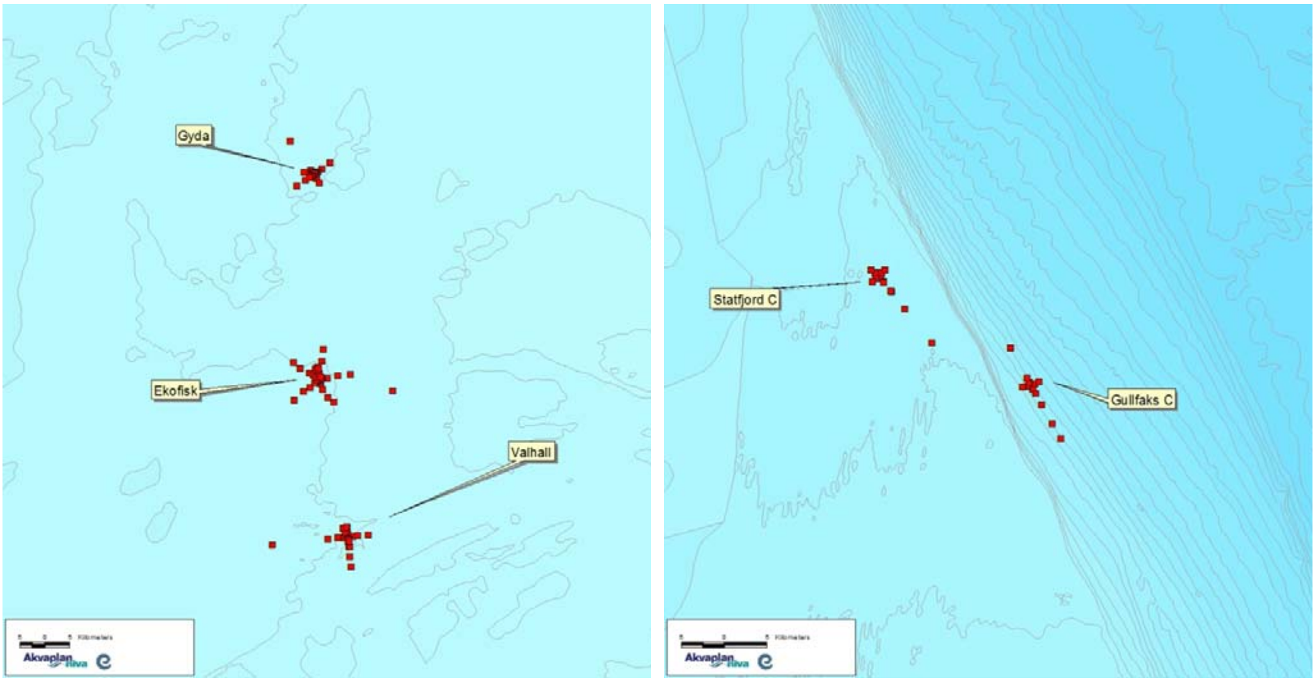

Figure 25. Location of stations where data was extracted from the MOD database.

All stations were dominated by the sand fraction (average 92 %). The reference stations (> 5000 m from the installations) had an average TOM content of 0.97 %.

Of the 647 data points (one station – one year), THC data are available for all, while biological data are available for 349 data points.

11.5.3.1 THC concentrations

Background concentrations of THC at the reference stations over time are shown in Figure 26. As will be seen from the figure, background concentrations are around 5 ppm. Linking this to the zone system in Davies at al. (1984), this will give 50 ppm as the concentrations where biological effects may occur, coinciding with the THC threshold level referenced by Renaud et al. (2008).

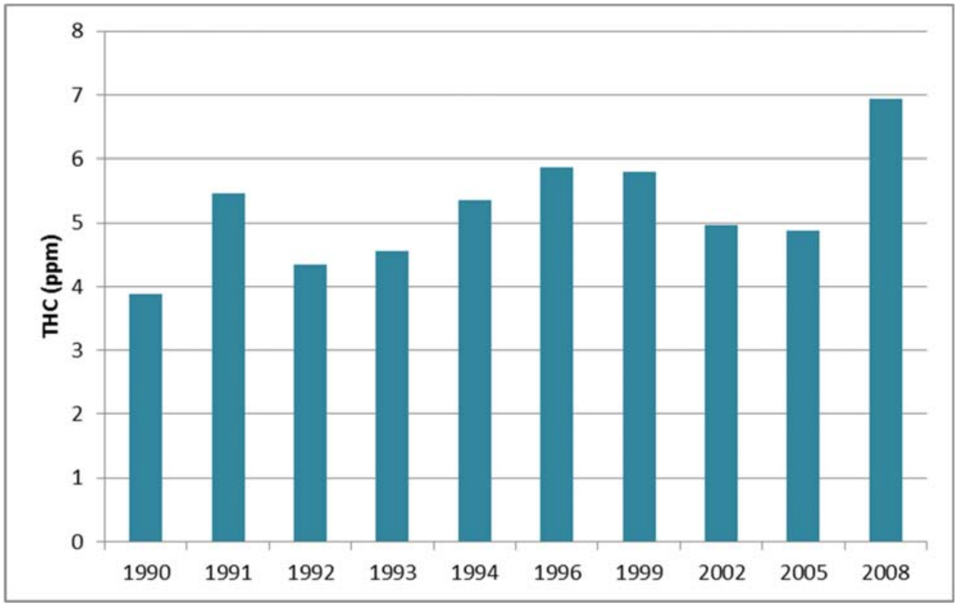

Figure 26. THC concentrations in 0-1 cm surface sediments from stations 5000 m or more from the installation.

One hundred and nine data points showed THC levels exceeding 50 ppm, while only two had THC levels exceeding 3500 ppm (700 x background, Zone 1 according to Davies et al., 1984).

The development in THC levels over time for the most contaminated station (SFC-01) is depicted in Figure 27. As shown, levels exceed 50 ppm in 2008, 15 years after discharge from OBMs were banned.

As these contaminant levels may be higher than what might be the typical case from an offshore oil release, data from less contaminated stations, at 500 and 1000 m from the installations where THC concentrations exceeded 50 ppm, are presented in Figure 28. While there seems to be an initial early decline, average concentrations also here seem to stabilise at a level above 100 ppm. Observations of stable and/or increasing concentrations after cessation of further input may be attributed to a number of factors, including resuspension and redistribution, as well as mobilisation from deeper sediment layers through bioturbation (see e.g. Renaud et al. 2008).

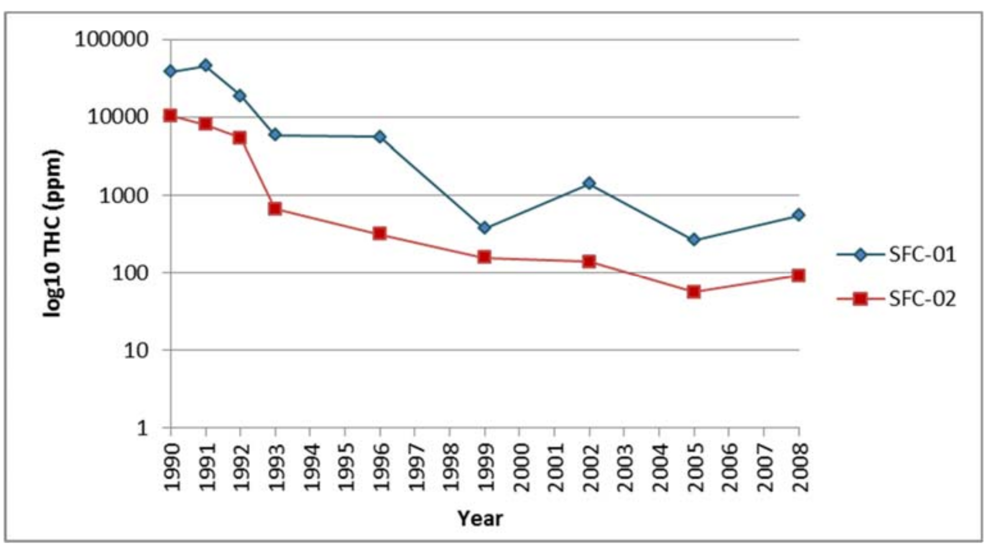

Figure 27. THC concentrations in surface sediments over time for most contaminated stations. Please note the logarithmic scale.

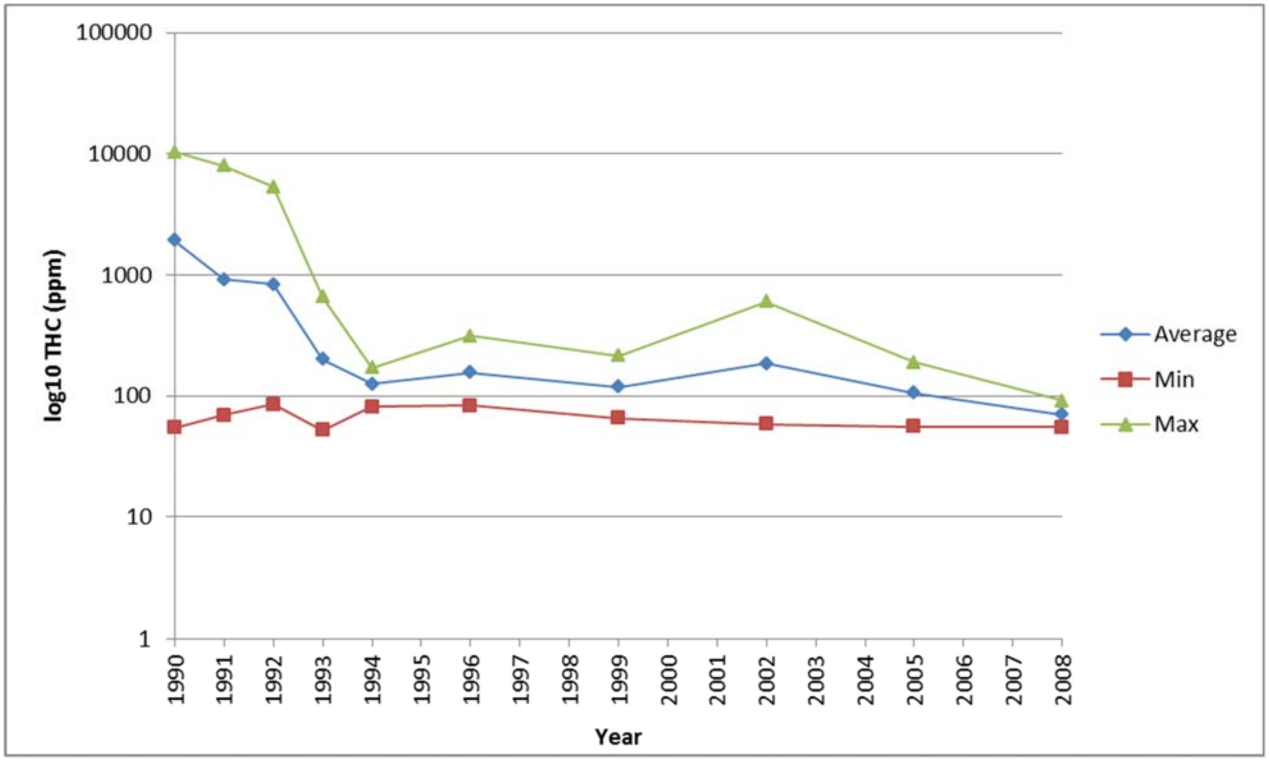

Figure 28. THC concentrations over time for stations 500 and 1000 m distance from the installation. Please note the logarithmic scale.

11.5.3.2 Faunal Indices

There were no clear trends in the faunal indices over time for the 500 to 1000 m stations over time. Neither was that found for the two most contaminated stations, as shown in Figure 29.

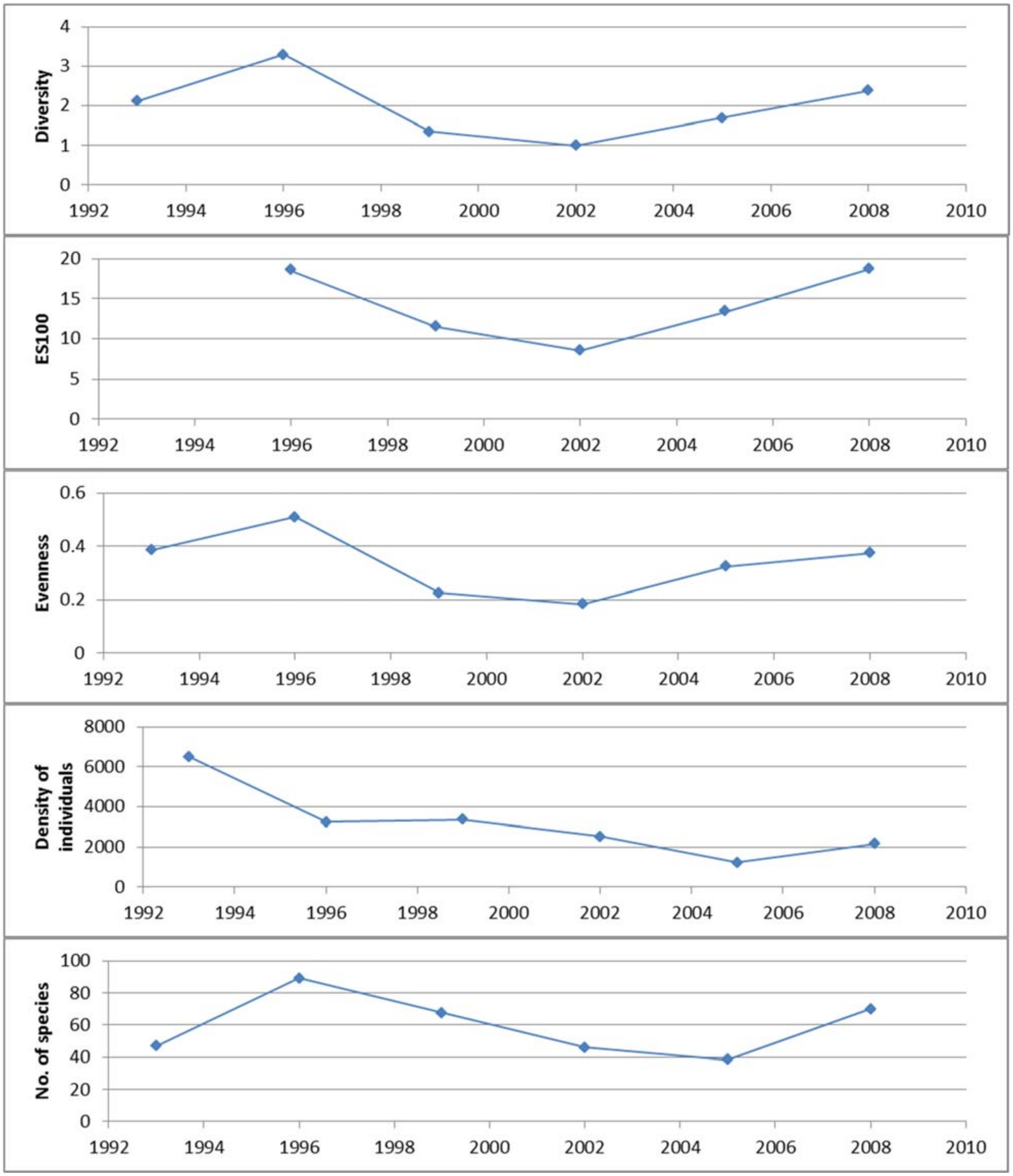

Figure 29. Development over time in faunal indices for the two most contaminated stations.

11.5.4 Recovery Function for General Sediment Sub-Compartment

As will be seen from the preceding sections, field studies show that there are significant variations in development in hydrocarbon concentrations in surface sediments after contamination has stopped. There are a number of factors causing this, and most of these will affect sedimented oil after an accidental release.

However, from the data retrieved from the selected fields from the MOD database, THC levels at contaminated stations exceeded 10 times background concentrations more than 10 years after the supply of contaminants ended.

While no relationships between THC levels and faunal indices were found in the data extracted from the MOD database, Renaud *et al.* (2008) reference 50 ppm THC as the generally accepted level for having effects on faunal communities. Olsgård & Gray (1995) presented a linear relationship between THC related to background versus diversity related to background (Figure 30). At approximately 400 times background THC, diversity was reduced by approximately 50 %, while a 10 % reduction in diversity was estimated at around 10 times background concentrations of THC.

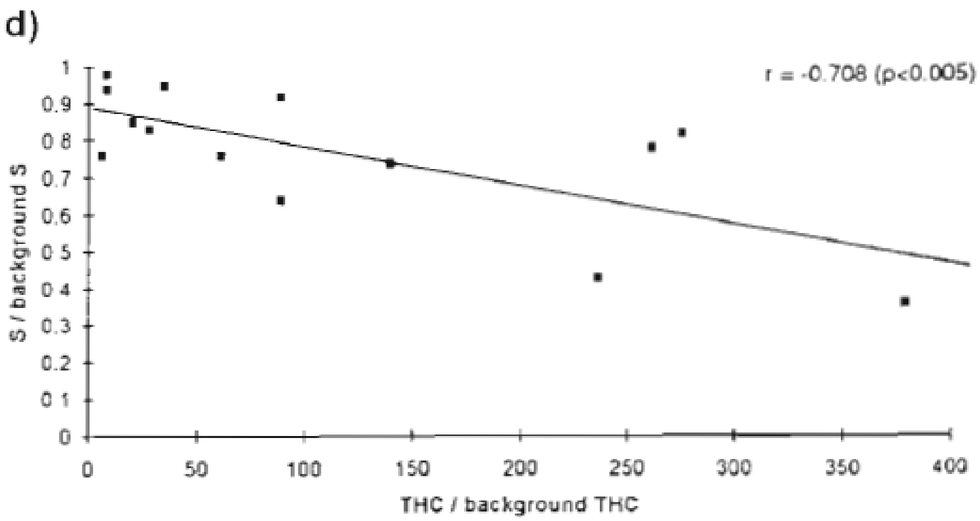

Figure 30. Relationship between relative diversity against relative values of THC. From Olsgård & Gray (1995).

It should be kept in mind that there are other methods and approaches that possibly could detect environmental effects that are not detected by the most widely used faunal indices, ref. e.g. Renaud *et al.* (2008).

Also, as pointed out by Bjørgesæter and Bakke (pers. comm.), results from mesocosm studies (e.g. Bakke *et al.*, 1989) and semi-field studies indicate longer recovery times than field surveys, if resuspension and remobilisation/spreading do not take place. It should however be noted that such processes do take place in the field, an issue to take into account when deriving restitution times.

For the ERA Acute model, it is suggested that a simple restitution algorithm is suggested. As the extracts from the MOD database proved inconclusive, it was decided to base the algorithm on previously cited literature.

From this, and given the sensitivity and limitations of most widely used methods and faunal indices, a THC level of less than 10 times the background concentration (equalling 50 ppm for the North Sea) should be reached before restitution is considered to be achieved (threshold level). In the case of significant contamination, the time frame is anticipated in the order of 20 years, if resuspension and/or redistribution do not take place. It is suggested to use this as a standard conservative approach, unless there is site-specific knowledge that documents resuspension and/or redistribution of surface sediments.

The following algorithm is thereby nominated for use in the initial phase of ERA Acute for the sediment compartment, to be modified as additional data and knowledge becomes available.

Equation 10 $T_{res,sed}$ *(years)* $= (C_{THC,sed} - C_{threshold,sed})/C_{benchmark\text{-}max,sed} \times 20$ *years*

Where:

$C_{THC,sed}$: Concentration of THC in sediments

$C_{threshold,sed}$: Concentration of THC at which effects on faunal communities in sediment cannot be detected. E.g. in the North Sea: 50 ppm (as per current knowledge)

$C_{benchmark\text{-}max,sed}$: The expected maximum concentration of THC resulting from sedimentation of oil from an accidental release. E.g. estimated from the above: 1000 ppm

11.6 Longer-than-Normal Restitution Times for Sensitive Resources (SF at level B)

To allow for specific knowledge of longer-than-normal restitution times of specific resources that leads to a higher sensitivity to loss of resource than otherwise would be expected from the same $C_{THC,sed}$, a sensitivity factor is allowed for at level B also, entered into the VEC file. For VECs that consist of several feeding modes, the SF is chosen for the most sensitive (to reduce complexity). The factor may e.g. be relevant if a VEC is known to be less competitive.

Default value = 1, implying no change to the calculation.

Part 2: Model Technical Description and Calculation Steps

This section describes the calculation steps as they are to be carried out or implemented in a software calculation tool. It consists of the chapters 12 through 15.

12 Calculation Steps of Impact Functions Sediment Compartment-Specific

For the discussion of the theoretical rationale behind the equations, see Chapter 6.

Following the calculation of the lethality outlined below, the total impact from the DSHA is calculated as described in ERA Acute documentation for ERA Acute Level A (Spikkerud *et al.,* 2010).

This chapter (12) contains the calculation steps specific for the seafloor compartment and its sub-compartments. The calculation steps in chapter 12.7 are common to all main compartments. In these two chapters – some steps are denoted StepXMap or StepXGraph. This denotes the same step calculated so it can be shown either in a map (cell-based) or in a graph (summed up over all cells).

Recap of the notation and indices used:

r: relating to a Resource (VEC)

seafl relating to the seafloor main compartment (overall compartment equations)

sed: relating to the sediment sub-compartment

Relating to exposure routes (sub-compartments):

- LWC: Lower water Column
- IW: Interstitial Water/Pore water
- Ing: Ingestion

C: Concentration

N: fraction of the population or resource unit

p: probability

exp: exposure

let: lethality

Imp: Impact

e: expected (includes probability of oiling above threshold)

E: expected (includes probability of scenario)

SF: Sensitivity Factor

A: relating to level A

B: relating to level B

Sens: Sensitive organism

Coral: Denoting that VEC is a coral or sponge

Other denotations are non-ERA Acute-specific (i.e. general scientific) abbreviations. They are defined in the theory section. In the following sections, the index "*seafl*" is used to denote the general seafloor main-compartment and "*sed*" is used to denote the sediment sub-compartment, where a distinction is relevant.

12.1 Sediment Impact Step 1. Common for Level A and Level B:

12.1.1 Calculation of C_{THCsed} from Oil Drift Simulations and Common Parameters

Note that per today, the SdMas_g_m2 value is calculated in the cell from one simulation and one time-step only. The value can be an average/mean value from every simulation if using an oil drift model that reports oil in sediments for each simulation and calculates statistical values in the output file.

When using OSCAR in the single-simulation mode, the user should prepare a .txt file from the converted shape file (.dbf) that contains the SdMas_g_m2 values in the grid cells on the same grid that is used in the ERA Acute model.

For organisms exposed in the pore water (interstitial water phase) (IW), calculate *plet* from the concentration of THC in the sediment, C_{THCsed} obtained from oil drift simulations (e.g. single-simulation runs of OSCAR):

Step 1.1. $C_{THCsed,cell,sim}$ is obtained from oil drift simulations (See 0 and 16.2.2) as .kilograms/m^2 (SdMas_g_m2 if OSCAR from NetCDF-files)

Step 1.2: Read the following parameters from the VEC file lookup-file:

- Mixing depth (BDepth): Depth of bioturbated layer in m (meters). Used to derive THC concentrations in sediments from THC/m^2
- WatC: Water content of sediment = porosity (void volume) (given as Volume fraction 0-1 where 1= 100 %)
- TOC: Concentration of TOC in habitat, is sediment (as fraction) = foc
- DryDens: Density of dry weight fraction of sediment.

Step 1.3. Calculate:

$C_{THCsed,cell,sim}$ (mg/kg) (dry) = ($C_{THCsed,cell,sim}$ (g/m^2) × 1000 mg/g × 1/BDepth (m) × (1-WatC))× 1/DryDens (kg/m^3)

= $C_{THCsed,cell,sim}$ = $C_{sed,cell,sim}$ as mg THC/kg dry weight sediment

$$C_{THC,sed,cell,sim}(\frac{\mathrm{mg}}{\mathrm{kg}}) = \frac{C_{sed,cell,sim}\left(\frac{\mathrm{g}}{\mathrm{m}^2}\right) \times 1000 \left(\frac{\mathrm{mg}}{\mathrm{g}}\right) \times \frac{1}{BDepth\ (m)} \times (1 - \mathrm{WatC})}{DryDens\ (\frac{kg}{m^3})}$$

$$C_{THC,sed,cell,sim}(mg/kg) = \frac{\mathrm{SdMas\_g\_m2} \times 1000 \times \frac{1}{BDepth} \times (1 - \mathrm{WatC})}{DryDens}$$

Record the $C_{THCsed,cell,sim}$ in output file for other uses (See section 15.5)

Step 1.4. Calculate Mean K_{OW} from

Table 4 (use manual input or create computer formula to extract general concentrations) of the fractions of HC in sediment

Step 1.5. Calculate K_{OC} using:

$Log_{10}K_{OC} = 0.00028 + 0.983 \times (Log_{10} K_{OW})$ (Equation 5) ((K_{oc} is not usually measured directly but is closely related to the octanol-water partition coefficient (K_{ow}), and is recommended to be used directly if no value for K_{oc} is available) (Equation 5)

Step 1.6. Read sediment fraction of organic carbon, f_{OC} from VEC file (=TOC)

Step 1.7. Calculate $C_{IW,cell,sim} = C_{THCsed,cell,sim} / (foc \times Koc)$

12.2 Sediment Impact Step 2A: Calculation of $p_{let,sed}$ – Level A

12.2.1 Level A.1 – Sensitive resources assumed to be everywhere

Step 2A1.1. Calculate the corresponding $p_{let,cell,sim}$ from the input of $C_{IW,cell,sim}$ using the water column *plet* curve (implemented in ERA Acute 2010). Record the $p_{let,cell,sim}$ value in output file for other uses (See section 15.5).

Step 2A1.2. Calculate the impact in the cell assuming sensitive resources are present in all grid cells $Imp_{,cell,sim,sed}$. Multiply by the Sensitivity factor (SF) for most sensitive organism (here e.g. *Sens*= most sensitive resource, e.g. amphipods, isopods or others). The SF-value is read from a look-up table entered by the user (Table 8).

Equation 11 $$\mathrm{Imp}_{A1IW,cell,sim,sed,month} = p_{exp,cell,sim,sed} \times p_{letIW,cell,sim,sed} \times SF_{A,sens}$$

$p_{exp,r,cell,sim,sed} = 1$

$SF_{A,sens}$ is read from Table 8, alternately entered manually. It is strongly recommended to implement Table 8 as a lookup-file that can be changed by the user or entered manually!

$p_{let,r,cell,sim,sed}$ = calculated from step 2A.1

The structure of the table is shown in the model implementation section (

Table 8 Structure of a lookup-file of user-entered sensitivity factors for differentiation of sensitivity of VECs for use in level A, based on different restitution times (if known).

VEC	**SFA**
Most sensitive species	SFA,sens
VEC1	SFVEC1
VEC2	SFVEC2

12.2.2 Level A.2 – Sensitive resources in presence/absence form data sets

Step 2A2.1. Calculate the corresponding *plet* from the input of C_{IW} into the water column main compartment *plet* curve (implemented in ERA Acute 2010).

Step 2A2.2. Calculate the impact in the cell for the resource $Imp_{r,cell,sim,sed,month}$. Multiply by the Sensitivity factor for the

mode resource group. (Read from Table 8)

Equation 12 $$\mathrm{Imp}_{A2IW,r,cell,sim,sed,month} = p_{exp,r,cell,sim,sed} \times p_{letIW,r,cell,sim,sed} \times N_{r,cell,sed,month} \times SF_{A,r}$$

$N_{r,cell,sed,month}$ is read from the VEC file (Rel_Jan to Rel_Des) (Section 15.2.2.3).

Record the $N_{r,cell,sed,month}$ value in the output file for other uses (See section 15.5).

$p_{exp,r,cell,sim,sed} = 1$

$SF_{A,r}$ is read from Table 8, alternately entered manually.

$p_{let,r,cell,sim,sed}$ = calculated from step 2A2.1

12.3 Sediment Impact Step 3AMap – Level A

At level A, the impacts calculated above are used directly as the impact in the cell for a month.

Step 3 A.1 $Imp_{A,r,cell,sim,sed,month} = Imp_{A1IW,cell,sim,sed,month}$

OR

Step 3 A.2 $Imp_{A,r,cell,sim,sed,month} = Imp_{A2IW,r,cell,sim,sed,month}$

Visualisation at this step:

- The total geographical area with impact above a chosen threshold and showing impact intervals should be shown in a map (Level A).
- Calculation of total area (km^2) with impacts above a chosen threshold and at impact intervals can be shown in a graph.
- Sub-sets or the whole of the VEC data sets should be possible to manually select (select by dragging cursor in map, see Figure 31) and to summarize:
    - Number of cells in the selected area with $Imp_{A,r,cell,sim,sed,month}$ above a user-selected threshold
    - Total Area (km^2)
    - Fraction of the total VEC (fraction of N_{tot}) in the selected area that is above the threshold impact
    - Fraction of the total VEC (fraction of N_{tot}) in the selected area that killed (= Average p_{let} value in the cells)
    - These summarizations should be exported to an output file (e.g. as a text file for use in spreadsheets etc. for particular purposes.

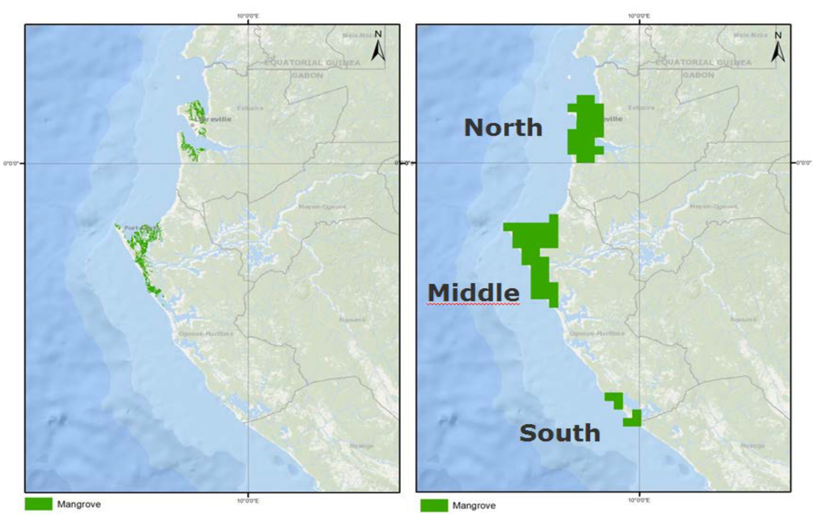

Figure 31. Example of VEC data set for which a subset can be selected (from Totals presentation, J.-M. Libre).

12.4 Seafloor Impact Step 2B: Calculation of $p_{let,seafl}$ values and Impact Level B

Sensitivity factors due to poor restitution ability of certain organisms (if known) $SF_{A,r}$ are not used at level B, as the restitution time is used directly in the impact assessment calculations.

Impact to a resource in a cell is calculated per exposure route for each simulation, depending on the feeding modes defining the exposure routes. For organisms exposed through several routes, all will contribute to the impact.

12.4.1 Organisms Exposed in Lower Water Column (Corals and Sponges)

A future option for calculating plet as a potential lethality directly in OSCAR has been proposed by SINTEF (Brönner & Nortug, 2015) and may be implemented when available. Until this is in place, $p_{let,r,cell,sim,seafl(LWC)}$ is calculated from the THC concentration in the water column and the same p_{let} curve as in WC is used.

Step 2BLWC.1. Calculate the corresponding *plet(LWC)* from the input of THC_{WC} into the water column main compartment *plet* curve (implemented in ERA Acute 2010). If a specific file containing only THC values from the lower water column is desired (from a single simulation), this may be used, giving only the THC values for the lower water column.

Step 2BLWC.2: Calculate the impact contribution from the exposure route in the cell for the resource $Imp_{r,cell,sim,seafl(LWC)}$.

Equation 13 $$\mathrm{Imp}_{BLWC,r,cell,sim,seafl,month} = p_{\exp r,cell,sim,seafl} \times p_{letWC,r,cell,sim,seafl} \times N_{r,cell,seafl,month}$$

$N_{r,cell,seafl,month}$ is read from the VEC file (Rel_Jan to Rel_Des) (Section 15.2.2.3). Record the $N_{r,cell,seafl,month}$ value in the output file for other uses (See section 15.5).

$p_{exp,r,cell,sim,seafl} = 1$

$p_{letWC,r,cell,sim,seafl}$ = calculated from step 2BLWC.1

12.4.2 Organisms Exposed through Interstitial (Pore) Water

For organisms exposed only in interstitial (pore) water:

Step 2BIW.1. Calculate the corresponding *plet(IW)* from the input of C_{IW} into the water column *plet* curve (implemented in ERA Acute 2010). (Mathematically equivalent of $plet_{sed}= Kp \times plet_{WC}$)

Step 2BIW.2: Calculate the impact contribution from the exposure route in the cell for the resource $Imp_{r,cell,sim,sed(IW)}$.

Equation 14 $$\mathrm{Imp}_{BIW,r,cell,sim,seafl,month} = p_{\exp r,cell,sim,seafl} \times p_{letIW,r,cell,sim,seafl} \times N_{r,cell,seafl,month}$$

$N_{r,cell,seafl,\ month}$ is read from the VEC file (Rel_Jan to Rel_Des) (Section 15.2.2.3). Record the $N_{r,cell,seafl,month}$ value in the output file for other uses (See section 15.5).

$p_{exp,r,cell,sim,seafl} = 1$

$p_{letIW,r,cell,sim,safl}$ = calculated from step 2BIW.1

12.4.3 Organisms Exposed through Sediment Ingestion

Step 2BIng.1. Calculate Bioconcentration factor (BCF) from log K_{OW} from step 1.4:

Log BCF= 0.85log K_{OW} – 0.70 (Equation 15)

Step 2BIng.2. Calculate Biota- sediment-accumulation factor

$BSAF = BCF / K_{oc} \times f_{oc}$

Step 2BIng.3. Calculate: $C_{biota} = BSAF \times C_{IW}$

Step 2BIng.4. Using C_{biota} as the equivalent of the THC concentration, read the corresponding *plet(Ing)* from the water column plet curve.

Step 2BIng.5: Calculate the impact contribution from the exposure route in the cell for the resource $Imp_{BIng,r,cell,sim,sed}$.

Equation 16 $$\mathrm{Imp}_{BIng,r,cell,sim,seafl,month} = p_{\mathrm{exp}r,cell,sim,seafl} \times p_{let(Ing),r,cell,sim,seafl} \times N_{r,cell,seafl,month}$$

$N_{r,cell,seafl,month}$ is read from the VEC file (Rel_Jan to Rel_Des) (Section 15.2.2.3). Record the $N_{r,cell,seafl,month}$ value in the output file for other uses (See section 15.5).

$p_{exp,r,cell,sim,seafl} = 1$

$p_{let(Ing),r,cell,sim,seafl}$ = calculated from step 2BIng.4.

12.5 Sediment Impact Step 3B.1: Level B Combination of Exposure and Lethality Functions for Feeding Modes to Impact in a Cell for a Resource for a Simulation

For level A, only this step is used at step 3 (for cell-based calculation). For level B, Step 3BMap is also included (see below).

For data sets of organisms with feeding modes that combine exposure routes, it is assumed that the most robust approach is to add an additional probability of lethal effect by adding the impacts from each exposure route.

Table 3 (overview of primary exposure routes for different feeding modes, section 4.6) and Table 9 give the following algorithms to be implemented in the first step of the level B impact calculation:

Read from VEC-file for Resource: True/False in Column: LWC, IW and Ing (exposure route based on feeding mode):

If LWC = True and IW = False and Ing = False Then $Imp_{B1,r,cell,sim,seafl,month} = Imp_{BLWC,r,cell,sim,seafl,month}$

If LWC = False and IW = True and Ing = False Then $Imp_{B1,r,cell,sim,seafl,month} = Imp_{BIW,r,cell,sim,seafl,month}$

If LWC = True and IW = False and Ing = True Then $Imp_{B1,r,cell,sim,seafl,month} = Imp_{BLWC,r,cell,sim,seafl,month} + Imp_{BIng,r,cell,sim,seafl,month}$

If LWC = False and IW = True and Ing = True Then $Imp_{B1,r,cell,sim,seafl,month} = Imp_{BIW,r,cell,sim,seafl,month} + Imp_{BIng,r,cell,sim,seafl,month}$

Note! Step 3B.1 is carried out for each feeding mode (FM) in the VEC file.

For each feeding mode FM1-FM7 there is a $Imp_{r,cell,sim,seafl,month,FM1}$, $Imp_{r,cell,sim,seafl,month,FM2}$, *etc. to* $Imp_{r,cell,sim,seafl,month,FM7}$.

*Table 9 Combination of impact functions based on **primary** route of exposure for the different feeding modes. (Ref. Table 3). Exp_LWC/IW/Ing = True/False refers to the column in the VEC file.*

Feeding mode of representative organism (most sensitive in restitution)	***WC Impact function***	***IW impact function***	***Ingestion***	***Total function*** $Imp_{Br,cell,sim,sed,month}$
Carnivores (FM1 and FM2)	$Imp_{BWC,r,cell,sim,sed}$ FM1; Exp_WC= True FM2; Exp_WC= False	$Imp_{BIWr,cell,sim,sed}$ FM1; Exp_IW= False FM2; Exp_IW= True	(disregard biomagnification) FM1; Exp_Ing= False FM2; Exp_Ing= False	$Imp_{r,cell,sim,sed,\ month}$ Is either *FM1:* $Imp_{BWC,r,cell,sim,sed,\ month}$ OR FM2: $Imp_{BIW,r,cell,sim,sed,\ month}$
Herbivores (FM3)	$Imp_{BWC,r,cell,sim,sed}$ FM3: Exp_WC= True	FM3: Exp_IW= False	FM3: Exp_Ing=False	*FM3:* $Imp_{BWCr,cell,sim,sed,\ month}$
Suspension feeders (FM4 and FM5)	$Imp_{BWC,r,cell,sim,sed}$ for organisms primarily in WC FM4; Exp_WC= True FM5; Exp_WC= False	$Imp_{BIW,r,cell,sim,sed(IW)}$ for organisms primarily buried in sediment FM4: Exp_IW= False FM5: Exp_IW=True	FM4: Exp_Ing=False FM5: Exp_Ing=False	$Imp_{r,cell,sim,sed,\ month}$ Is either *FM4:* $Imp_{BWC,r,cell,sim,sed,\ month}$ OR *FM5:* $Imp_{BIW,r,cell,sim,sed,\ month}$
Surface deposit feeders (FM6)	$Imp_{BWC,r,cell,sim,sed}$ FM6: Exp_WC= True	FM6: Exp_IW=False	$Imp_{BIng,r,cell,sim,sed}$ FM6: Exp_Ing=True	*FM6:* $Imp_{r,cell,sim,sed} = Imp_{BWC,r,cell,sim,sed} + Imp_{BIng,r,cell,sim,sed}$
Sub-surface deposit feeders (FM7)	FM7: Exp_WC=False	$Imp_{BIW,r,cell,sim,sed}$ FM7: Exp_IW= True	$Imp_{BIng,r,cell,sim,sed}$ FM7: Exp_Ing=True	$Imp_{r,cell,sim,sed} = Imp_{BIW,r,cell,sim,sed} + Imp_{BIng,r,cell,sim,sed}$

12.6 Seafloor Impact Step 3B.2 Map

The resulting $Imp_{r,cell,sim,seafl,month}$ denoted $Imp_{r,cell,sim,seafl,month,FM1}$, $Imp_{r,cell,sim,seafl,month,FM2}$, $Imp_{r,cell,sim,seafl,month,FM3}$ etc. are summarized to a total $Imp_{r,cell,sim,seafl,month}$ for the VEC in the cell, based on the fractions of organisms present with each feeding mode. (Relevant for habitat VECs, single group/species-VECs will have FM=0 in all but one column. This allows for flexibility for the user in preparing VEC files for habitats (sediment types) or single species).

Equation 17

$$Imp_{r,cell,sim,seafl,month} = Imp_{r,cell,sim,seafl,month,FM1} \times (FM1) + Imp_{r,cell,sim,seafl,month,FM2} \times (FM2) + Imp_{r,cell,sim,seafl,month,FM3} \times (FM3) + Imp_{r,cell,sim,seafl,month,FM4} \times (FM4) + Imp_{r,cell,sim,seafl,month,FM5} \times (FM5) + Imp_{r,cell,sim,seafl,month,FM6} \times (FM6) + Imp_{r,cell,sim,seafl,month,FM7} \times (FM7)$$

Where FM1 = value in column FM1 in VEC_list file
Where FM2 = value in column FM2 in VEC_list file

Where FM3 = value in column FM3 in VEC_list file
Where FM4 = value in column FM4 in VEC_list file
Where FM5 = value in column FM5 in VEC_list file
Where FM6 = value in column FM6 in VEC_list file
Where FM7 = value in column FM7 in VEC_list file

Record the $Imp_{,r,cell,sim,seafl,month}$ value in the output file for other uses (See section 15.5).

Visualisation at this step:

- The whole geographical area with impact above a chosen threshold and showing impact intervals should be shown in a map.
- Calculation of whole area (km^2) with impacts above a chosen threshold and at impact intervals can be shown in a graph.
- Sub-sets or the whole of the VEC data sets should be possible to manually select (select by dragging cursor in map, see Figure 31) and to summarize:
  - Number of cells in the selected area with $Imp_{r,cell,sim,seafl,month}$ above a user-selected threshold
  - Total Area (km^2)
  - Fraction of the total VEC (fraction of N_{tot}) in the selected area that is above the threshold impact
  - These summarizations should be exported to an output file (e.g. as a text file for use in spreadsheets, risk matrixes etc. for particular purposes.

12.7 Seafloor Impact Step 3B.3 Map: Including Time Factors in the Impact Calculation – Level B

12.7.1 Inclusion of Time Factors T_{imp} , T_{lag} og T_{res}

At Level B, the impact calculation $Imp_{r,cell,sim,seafl}$ is modified by including the time factors as defined in chapter 11 for the sediment compartment resources: T_{imp}, T_{lag} and T_{res}. There is separate implementation of the time factors for corals/sponges (based on corals) ($T_{lag,coral}$ and $T_{res,coral}$) and general sediment habitats ($T_{lag,sed}$ and $T_{res,sed}$).

The reason for including these factors at the earliest possible stage in the implementation is to benefit from all mapping and graphing possibilities outlined in the following calculation steps.

NOTE! This is specific for the sediment compartment as restitution time within a cell is not dependent on the total population fraction lost as for e.g. sea birds, but is dependent on the THC concentration in that cell's sediment or on the impact on the corals.

Record the sum of $Tlag + Tres$ as a value in the output file for other uses (See section 15.5).

12.7.1.1 General Sediment Time Factors

Read from VEC_list.txt, column Res_func which restitution function is to be used. If column Res_func is empty then use formula:

$T_{res,sed}$ (years) = $(C_{THC,sed} - C_{threshold,sed})/C_{benchmark\text{-}max,sed} \times 20$ *years*

$T_{lag,sed}$ (years)= 0

12.7.1.2 Corals and Sponges Time Factors (Lower Water Column)

Read from VEC_list.txt, column Res_func which restitution function is to be used. If the VEC is a coral or sponge:

If Res_func is " Shallow coral/sponge" or "Deep Sea coral/sponge" then T_{lag} and T_{res} are read from the lookup-table Table 10.

*Table 10 Suggested **preliminary** lookup-table for lag- and restitution time for corals and sponges, based on lethality level in a cell. Should be possible to change by user!*

Coral habitat (group) VEC	p_{let}	Suggested preliminary lag-time values (best guess) $T_{lag,coral}$	Suggested preliminary restitution values (best guess) $T_{res,coral}$
Shallow coral/sponge	<20 %	1	10 years
Shallow coral/sponge	20-30 %	1	20 years
Shallow coral/sponge	30-50 %	1	50 years
Shallow coral/sponge	> 50 %	2	100 years
Deep sea coral/sponge	<20 %	2	20 years
Deep sea coral/sponge	20-30 %	2	40 years
Deep Sea coral/sponge	30-50 %	5	100 years
Deep Sea coral/sponge	> 50 %	5 (minimum)	200 years

12.7.1.3 Sensitivity due to extended recovery times

To allow for the user to change the restitution time based on specific knowledge of a resource-specific sensitivity due to prolonged restitution time compared to other resources generally found in the habitat, a sensitivity factor (SF) is entered in the data set VEC_list and can be used if knowledge exists. Default value = 1 (no change to the calculation).

12.7.1.4 Calculation at Step 3B3Map

Enter appropriate T_{lag} or T_{res} value (default or for corals/sponges) from above calculations and SF from VEC-list.

Equation 18

$$ImpB_{r,cell,sim,seafl,month} =$$

$$(Imp_{r,cell,sim,seafl,month} \times T_{imp})/2 + (Imp_{r,cell,sim,seafl,month} \times T_{lag}) + (Imp_{r,cell,sim,seafl,month} \times (T_{res} \times SF)/2$$

NOTE! In all following calculation steps, $Imp_{r,cell,sim,seafl} = ImpB_{r,cell,sim,seafl}$ for level B.

Visualisation at this step:

- The geographical area with impact above a chosen threshold and showing impact intervals can be shown in a map (Level B).
- Calculation of area (km^2) with impacts above a chosen threshold and at impact intervals can be shown in a graph.

- T_{lag} for each cell
- T_{res} for each cell
- Longest T_{lag} for any cell
- Longest T_{res} for any cell
- Sub-sets or the whole of the VEC data sets should be possible to manually select (select by dragging cursor in map, see Figure 31) and to summarize:
    - Number of cells in the selected area with $ImpB_{r,cell,sim,seafl,month}$ above a user-selected threshold
    - Total Area (km^2)
    - Fraction of the total VEC (fraction of N_{tot}) in the selected area that is above the threshold impact
    - T_{lag} for each cell in the sub-selection
    - T_{res} for each cell in the sub-selection
    - These summarizations should be exported to an output file (e.g. as a text file for use in spreadsheets, risk matrixes etc. for particular purposes.
-

12.8 Step 3Graph Sum of Impacts to a VEC (*r*) over all Cells for a Simulation

Note! The following steps are the same for both level A and level B. Both levels should be implemented separately, using $Imp_{Ar,sim,cell,seafl,month}$ and $Imp_{Br,sim,cell,seafl,month}$ as $Imp_{r,sim,cell,seafl,month}$, respectively.

For each resource in the sediment, the resulting impact from a single simulation ($Imp_{r,cell,sim,sed}$) can be summarized over all cells. The result can no longer be presented in a map, but in a graph or table (e.g. to compare between resources).

Equation 19 $$\mathrm{Imp}_{\mathrm{r,\,sim,\,seafl,\,month}} = \sum_{cell=1}^{cell=n} \mathrm{Imp}_{r,sim,cell,seafl,month}$$

13 Calculation Steps of Initial Impact Functions – Common for All Compartments

13.1 Sediment Compartment Impact Calculations as for all Compartments

In the following sections, the index "*seafl*" is used to denote the seafloor main-compartment and "*sed*" is used to denote the sediment sub-compartment, this can be generalized for any compartment "*comp*". The following steps are the same for Level A and Level B, as – for the sediment – the time factors are dependent on the THC concentrations in the sediment, and are therefore calculated into the initial impact function at step 3BMap (section 12.7). This is done in order for the potential impact steps that are calculated in steps 3 to 6 (below) to contain the time factors that modify the dimension-less "population-equivalent"-based impact of level A to "impactyears" at level B.

13.2 Step 4Map: Expected Impact in a Cell from a Scenario

13.2.1 Expected impact for a scenario (when several simulations are carried out)

Note! This is a description of a possible future implementation for the sediment compartment

This section is based on the current implementation in Level A (Spikkerud et al. 2010). The potential average impact is based on all the simulations in the implemented version and for other compartments where the THC/oil amount is reported in the output from stochastic simulations. It is therefore currently not available for the sediment compartment, but is described here for future implementation.

The average impact is calculated for each grid cell based on the individual $Imp_{r,cell,sim,sed}$, from each simulation. This is done separately for each compartment *comp* (WC, SH, SU – and in the future; SED), and resource *r*. The average $aveImp_{r,cell,comp}$ is calculated for each resource for a grid cell over all simulations in a scenario (combination of rate and duration). This was considered to be sufficient for Level A. The average impact is calculated as the average of the impacts where $Imp_{r,sim,comp,cell,month} > 0$.

To calculate an expected average impact in a cell given that the scenario *scen* (one rate and duration) occurs, $aveImp_{r,scen,comp,cel,monthl}$ should now be related to the probability of oil contamination of the cell from the oil trajectory modelling. This is given that sediment compartment results are reported as THC in sediment in the oil drift modelling in statistical outputs from several single simulations (varying by start-date only).

This is carried out in two steps, first calculating the expected impact in a cell

1 $P_{hit,scen}$ = Fraction of simulations in which $Imp_{r,sim,cell,seafl,month} > 0$

= # simulations where $Imp_{r,sim,cell,seafl,month,} > 0$ / Total # of simulations for the scenario *scen* in the *month*

Then, calculating the "expected impact" to the resource in the sea floor compartment of the cell: $eImp_{r,scen,cell,seafl}$. (See section 5.3 of Spikkerud *et al.*, 2010).

2 $eImp_{r,scen,cell,seafl} = aveImp_{r,scen,cell,seafl} \text{ x } P_{hit,scen}$

Equation 20 $$\mathrm{eImp}_{\mathrm{r,scen,cell,seafl,month}} = \frac{\sum_{sim=1}^{sim} \mathrm{Imp}_{r,sim,cell,seafl,month}}{\text{Tot \# of sims in scen, month}}$$

For each cell we have an expected impact, valid for one rate and duration (scenario, *scen*), denoted $eImp_{r,scen,cell,seafl}$ given that the scenario *scen* occurs, and based on the statistics of all the simulations. This stage of the results can be shown in a map or graph/matrix for different scenarios, $scen_1$ to $scen_n$.

From each combination of rate and duration (scenario, *scen*), we now have an expected impact given that the scenario occurs, denoted $eImp_{r,scen,cell,seafl,month}$ for each grid cell in the sediment compartment and for each individual VEC (*r*).

Visualisation at this step:

- The geographical area with expected impact above a chosen threshold and showing impact intervals from a scenario should be shown in a map.
- Calculation of area (km^2) with impacts above a chosen threshold and at impact intervals can be shown in a graph
- Sub-sets or the whole of the VEC data sets should be possible to manually select (select by dragging cursor in map, see Figure 31) and to summarize:
    - Number of cells in the selected area with $ImpB_{r,cell,sim,sed,month}$ above a user-selected threshold
    - Total Area (km^2)
    - Fraction of the total VEC (fraction of N_{tot}) in the selected area that is above the threshold impact
    - These summarizations should be exported to an output file (e.g. as a text file for use in spreadsheets, risk matrixes etc. for particular purposes.
-

13.2.2 Current implementation (single simulation representative of a scenario)

For the sediment compartment, using a representative simulation to obtain values of THC from a relevant time-step in sediments is the option that currently can be implemented. Therefore, it is suggested to use the result from a well chosen representative simulation as the expected impact for a scenario directly:

Equation 21 $$eImp_{r,cell,seafl,month} = Imp_{r,cell,sim,seafl,month}$$

This stage of the results can be shown in a map for different scenarios, $scen_1$ to $scen_n$. From each combination of rate and duration (scenario, *scen*), we now have an expected impact given that the scenario occurs, denoted $eImp_{r,scen,cell,seafl,month}$ for each grid cell in the sediment compartment and for individual VEC resources. This can be shown on a map.

13.3 Step 4Graph: Total Expected Impact for a Scenario over all Cells if the Scenario Occurs

The total expected impact for the scenario (one rate/duration combination) over all cells ($eImp_{r,scen,seafl}$), *given that the scenario does occur*, is calculated from the impact contributions from all cells summarised (for each compartment separately):

Equation 22 $$eImp_{r,scen,seafl,month} = \sum_{cell=1}^{cell} eImp_{r,scen,cell,seafl,month}$$

Visualisation at this step: For each resource in the seafliment compartment, the total expected impact to the resource from a scenario $eImp_{r,scen,seafl,month}$ can be plotted in two graphs to compare:

- $eImp_{r,scen,seafl,month}$ results between resources
- $eImp_{r,scen,seafl,month}$ results between scenarios

Output for other uses:

Both values above should be exported in a format suitable for implementation in a risk matrix for decision-making that uses probabilities of the scenario plotted against the expected impact from the scenario as e.g. in

Figure 32. The probability values are the same that are given as input to the *following* calculation steps (*probability*$_{scen}$). See suggested output format in 15.5.

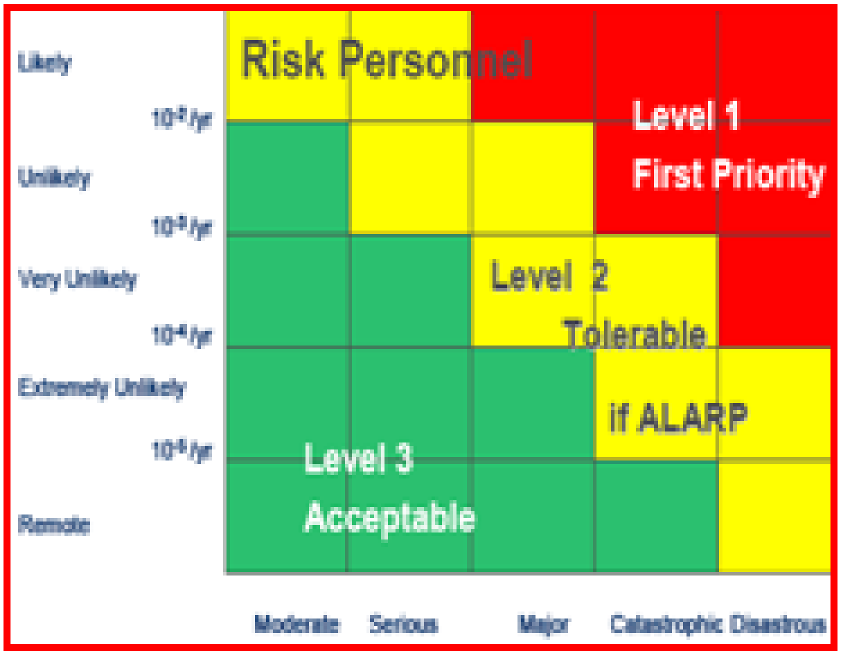

Figure 32 Example of a possible use of intermediate ERA Acute risk results from the various impact steps. (From Total's presentation, J.-M. Libre).

13.4 Step 5Map: Probability Contribution of a Scenario to the Total Expected Impact to a Resource in a Cell

To provide the probability-derived contribution to the total expected impact to a resource in the seafliment compartment for the scenario for each cell, $eImp_{r,scen,cell,seafl}$ is multiplied by the probability for the scenario (from the rate-duration matrix). This we denote $EImp_{r,\ scen,cell,seafl}$ to distinguish it from $eImp_{r,scen,cell,seafl}$ which only includes the probability of contamination *given that* the scenario *scen* does occur.

Equation 23 $EImp_{r,scen,cell,\ seafl,\ month} = eImp_{r,scen,cell,seafl,month} \times probability_{scen}$

$EImp_{r,scen,cell,seafl}$ can be seen as the impact contribution from the cell to the total impact from the scenario.

Visualisation at this step:

- The geographical area with individual contributions from a cell to the total impact above a chosen threshold and showing impact intervals from the scenario could be shown in a map.
- Calculation of area (km^2) with impacts above a chosen threshold and at impact intervals can be shown in a graph

13.4.1 Including Risk Reducing Measures

If risk reduction measures leading to a lower probability for a given combination of rate and duration are implemented, the above equation is re-calculated using the new probability.

13.5 Step 5Graph: Total Impact for a Scenario over all Cells

A total expected impact for the scenario (rate/duration combination) over all cells ($EImp_{r,scen}$), is calculated by summarising impact contributions from all cells:

Equation 24 $\mathrm{EImp}_{r,scen,seafl,month} = \sum_{cell=1}^{cell} \mathrm{EImp}_{r,scen,cell,seafl,month}$

Visualisation at this step: For each resource in the sediment compartment, the total expected impact to the resource from a scenario $EImp_{r,scen,seafl}$ can be plotted in two graphs to compare:

- $EImp_{r,scen,seafl,month}$ results between resources
- $EImp_{r,scen,seafl,month}$ results between scenarios

13.6 Step 6Map: Expected Impacts for a DSHA

By summarising for each cell the expected impacts of all scenarios for that cell (function of potential impact and the probability of the scenario), a total impact for the DSHA per cell is calculated (for each compartment separately), given that the DSHA occurs (includes the probability distribution between scenarios).

Equation 25 $\mathrm{EImp}_{r,cell,DSHA,seafl,month} = \sum_{scen=1}^{scen} \mathrm{EImp}_{r,scen,cell,seafl,month}$

Visualisation at this step:

- The total expected impact in each cell for the DSHA can be shown in a map. Each compartment and/or resource is calculated and can be shown separately.
- Calculation of area (km^2) with impacts above a chosen threshold and at impact intervals can be shown in a graph

13.7 Step 6Graph: Total Impact for a DSHA over all Cells

The total expected impact from all cells can be summarised to provide a total expected impact from the DSHA:

Equation 26 $\mathrm{EImp}_{r,DSHA,seafl,month} = \sum_{cell=1}^{cell} \mathrm{EImp}_{r,cell,DSHA,seafl,month}$

Compared to other DSHAs from other activities, this total can be plotted vs. frequency in a matrix.

Visualisation at this step: For each resource in the sediment compartment, the total expected impact to the resource from a DSHA $Eimp_{r,DSHA,seafl}$ can be plotted in a graph to compare:

- $Eimp_{r,DSHA,seafl,\ month}$ results between resources
- $Eimp_{r,DSHA,seafl,\ month}$ results between scenarios

Output for other uses:

- Both values above should be exported in a format suitable for implementation in a risk matrix for decision-making that uses probabilities of the scenario plotted against the expected impact from the scenario as e.g. in Figure 32. The probability values are the same that are given as input to the *following* calculation steps ($probability_{DSHA}$).

14 From Impact to Risk

14.1 Step 7 Map: Calculation of Risk at Level A for the Sediment Compartment in a single Cell

Individual risk contributions from each cell can be calculated for the sediment compartment at level A by multiplying the expected impact in a cell for a DSHA with the frequency of the DSHA. *Note: If the DSHA frequency is given as a total frequency of a blow-out, and a separate probability distribution between subsea and surface blow-out is given in addition, the frequency must be adjusted before being entered into the calculator.*

For the sediment compartment , the risk contribution of a cell to the total risk is calculated:

Equation 27 $$Risk_{r,cell,DSHA,seafl,month} = EImp_{r,cell,DSHA,seafl,month} \times frequency_{DSHA}$$

Visualisation at this step:

- $Risk_{r,cell,DSHA,seafl,month}$ can be shown in a map for a species and for each compartment and or/ resource separately, to illustrate the risk contribution of that cell to the total risk from the DSHA.
- Calculation of area (km^2) with risk above a chosen threshold and at risk intervals can be shown in a graph

14.1.1 Including Risk Reducing Measures

If risk reduction measures leading to a lower *frequency* for a given DSHA are implemented, the above equation is re-calculated using the new frequency.

14.2 Step 7 Graph: Calculation of Total Risk at Level A for the Sediment Compartment

The total risk for a given DSHA can be calculated as follows for the sediment compartment, by summarising the risk contributions from all cells in that DSHA.

Equation 28 $$Risk_{r,DSHA,seafl,month} = \sum_{cell=1}^{cell} Risk_{r,cell,DSHA,seafl,month}$$

Visualisation at this step: For each resource in the sediment compartment, the total expected risk to the resource from a DSHA $Risk_{r,DSHA,seafl}$ can be plotted in a graph to compare the following (the calculations are carried out for each compartment separately):

- $Risk_{r,DSHA,seafl,month}$ results between resources
- $Risk_{r,DSHA,seafl,month}$ results between scenarios

15 Suggested Technical Description of Model - Flowsheet

15.1 Modules

The sediment model consists of a module for Level A (to be implemented in the existing ERA Acute tool based on the model development for the other compartments (Spikkerud *et al.*, 2010)) and a module for level B.

Input data are described in the technical flow sheet provided as an additional PDF file to this report. (Stephansen, 2015).

15.2 Input data

15.2.1 Oil drift simulations

External oil drift simulation models are used to give the following input files:

1. .txt-file containing the QOil/Ctot value used for $C_{THC,WC}$ (for organisms exposed through water column). If the oil drift model gives the values in the lower water column separately, this would be preferred, and the implementation of the model should contain a user input window specifying the name of the parameter that gives this value.
2. .txt-file containing SdMas_g_m2 values from a single simulation (if current OSCAR version is used) (see guideline in chapter 16) or (preferably) statistical values from multi-simulation runs of an oil spill model. The implementation of the model should contain a user input window specifying the name of the parameter that gives this value.

15.2.2 VEC Files Data structure

The data structure for VECs in the ERA Acute sediment compartment comprises the following three tables:

- VEC_list: A list of VECs with information on feeding modes and SSD link
- VEC_expmode: A table containing information on exposure routes/modes for individual feeding modes
- VEC_distr: A table giving monthly distribution of the VEC population/area per grid cell

The structure and content of these tables are given below.

15.2.2.1 Vec_list

This file will contain one line per VEC, with columns and content as given below. The VEC_list file format opens for that the VEC can be a habitat or a single species/group etc.

Column name	*Comments*
Main_hab	Main habitat
Sub_hab	Subgroup within main habitat, if relevant
Species_Eng	English species name, if relevant (if VEC is a species)
Species_Sci	Scientific name, if relevant
v_Jan	Numerical value, linking to an SSD curve. Will allow for improvement and development over time, and for different SSD curves in individual months if required.
v_Feb	As above
v_Mar	As above
v_Apr	As above
v_May	As above
v_Jun	As above
v_Jul	As above

v_Aug	As above
v_Sep	As above
v_Oct	As above
v_Nov	As above
v_Dec	As above
Filename	Name of VEC file
Data source	Name of provider of data
Updated	Last update of this VEC
FM1	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
FM2	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
FM3	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
FM4	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
FM5	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
FM6	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
FM7	Designates the fraction of organisms in the habitat VEC that have this feeding mode if relevant. Value is given as a fraction between 0 and 1, 0= absence
Res_func	Text string designating a specific recovery function.
DryDens	Density of dry weight fraction of sediment
WatC	Water content of sediment
BDepth	Depth of bioturbated layer in m. Used to derive HC concentrations in sediments from HC/m^2.
TOC	Concentration of TOC in habitat sediment. Default value 1 %.
SF	Sensitivity factor of most sensitive organism in VEC habitat (or species speciefic) (if known). If unknown: SF=1.

15.2.2.2 VEC_expmode

This file will contain one line per feeding mode, with columns and content as given below.

Column name	***Comments***
FM	Feeding mode
Exp_WC	Designates the exposure to water column HC concentrations
Exp_IW	Designates the exposure to interstitial water HC concentrations
Exp_Ing	Designates the exposure to ingested particulate HC concentrations

15.2.2.3 VEC_distr

This file will contain one line per cell, with columns and content as given below.

Column name	*Comments*
Id	Grid cell ID
Rel_Jan	Fraction of VEC within the grid cell in given month
Rel_Feb	As above
Rel_Mar	As above
Rel_Apr	As above
Rel_May	As above
Rel_Jun	As above
Rel_Jul	As above
Rel_Aug	As above
Rel_Sep	As above
Rel_Oct	As above
Rel_Nov	As above
Rel_Dec	As above

15.3 Look-up files, additional calculators or other user inputs

15.3.1 Mean K_{OW}

The user should enter a value for K_{OW} valid for the hydrocarbon mix in the sediments. This can be based on manual calculations using the list of pseudocomponent groups in the sediment (Figure 39) and K_{OW} values for these, e.g. using

Table 4 to calculate a mean value that is entered manually by the expert user. If desired, the table can be implemented in the model, and the user can select the components to be used for the calculation of the mean K_{OW} value.

15.3.2 Sensitivity Factor for Resources (Level A)

At level A, sensitivity factors could be entered in the form of a look-up table or equivalent, for the user to enter and change as needed. (Sens denote most sensitive resource, for level A.1)

Resource	Sensitivity factor
VEC1	$SF_{A,VEC1}$
VEC2	$SF_{A,VEC2}$
VECsens	$SF_{A,sens}$

15.4 Model Flow Sheet

The calculation steps in chapters 12, 13 and 14 are described in a flow sheet document given separately (Stephansen, 2015), as the figure would not be readable if entered into this report.

15.5 Summary file for Scenario Based Approach for Seafloor for Other Uses

Other risk assessment methods may require output of intermediate steps in the ERA Acute calculations. For Total, the following output file is needed for a company-specific approach at the seafloor (Jean-Marie Libre, *pers comm.)*.

15.5.1 Output file from ERA Acute

The table below should be produced for a given scenario for:

- each simulation
- each VEC
- each month:

The step from which the value is obtained and recorded, is given in the value field in parenthesis.

Table 11. Proposed output file for recording step-wise outputs from ERA Acute calculations for multiple uses.

Sim No														
	VEC1,r								VEC2,r					
CellID	$C_{THCsed,cell,sim}$	$p_{let,cell,sim,r}$	$T_{imp, cell,sim,r}$	$T_{lag, cell,sim,r}$	$T_{res,cell,sim,r}$	$N_{cell,r,month}$	$Imp_{r,cell,sim,seafl,month}$	$Area_{cell}$ (km^2)						
From UTM grid file	(Step 1 Sec.12.1.1)	(Step 2B Sec.12.4)	Step 3B3 Sec.12.7.1)	Step 3B3 Sec.12.7.1)	Step 3B3 Sec.12.7.1)	(from VEC-file)	Step 3B2 (Sec.12.6) Or @level A Step	Cell size						
1														
2														
3														

16 Manual Generation of Oil Drift Input File

16.1 Preliminary approach

The below given information is given as a user guide for selection of a simulation, re-running in single-simulation mode and creating output of file containing sediment THC suitable for the UTM 33 projection used in ERA Acute.

16.2 How to obtain data from single simulations

16.2.1 Choice of Simulation

Among the single simulations that have been run in OSCAR in stochastic mode, choose the simulation with the highest THC in the water column. This is expected to give the highest amounts of THC in the sediments. The description of how to find this can be found in the OSCAR user manual.

16.2.2 THC in Sediments

How to export sediment concentrations for ERA Acute using OSCAR in single-simulation mode

1. Run the chosen simulation in single-simulation (deterministic mode) in OSCAR. Figure 33 shows an example with oiling of the sediments, more than 19 % on the final simulation day (day 82) in a simulation of a surface release with a duration of 52 days and 30 days follow-up time.

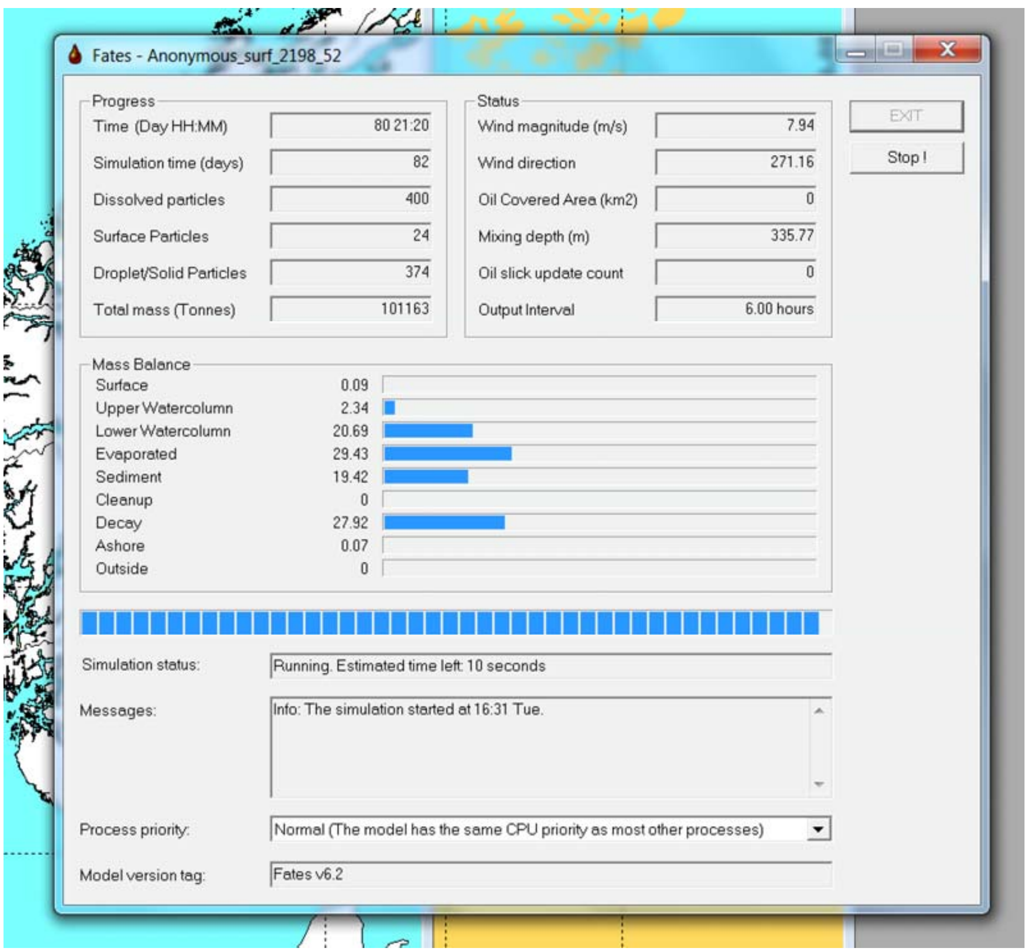

Figure 33 Towards the end of this simulation run (52 days surface release) and 30 days follow-up time) the amount of oil in the sediment is reported to be approx. 19.4 % of the mass balance. A run of Fates in stochastic mode would show this oil as being outside the grid.

2. Turn on the "View Sediment Concentrations" button and choose "mass/area". This can be animated to see the development of oiling of the sediments. In the example in Figure 34, the oiling of the sediments in mass/area (kg/m^2) is shown for day 82 (left) and on the final day of a second simulation using a total of 200 days (right). The output file from OSCAR gives the mass in g/m^2. Oil mass per area needs to be recalculated into oil mass/mass sediment (dry weight) which is the initial step in ERA Acute, which uses Sd_mas_g_m2 as input. See Calculations section 12.1.1. The viewer show the oil amount as kg/m^2.

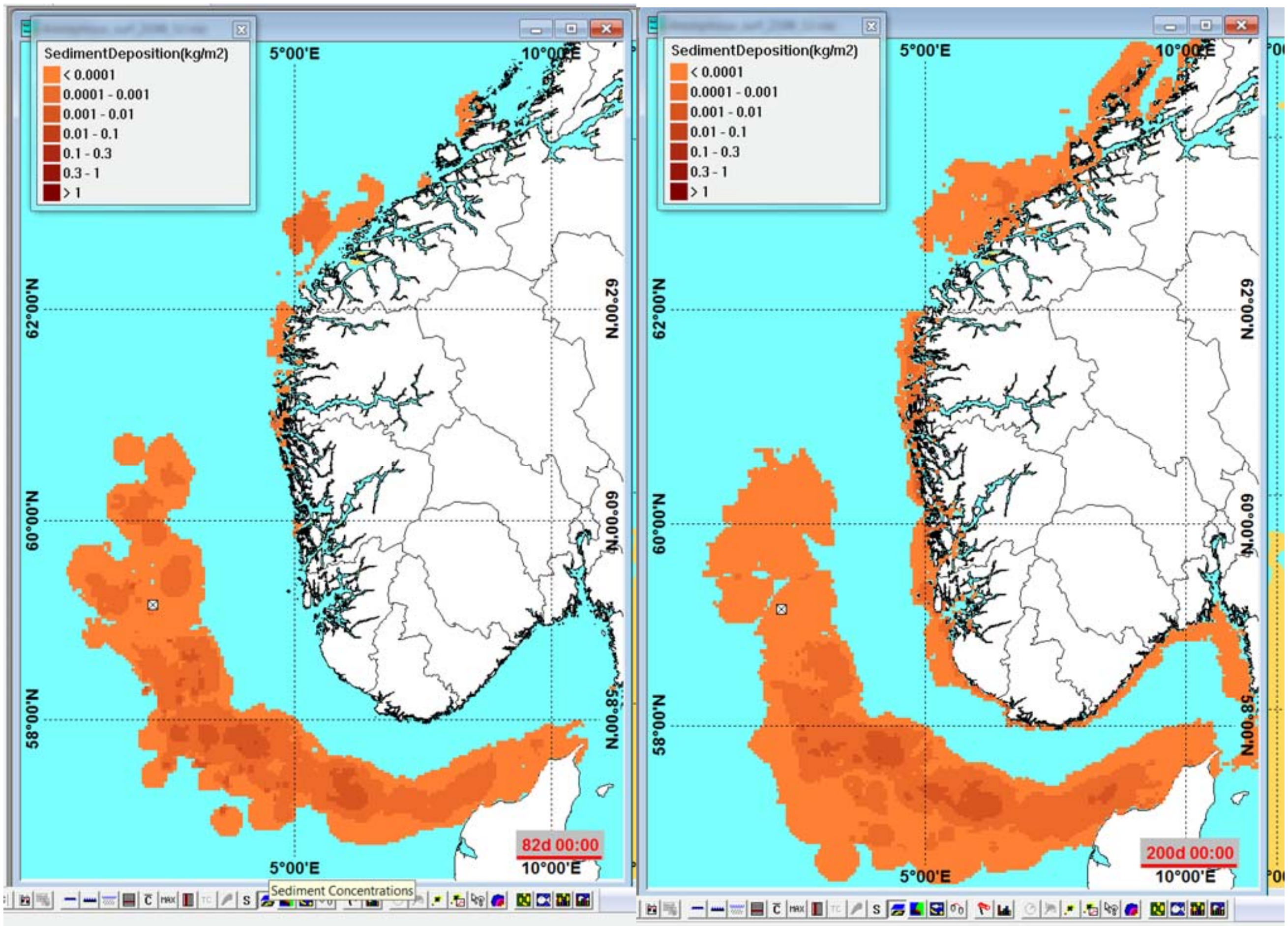

Figure 34. Mass/ area of THC in the sediments after 82 days (left) and 200 days (right).

3. A starting point time step for the toxicological assessment needs to be chosen. As can be seen from the mass balance in the first simulation using 30 days follow-up time (Figure 35), the sedimentation does not seem to have peaked at 82 days. Investigation of the "peak" oil-in-sediments day should be investigated. In the test, re-running the chosen simulation using a total of 200 days shows that sedimentation *mass* (tonnes in the sediments) seems to peak at around day 110 (Figure 36). The number of cells with sedimented oil increases (see the prt file results below (Table 12); these showed still-increasing number of cells at the end of the spill (from 1999.75 to 200.00 days). The total mass (tonnes in the sediments had begun to sink at this point due to degradation of oil. The amount of oil in the sediments peaked around day 110, the spreading of the oil to new cells continued, but the total mass decreased, this implies that the compartmentalisation of oil in the environment is still very dynamic at this point. (Figure 36 shows the mass balance in tonnes, Figure 37 in % of the total release).

Table 12 Outputs available listed in the prt file.

199.75 days	200.00 days
Number of grid-cells	Number of grid-cells
====================	====================
Wat-Column : 135275 (Conc. > threshold)	Wat-Column : 137377 (Conc. > threshold)
Wat-Column+: 366027 (Concentration > 0)	Wat-Column+: 366427 (Concentration > 0)
Wat-Column*: 366027 (SameVal.Compres'n)	Wat-Column*: 366427 (SameVal.Compres'n)
Surface : 73	Surface : 50
Sediment : 12271	Sediment : 12281
Shore-line : 330	Shore-line : 330
	====================
cumulative sediment area exposure over the threshold was 0.510E+11 sq-m-days.	cumulative sediment area exposure over the threshold was 0.511E+11 sq-m-days.

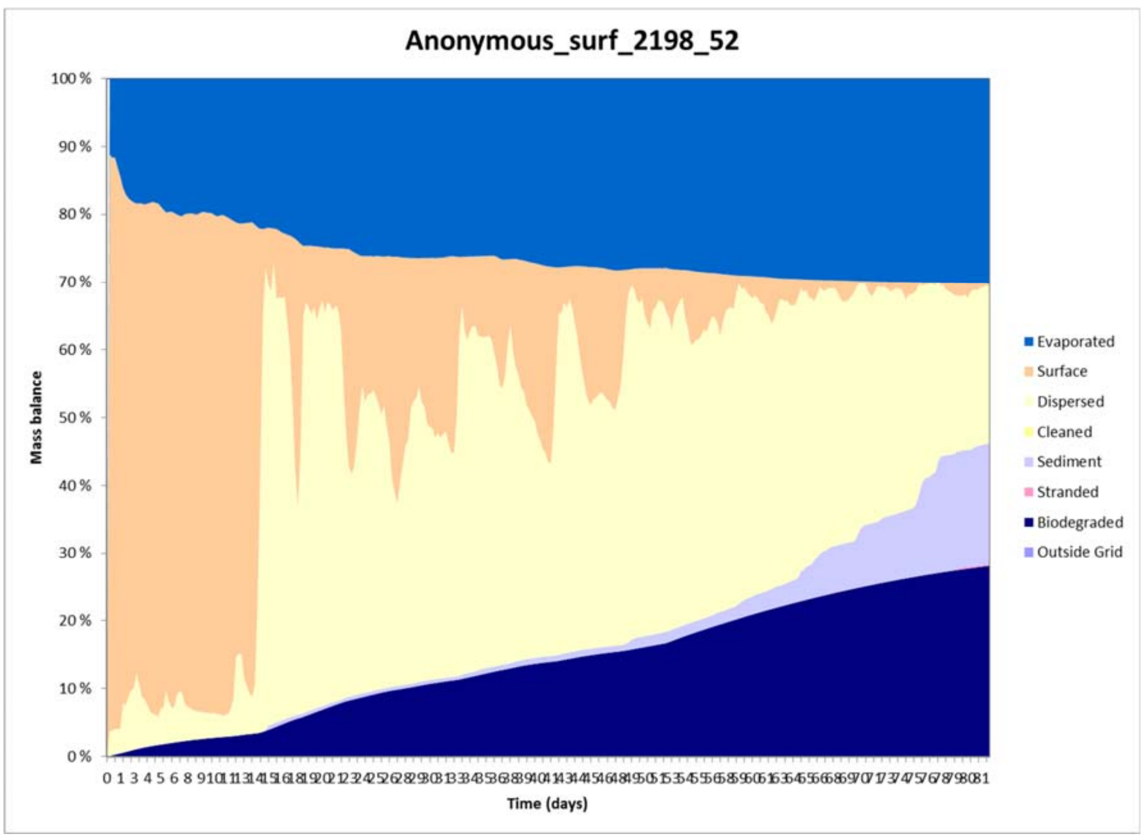

Figure 35. Mass balance of a test case that reaches the sediments (surface spill 2198 Sm^3/day for 52 days). At the end of the simulation, the mass in the sediments seem not to be maximized yet, indicating that a longer follow-up time should be considered.

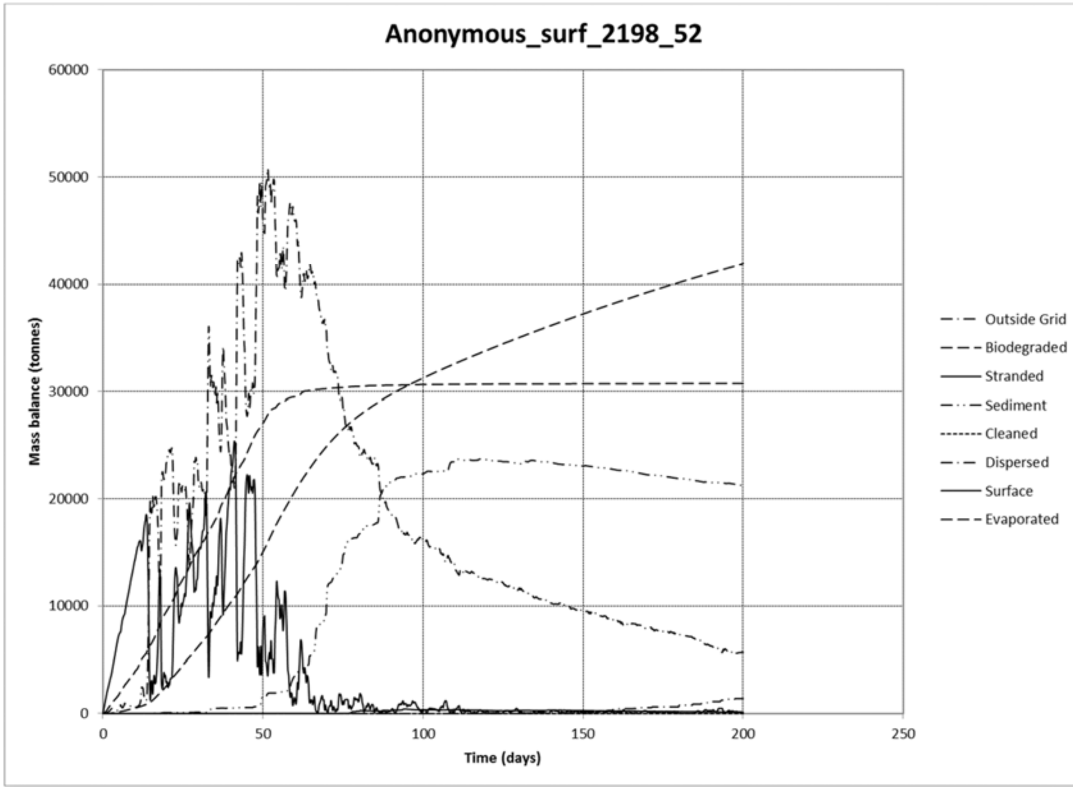

Figure 36. Mass balance in tonnes with a longer follow-up time (total 200 days, including 52 days release). (Mass balance XY) showing that the peak sediment amount is found after approximately 110 days.

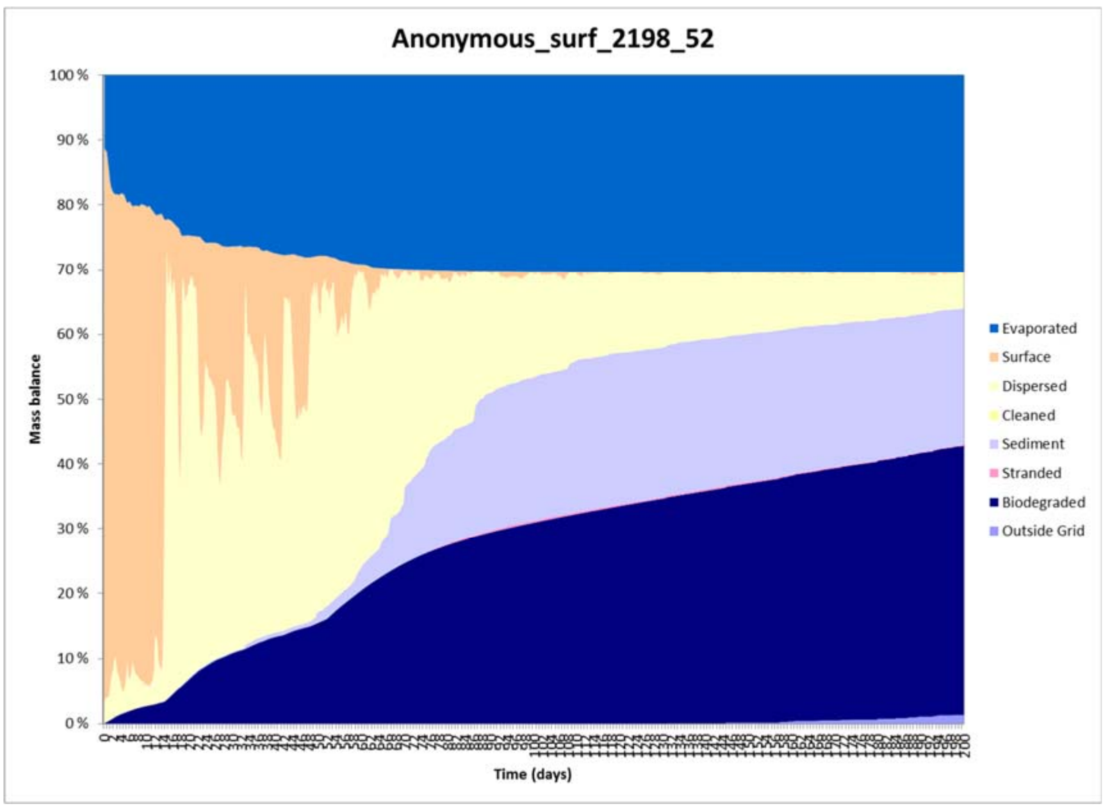

Figure 37. Mass balance in % for the same surface spill using a longer follow-up time (total simulation time 200 days).

4. When the "peak sediment mass" timestep has been chosen, select the timestep in MEMW and view the sediment grid (Figure 38). (By selecting the mass balance and spooling backwards and forwards the timestep can be selected accurately).

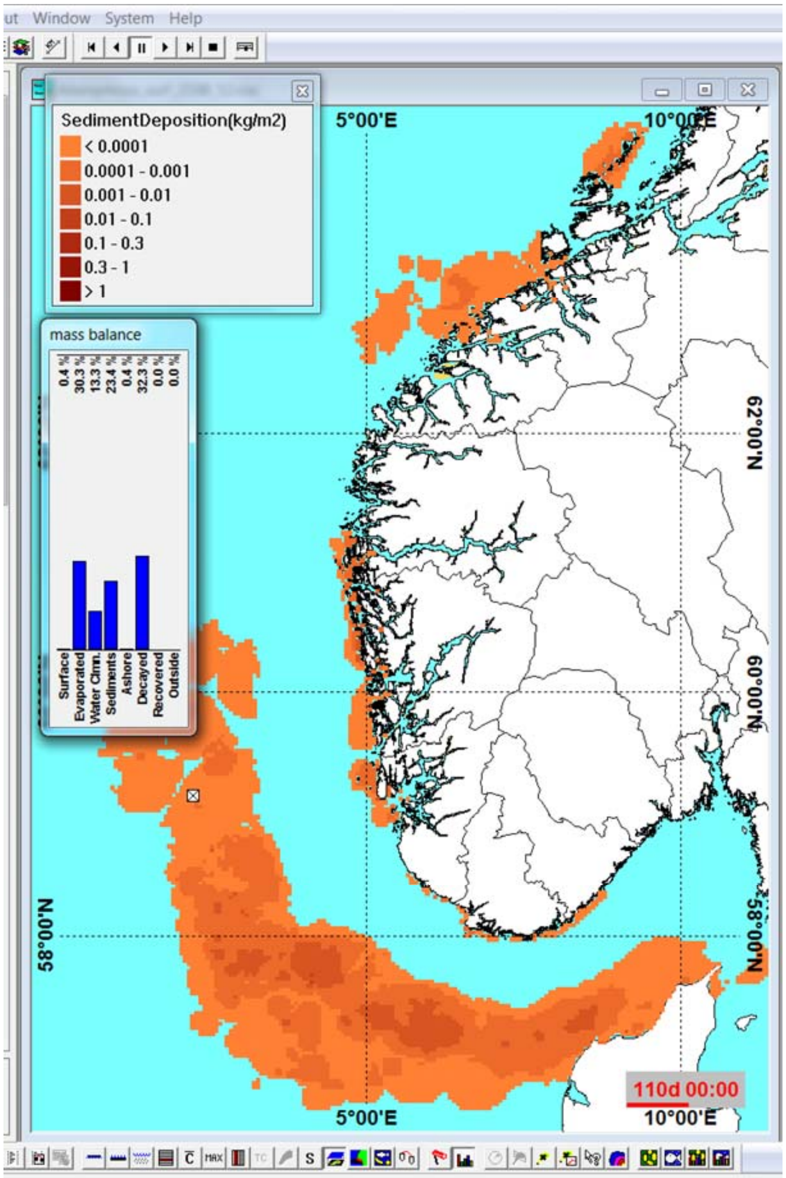

Figure 38. Mass balance and the sediment grid (mass/area) on day 110.

5. Now we export the mass/ area to a shape file to view in a GIS or to import as a cell-based output to ERA Acute. Select components to view in the sediment grid using the "Select components" button. By default all are selected. Only the components that actually reach the sediment will contribute to the mass, and will show in the sediment grid viewer. E.g. Oscar pseudo-group Naphthalenes 1 (C0-C1-alkylated) do not show in the grid, their solubility is too high. From Figure 39 we see the component pseudo groups that reach the sediments and which comprise the mass.

Choose: File – Export – Grid output and select the GIS folder of the MEMW workbench. The resulting files are:

.dbf
.shp
.shx
.txt

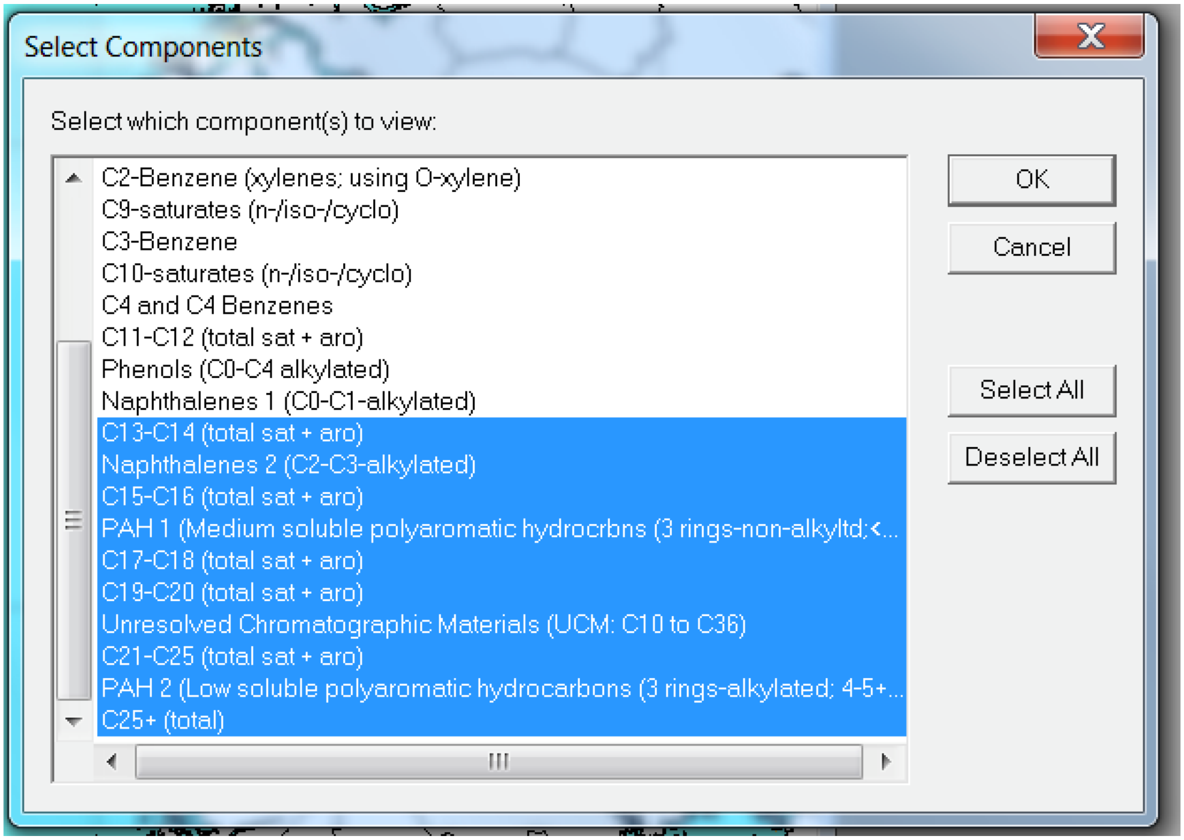

Figure 39. Selection of the components that comprise the sediment THC mass.

Select Map – Layers, and select the resulting shape file for viewing in MEMW. The file format is in in decimal degrees and now needs to be converted to UTM33 and transcribed to the user grid used in ERA Acute before ERA Acute can be run. The cells shown are the same as in the habitat grid.

The values in the cells are:

SdMas_g_m2: Sedimented sum of the selected pseudo-components in g/m^2.

Resulting shapefiles must be reprojected as required to the correct projection, and then intersected to the same grid as used in other ERA Acute data sets and oil drift simulations for the other compartments. This is carried out manually until the relevant development of OSCAR is in place, or if another oil drift model is used that needs other manual changes to be made to the data set.

The resulting .dbf-file created in the GIS can be exported to a txt file containing the parameters cell identificator and the Sd_mas_g_m2 (oil amount in sediments) value.

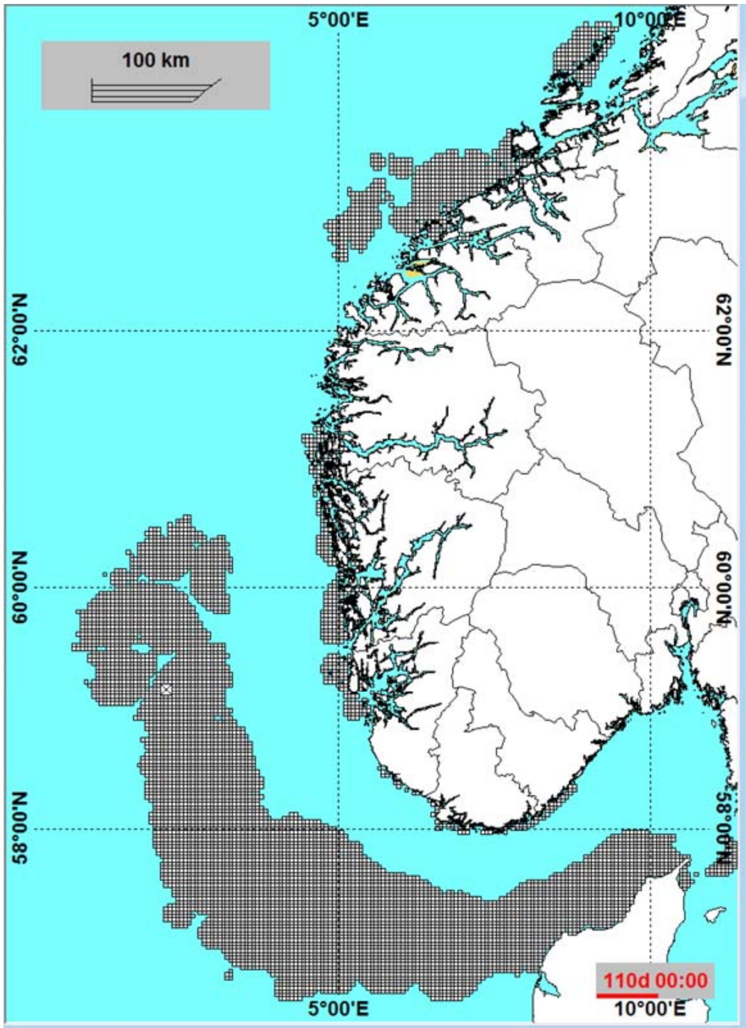

Figure 40. Map of the grid cells with THC above the threshold value at the time-step of peak oil mass in the sediments.

16.2.3 THC in the Lower Water Column

Theoretically, it would be preferred to use the concentrations of THC in the *lower* water column for organisms at the seafloor that are exposed to THC in the water column. This is considered a more accurate measure of THC exposure for the species that are exposed through water column only or in addition to another exposure route. Oil spill models that give this output separately in the output from statistical simulations can be used directly in the ERA Acute model.

In the current OSCAR version, oil concentrations in the lower water column are given in single-simulation mode, as for the sediment concentrations. Similarly, the concentrations of THC in the lower water column may be exported from the single simulation if the user decides to use these values for corals, sponges and other organisms exposed through the water column. The simulation with the most relevant concentration in the lower water column needs to be chosen, and to find the most accurate recommendation has been outside the scope of this project. However, it is assumed that the simulation that gives the highest concentration on the water column (which is exported to the output file) is a suitable candidate for re-running in single-simulation mode. This is the same simulation as suggested for extraction of sediment compartment results. In the example below, the water column concentration of THC on the last day of the spill duration was used, in the same simulation that was used to extract THC concentrations in the sediment. The final day of the release has the highest amount of released, but not-yet degraded oil, and fresh oil from the final release day before the follow-up time. The time-step should be checked in the mass balance files. Export is carried out in the same way as for sediment concentrations by selecting the timestep, relevant parameter, exporting to shape file and converting to the relevant transformation and grid.

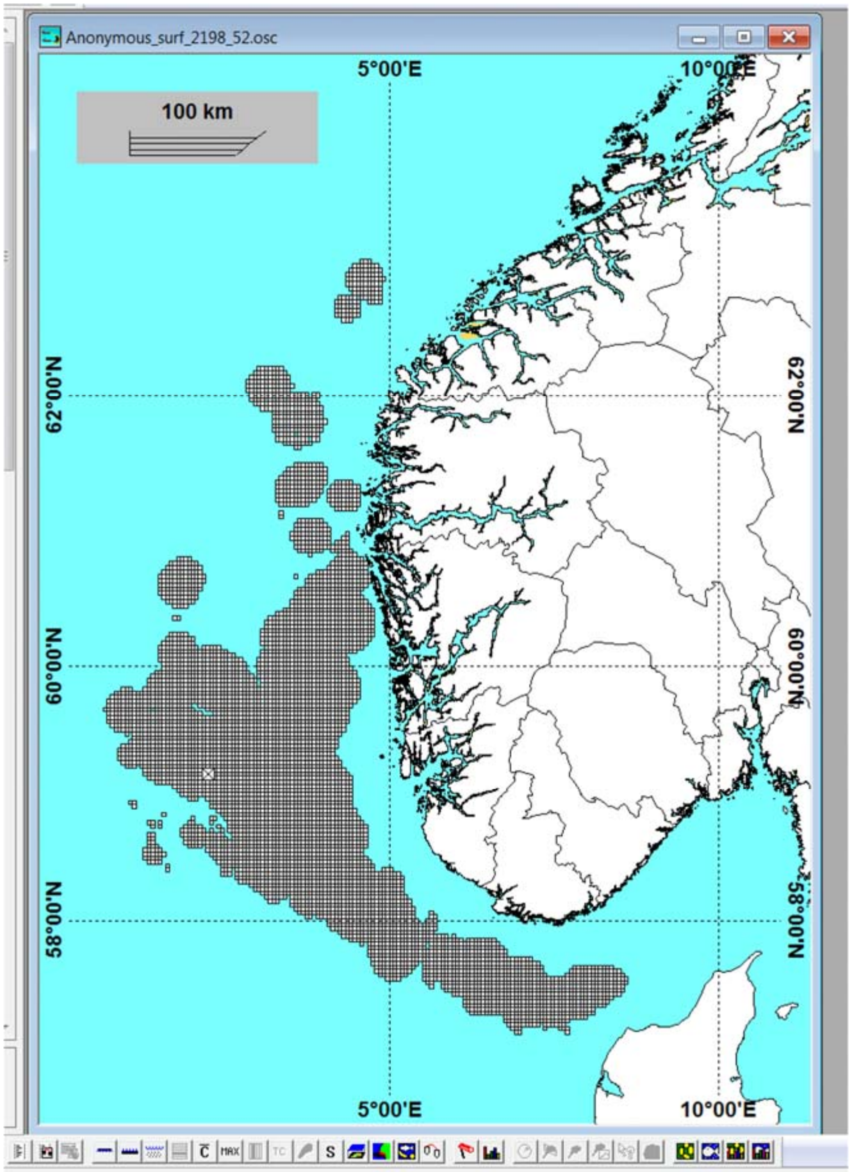

Figure 41. Map of the grid cells with THC above the threshold value at the time-step of peak oil concentrations in the lower water column (day 52 of the simulation).

16.3 Conversion of the OSCAR Shape File into an ERA Acute Grid (ArcView example guide)

Input: Shapefile from OSCAR with the format:

Shape	Sdmas_g_m2
Polygon	(value of THC in g/m^2)

Step 1: Conversion of the shape file from Decimal degrees to UTM33

- Output units: meters
- Category: UTM 1983
- Type Zone 33
- Projection: Transverse Mercator
- Spheroid: WGS 84

Recalculate the area add to a view which is in UTM33 and save the file to disk. Result is the file in the same grid, but with the UTM 33 projection.

Step 2: Go to the UTM 33 View

- You should have the result file in the GIS View
- Add the base grid (e.g. 10x10 km grid or other used in ERA Acute) to the view
- Both have a Shape column, but different sizes
- Intersect themes:
  - Choose the converted OSCAR output file as input theme and select the Sdmas_g_m2 field
  - Choose the grid file and select all the fields
  - Save the output file (intermediate file)

Step 3: Open the attribute table of the resulting intermediate file:

- Select the field with the cell ID
- Calculate this field: Select the Sdmas_g_m2 field and choose to Average the values.

The resulting file contains Cell IDs with average Sdmas_g_m2 values. Other values may be chosen at the users choice.

17 Uncertainties

As a starting point – attempt a joint understanding of the term uncertainty. For our purposes, the following definition of uncertainty analysis from Wikipedia is considered relevant:

«Uncertainty analysis investigates the uncertainty of variables that are used in decision-making problems in which observations and models represent the knowledge base. In other words, uncertainty analysis aims to make a technical contribution to decision-making through the quantification of uncertainties in the relevant variables.

In physical experiments uncertainty analysis, or experimental uncertainty assessment, deals with assessing the uncertainty in a measurement. An experiment designed to determine an effect, demonstrate a law, or estimate the numerical value of a physical variable will be affected by errors due to instrumentation, methodology, presence of confounding effects and so on. Experimental uncertainty estimates are needed to assess the confidence in the results. A related field is design of experiments.

Likewise in numerical experiments and modelling uncertainty analysis draws upon a number of techniques for determining the reliability of model predictions, accounting for various sources of uncertainty in model input and design. A related field is sensitivity analysis.»

17.1 Uncertainty related to knowledge

This issue is discussed also in chapter 6 and 7.

The quality of knowledge and understanding of the natural environment and effects of contaminants will be reflected in the results of the assessment. The more detailed the assessment – the higher quality of underlying information and knowledge is required. There is a continuous process of increased understanding and knowledge through monitoring, research and development, and it should be the objective of any assessment to use the best available knowledge.

In the subsequent parts of this section, uncertainties related to the sediment compartment are addressed.

17.1.1 SSD Curves and Toxicity Data

The main issues relating to uncertainty in the SSD curves are: The selection of species used for the SSD curves are based on organisms in the water column, as there was found to be a lack of sediment-specific data for deriving SSD curves. The relevance of species used for the specific area under assessment will hold some uncertainty, as well as the lack of information on species that are too sensitive/fragile to hold in laboratory conditions. However, several articles state that organisms in sediment are not expected to be more sensitive in general than the organisms in the water column, hence the method is assumed to be valid.

17.1.2 EqP Theory

Use of the EqP theory holds some uncertainty, as we do not expect to reach equilibrium by the time-step during oil drift simulations that ca be used for ERA Acute. Also, the use of an average (mean) KOW value may hold some uncertainty.

17.1.3 Oil Spill Modelling and THC/HC Components Concentration Assessment

Oil spill modelling relies on a range of assumptions regarding weathering and distribution of oil. For the sediment compartment, uncertainties in the assessment will be related to insufficient knowledge, parameters include:

- The C_{THC} values are based on sediment THC concentrations from a specific time-step in a single simulation (if current OSCAR version is used). A statistical result from several simulations are preferred.
- Bottom layer water column concentrations (lowest 1 m)
- Current speed and direction throughout the water column
- Halocline & thermocline presence and depth
- Particle concentration and specific weight

17.1.4 Resource Unit

No uncertainties as such, it has been decided to present the risk result as both geographical area (km^2) and as numerical results. However, the lack of a common scale calls for caution by the user in interpreting results and comparing results.

17.1.5 Habitats and Communities

Insufficient knowledge of the composition of habitats and communities is an uncertainty if not the most sensitive component forms the basis for the assessment.

17.1.6 Resource Data Sets

Lack of availability and poor quality of resource data will for ERA Acute, as for any other assessment, be critical for the assessment results, and the ERA Acute level selected should take this into account.

Uncertainties will depend on geographical area and individual VEC data sets, and include:

- Whether the relevant VECs have been studied/mapped
- Geographical distribution
- Temporal presence

17.1.7 Experiences from Spills

There are a number of historical incidents resulting in oil spills, however, focus have in most cases been placed on shoreline studies and contaminant levels that may affect commercial fishing. As for the section below, variability in results is more a reflection of variability in biological and physical conditions than in the effects of the contaminant.

17.1.8 Use of Experience from Oil-Based Drilling Muds

This is probably the most comprehensive source of information on the effects of oil adhered to sedimented particles, including a range of experimental and mesocosm studies, as well as extensive and systematic monitoring over a number of years. As discussed in e.g. Renaud et al. (2008), there is a variability in discharge, deposition and redistribution patterns, resulting in a variability in impacts and restitution times, however these are not uncertainties per se, but lack of knowledge on these factors will affect assessment results.

17.2 Calculation of Uncertainties

There are no inherent uncertainties in the calculations as such. Sensitivity assessments of the calculations are recommended at a future point in time be applied to identify

- Most critical steps in the calculations
- Propagation issues

17.3 Importance and Ranking of Relevance of Uncertainty Issues

A preliminary ranking of uncertainty factors is given below, pending further testing and validation as suggested in the next section.

1. Resource data

2. Oil drift simulations used at a single time-step
3. Model results

17.4 Handling Uncertainty in ERA Acute

17.4.1 Discussions Across Compartments

It is suggested to have a joint discussion involving all compartment leads on this issue.

17.4.2 Conclusions

A statistical approach will in general contribute to reducing uncertainties. To further identify and quantify uncertainties, a scientific approach should be adopted, where individual factors/assumptions are changed and the implications on results reviewed.

As the ERA Acute model has similar challenges as the SYMBIOSES model when it comes to evaluation of uncertainties and sensitivities, a similar testing and validation exercise should be considered for ERA Acute.

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19 Attachments

Stephansen, C. (2015) Flow Sheet for ERA Acute Seafloor Model (PDF)