ERA Acute Report

WP2a – Seafloor Compartment Sensitivity Testing and Norwegian Sea Test Case Data

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Authors: ***Cathrine Stephansen, APN*** ***Anders Bjørgesæter, Acona AS*** ***Verified by: Tom Sørnes, APN***	***Version/Date: Final 21.12.2017*** ***Number of pages****: 93* ***Distribution: Project members*** ***Document ID: ERA Acute 2A-3***
Summary: Sensitivity of the equations used in the hard and soft substrate impact and restitution calculations in the seafloor compartment have been tested using ranges of input parameters. A literature study was carried out, and data available from MAREANO have been used to find relevant ambient parameters to use and to create a dataset for testing. The test data cover the Norwegian Sea, and are used in both the sensitivity testing described in this report as well as in the Norwegian Sea test case (separate report Document ID ERA Acute 2A-4)	
Task lead: Odd Willy Brude/Anders Bjørgesæter Odd Willy Brude	***Project Manager:*** Cathrine Stephansen Cathrine Stephansen

The ERA Acute project is carried out by a consortium of industry partners (Statoil, Total, Norwegian Oil and Gas Association) and experts in environmental risk analysis (Acona, Akvaplan-niva (Project Manager), DNV-GL and SINTEF), supported also by the Research Council of Norway.

ERA Acute is developed to provide a globally applicable, transparent method for quantitative environmental risk assessment of oil spills in four compartments: Sea surface, shoreline, water column and sea floor.

1 Introduction

1.1 Scope and approach of the study and document

ERA acute is a set of mathematical functions describing the mechanisms of action of impact and recovery, within the limitations of current implication possibilities. Every model therefore has some inherent uncertainty. In order to gain understanding of the precision level of a model, three steps are necessary:

- Model verification (check that the model calculates the algorithms correctly and meets specification) (WP1a) and that it delivers the necessary results (WP1b)
- Model sensitivity (analyse the effects of lack of knowledge and the model's response to changes in model input and parameters) (WP2a)
- Model validation (decide on the conformity/consistency between model results and observations and with other models) (WP2b and WP2c)

This report builds on a previous verification that the core calculations are correctly implemented (WP1a and 1b), and further presents the results from sensitivity testing of the input parameters in the equations for soft substrates in the seafloor compartment (2a). Seafloor compartment is also included in the Deepwater Horizon (DWH) case study carried out for the field validation (WP2b) by A. Bjørgesæter (2017, in prep.).

This document describes for WP2a, the sensitivity/uncertainty testing of the input parameters used for the seafloor compartment (mainly the soft substrates) in Sections 2, the sensitivity of feeding mode distributions in section 7, and the restitution parameters in section 8. These tests have resulted in conclusions about adjustments of some recommended parameters compared to parameters first used in the set-up, as well as some preliminary values proposed in the Phase 3 model development report (Stephansen & Sørnes, 2015).

The sensitivity testing of seafloor calculations has been carried out in parallel with the development of test data for the Norwegian Sea seafloor, based on data from the MAREANO program, which have been used in a case study of a single-scenario blowout case (Stephansen, 2017). The oil drift simulations that were carried out for the case study have been used in the sensitivity testing and the sensitivity testing was used to calibrate parameter values used in the case study. Due to the number of figures necessary to document this type of work, two separate reports were created for the two work packages. The two reports refer to each other. The description of the datasets – species and parameters are included in the current report, and not the case study, as the most complex use of the parameters are in the sensitivity testing of feeding modes and it was determined to be easier for the reader if the descriptions were included with the sensitivity tests.

Under WP 2c, a comparison with MIRA is not possible in the same way as for the other compartments, as sediment is not a part of the MIRA method. However, a case has been analysed serve two purposes: 1; To benchmark ERA Acute results and indicate the magnitude of the risk from a large spill case in the Norwegian Sea, under WP 2c, and 2; to test the restitution threshold value using a larger case. A literature study and data mining task preceded the testing on the Norwegian Sea case. Section 9 describes the development of data sets for the Norwegian Sea sediment VECs. Both "dummy data" and a limited set of real VEC data based on the MAREANO program have been developed, along with parameters that are recommended used in the resource setup-file. These recommended values are based on the results of the testing carried out in the first part of the work, and therefore tie in to the sensitivity testing. Therefore, having finalised the testing of the calculations and most of the individual input parameters, three runs of the Norwegian Sea case were carried out. Two runs with dummy data, mathematically equivalent to running level A.1 for impact, but which includes restitution modelling, were carried out using two different restitution thresholds. A final run is carried out using the VEC data derived from MAREANO. The latter has limited overlap with the oil drift.

1.2 The tests

Sensitivity testing has been carried out through a series of tests, covering different aspects. The main areas concerned are: 1) Parameters that influence THC concentrations in sediment and its bioavailability (tests 1a,b,c, 2 and 3 (section 2) including stochastic testing (section 6)) , 2) sensitivity of feeding mode (test 4, section 7) and parameters related to restitution factors (test 5, section 8). The final test 6 is the case study reported in a separate report (Stephansen, 2017).

1.2.1 Oil drift simulations

Oil drift simulations for the tests and case study were carried out using OSCAR (MEMW 8.1) for one rate (9000 Sm^3/day) and one duration (65 days). Reference oil type Oseberg Øst. Apart from the rate and duration, the spill site location, reference oil and other parameters were otherwise identical with the simulations carried out for the Norwegian Sea test cases for the other compartments in WP2c. The period was 2005 and 2006, OSCAR thereby gave 21 single simulations, one per month for almost two years (Table 1).

These simulations were used in two stages in the sensitivity testing of sea floor compartment. First, the simulations were used right at the beginning to find a relevant value of oil amounts in the sediment to use for sensitivity testing of the other factors (Tests 1-5 see above). Among the result values of THC in the sediment, a realistic, but high value of 0.1 kg/m^2 THC in sediment was used as input to the sensitivity tests of the initial calculations.

A series of data sets were developed for the seafloor compartment, using data sets on substrate types and sensitive organisms from the MAREANO Project, covering parts of the Norwegian Sea. The simulations were used to run an ERA Acute test case for the Norwegian Sea using the VEC data for the substrates and special species, split into the individual feeding modes as per updated recommendation. The parameters needed for the resource setup-files have been tested and are used as recommended based on the initial testing included in this version of the document.

Table 1. Start-dates of the 21 oil drift simulations carried out for the surface blowout of 9000 Sm3/day for 65 days. Reference oil type Oseberg Øst.

IDScen	Year	Month	Day	Hour	TDura	Random seed
1	2005	1	1	13	2040	41
2	2005	2	3	14	2040	18467
3	2005	3	8	15	2040	6334
4	2005	4	10	17	2040	26500
5	2005	5	13	18	2040	19169
6	2005	6	15	19	2040	15724
7	2005	7	18	20	2040	11478
8	2005	8	20	21	2040	29358
9	2005	9	22	22	2040	26962
10	2005	10	25	23	2040	24464
11	2005	11	27	23	2040	5705
12	2005	12	31	0	2040	28145
13	2006	1	1	1	2040	23281
14	2006	2	3	3	2040	16827
15	2006	3	8	5	2040	9961
16	2006	4	10	8	2040	491

17	2006	5	13	10	2040	2995
18	2006	6	15	12	2040	11942
19	2006	7	18	15	2040	4827
20	2006	8	20	17	2040	5436
21	2006	9	22	19	2040	32391

1.2.2 Eqp-related input factors (1a,b,c 2 and 3)

1.2.2.1 Deterministic sensitivity testing

An Excel spreadsheet containing the calculation steps used for soft sediment substrates in the seafloor compartment has been developed for two purposes: Firstly, under WP1a/b to verify the correctness of the ERA Acute Core Calculator programmed by SINTEF (Python script) and secondly this Excel calculator was then adapted to provide a document containing the spreadsheets for WP2a. One-by-one, individual, central calculations were tested with respect to the sensitivity to variability and uncertainty of input parameters. This was done by directly changing the parameters and calculating the relevant endpoints (sections 2 and parts of section 7). This testing has been carried out using a simple deterministic approach. For the deterministic testing, effort has been put into finding *field values* from literature to provide a relevant range for each parameter, this represents the boundaries of *uncertainty* of the values. The testing exercise, in addition to providing knowledge and familiarisation with the individual calculation steps, will also provide some guidance and input to the calibration phase (WP2d), as well as providing realistic and relevant values for the testing, using the ERA Acute core calculator for the Norwegian Sea test case.

1.2.2.2 Stochastic testing

For the initial calculation of concentration of THC in sediment, which currently is based on input of kg/m^2 of oil from oil drift simulations, as well as for lethality calculations, stochastic sensitivity tests were carried out as follows: Monte Carlo simulations were set up to draw the parameters stochastically. A Factor Prioritization by Reduction of Variance-analysis has been carried out to determine which of the parameters that the calculation is most sensitive to for the initial calculations of partitioning-based exposure.

1.2.3 Feeding mode distributions (4)

The impact algorithms for sediment initially aimed at using few VEC data based on substrate type. It therefore takes into account distribution of feeding modes (Stephansen *et al.* 2015) used to determine exposure (i.e. exposure modes). Although data on the percentwise distributions of Feeding modes (FMs) seem to be available within the extensive data gathered by MAREANO, compilation of these data to a full coverage of the Norwegian Sea and Barents Sea in the initially intended way is a comprehensive task. Based on testing and VEC data development (section 8.4) an alternate and simpler approach was tried out. VEC data with single feeding modes or definable combinations of FMs are proposed used instead of the substrate-based community approach. The results are expected to be more reliable (see section 8.4).

1.2.4 Restitution-related input factors (5)

The restitution times are calculated using a linear function of the oil amount in sediment. The leaching of THC from sediment to water phases depends on partitioning-related factors. For each substrate, a correcting sensitivity factor was introduced by a method of calculation (test 5A and 5B). Threshold and benchmark values were tested (5C) with varying input values of $C_{THC,sed}$ from the oil drift simulations and using two values of the currently static value of $C_{threshold,sed}$.

1.2.5 Norwegian Sea test case (6)

Sea floor is not a compartment in MIRA, so a direct comparison is not possible. However, to "benchmark" the ERA Acute risk result level in Sea floor compartment the case is run with the MAREANO data sets with *partial* coverage after the model was "tuned" following the deterministic testing and the Monte Carlos simulations that were carried out. ERA Acute Sea floor results using data sets with realistic values in cells provide experience with the magnitude of risk involved with this scenario for the cells covered by the MAREANO data. It is important to remember, however, that the MAREANO data are not complete.

Testing of feeding modes were performed for maximum potential impacts using the test scenario using dummy data of A.3 level where N=100 km^2 in each cell of all substrates and FMs.

In addition, a full case study of the Norwegian Sea Case was carried out for Level A.1, A.2 and A.3 impact assessments, as well as level B restitution modelling. This is reported in a separate report (Stephansen, 2017).

1.3 Summary of tests and endpoints (soft substrates)

Input oil amounts in sediment from oil drift simulations are given in the unit kg/m^2, which initially has to be converted to ppb by Equation 1.

The equation is multiplicative and includes three input parameters: Dry density (DryDens), water content (WatC) and bioturbation depth (BDepth); values that vary between sediment substrates, regions, water depth and distance to the coast (distance to river run-off), to name some.

The input values to be sensitivity-tested are shown in Table 2.

Table 2. Overview of all input parameters used in the ERA Acute Models in the seafloor compartment.

Test	Parameter	Description	Endpoint(s) affected
1	Mixing depth (BDepth)	The values of the parameters may vary widely between different sea bed habitats and benthic communities on a local and regional scale. The test is constructed to analyse the uncertainty associated with lack of knowledge about these parameters and investigate their importance (sensitivity)	Initial concentration in sediment, conversion from kg/m^2 to ppb **C_{THC}**,sed
	Water content in sediment (WatC)		
	Dry density of sediment (DryDens)		
2	Total Organic Carbon (TOC)	Total organic carbon will vary with sediment type and region. The test is constructed to analyse the uncertainty and natural variability associated with organic carbon content	**C_{IW}, p_{let}(IW)**
3	The octanol-water partitioning coefficient (K_{OW})	The test is constructed to investigate the effect of oil type on K_{ow} and subsequent endpoints related to THC in the sediments	**C_{IW}, C_{Ing}**, BCF, KOC, BSAF, Impact (Imp)
4A,B,C	Feeding modes	The tests were constructed to investigate the importance and sensitivity of feeding modes on various endpoints for all substrates.	Plet for different feeding modes, impacted areas
5 A/B	Sensitivity factor (SF) (Restitution correction factor)	A method was constructed to find recommended sensitivity factor (SF) values used as a correction factor in the restitution modelling, based on partitioning of THC from carbon-phase to water phase (leaching) and deterministic tests of the first implemented calculation	Restitution (T_{res})
5C	Concentration of THC with no effect ($C_{threshold}$)	A test constructed to analyse the importance of threshold value (set to 50 ppm in implemented version) use 50 ppm and 25 ppm	Restitution (T_{res})
6	Level A.1, A.2 and A.3 Level B	Risk assessments at the three levels of detail using VECs with individual FMs (See report Stephansen, 2017)	Several endpoints

1.4 Parameters and abbreviations used

$C_{THC,IW}$	Concentration of THC in interstitial water (=THC_{IW})
ERA	Environmental Risk Assessment
f_{OC}	Fraction of organic carbon
FM	Feeding mode
Ing	Ingested fraction
IW	Interstitial water
THC	Total Hydrocarbon
THC_{IW}	Concentration of THC in interstitial water = C_{IW}
sed	Denotes Sediment-compartment
TOC	Total organic carbon
K_{OW}	Octanol-water coefficient
$p_{let\mathrm{WC}}$	Probability of lethal effect at given exposure in the water column compartment
$p_{let\mathrm{IW}}$	Probability of lethal effect at given exposure in sediment interstitial water
$p_{let\mathrm{Ing}}$	Probability of lethal effect at given exposure due to ingestion of contaminated particles
WC	Water column
KOC	Organic carbon water partition coefficient
TOM	Total organic matter
ODS	Oil drift simulations
VEC	Valued Ecosystem Component

2 Oil drift simulations

2.1 Influence areas

Although the oil drift simulations are related to the Norwegian Sea test case (Test 6 -Norwegian sea Surface blowout case – Stephansen, 2017), all preceding tests use the input from the simulations, and the influence areas are therefore presented here.

The probability of oil amounts in the sediment exceeding an arbitrarily chosen threshold value of 0.00001 kg/m^2 in each 10x10km^2 cell is shown in Figure 1. The weighted average oil amount (kg/m^2) in each 10x10km^2 cell is shown in Figure 2, maximum oil amounts in each cell (in any simulation) are shown in Figure 3, and minimum amounts in any simulation are shown in Figure 4.

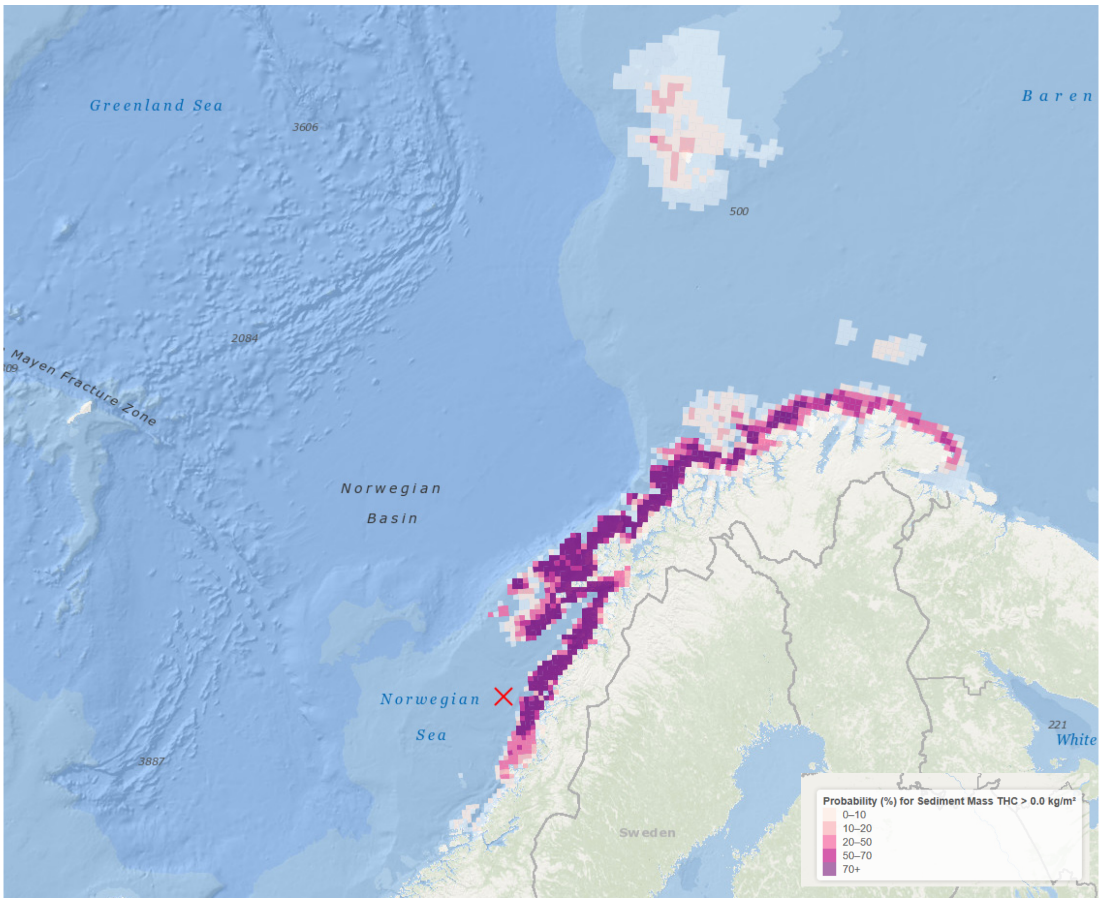

Figure 1. Probability of oil amounts above 0.00001 kg/m^2 sediment following 21 simulations of 9000 Sm3/day for 65 days.

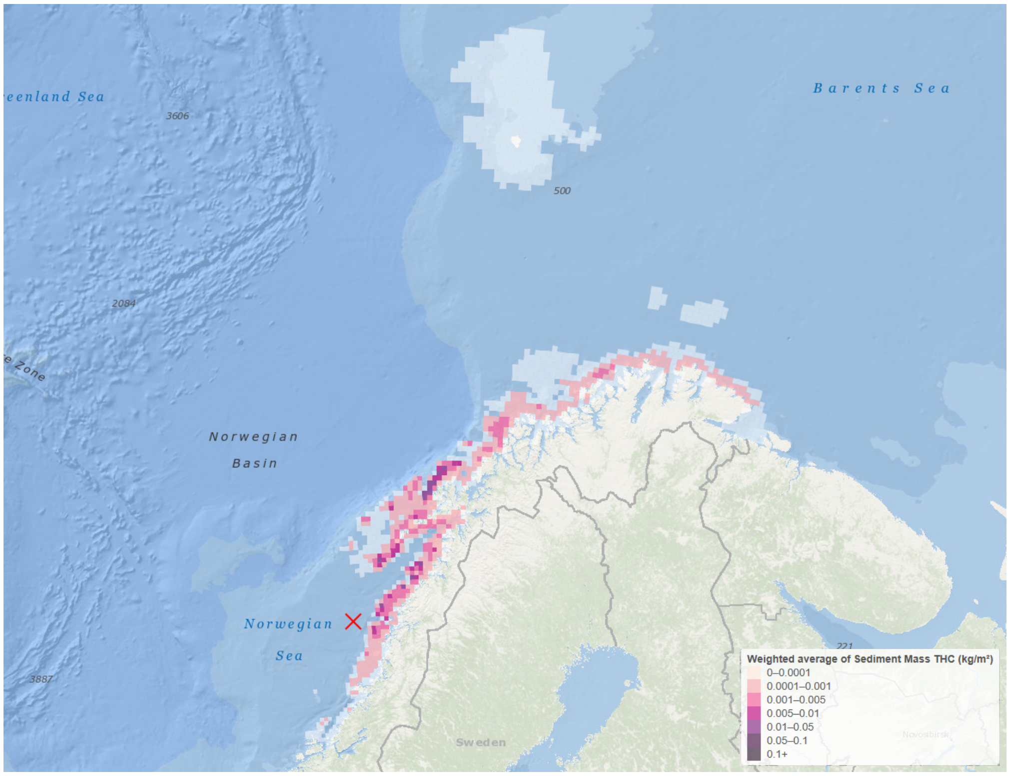

Figure 2. Average oil amounts in sediment following 21 simulations of 9000 Sm^3/day for 65 days.

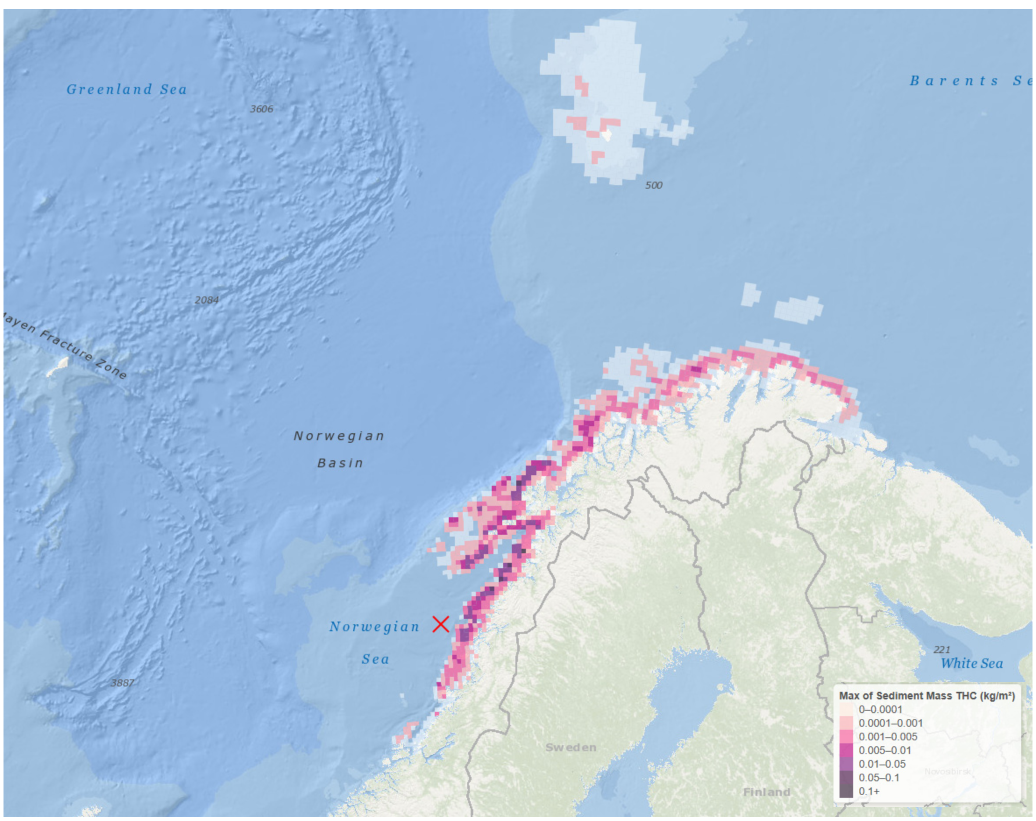

Figure 3. Maximum oil amounts in sediment in cells from any of the 21 simulations of 9000 Sm^3/day for 65 days.

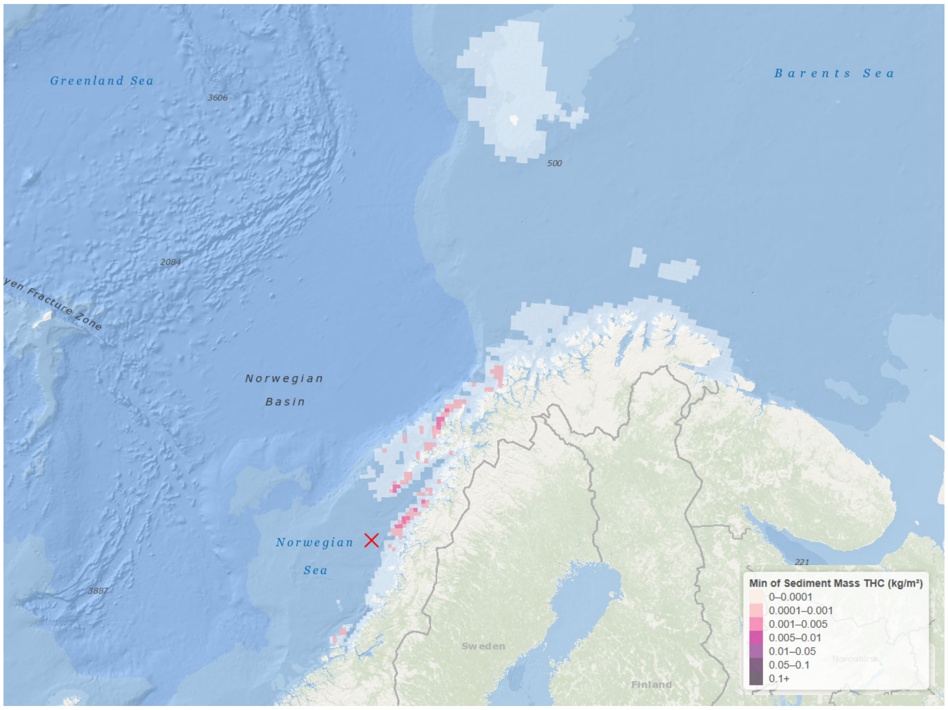

Figure 4. Minimum oil amounts in sediment in cells from any of the 21 simulations of 9000 Sm^3/day for 65 days.

2.2 Input oil amount for all tests

For most of the test cases, oil amount input values were set to be the same in each dummy cell, so only the respective input value to be studied was varied. In order to get realistically set values of oil input, the location in the Norwegian Sea was used to run 21 simulations of a surface blowout case releasing 9000 Sm^3 Oseberg East crude oil per day for 65 days. Of the 134 10 x 10 km cells that had a THC-amount in sediment exceeding 0.001 kg/m^2, the average amount over all simulations and cells was 0.0048 kg/m^2, and the highest *average* over all simulations in a single cell was 0.03 kg/m^2. Of all contaminated cells, the maximum value in a simulation was 0.135 kg/m^2. A value of 0.1 kg/m^2 was therefore used as a non-variable input value, a *possible* – but in this case very high and conservative value from one of the cells with the highest impact. Statistics of the cells with higher mass in sediment than 0.01 kg/m^2 are shown in Table 3 to illustrate this conservativity.

Table 3. Number of cells and average oil mass/area of the cells that exceeded 0.01 kg/m^2 in the oil drift simulations, showing that the chosen test value for oil input is conservative.

Simulation No	No of cells above 0.01 kg/m^2	Average value (in kg/m^2) the cells above 0.01 kg/m^2
1	15	0.019
2	11	0.019
3	11	0.018
4	17	0.017
5	19	0.022
6	22	0.022
7	26	0.026
8	20	0.022
9	14	0.021
10	17	0.022
11	21	0.023
12	21	0.02
13	19	0.02
14	11	0.08
15	5	0.015
16	19	0.025
17	27	0.025
18	8	0.016
19	3	0.014
20	6	0.014
21	16	0.016

3 Tests 1a,b,c: Sensitivity tests of values related to sediment concentrations

Testing the input values to the calculations of concentration of THC in soft sediment substrates from oil amount per area is necessary to decide and advise how much effort the user should put into finding specific values for a given region or area, or whether we can find and recommend default values. How much do the parameters mean mathematically in each individual cell-based calculation and what are the implications for the final resulting endpoint?

To find realistic ranges of the variable input values to be tested, a limited literature study was carried out to find test ranges that are in line with natural variations and ranges of the three values in relevant sea floor substrates.

Oil can be transported to sediments by the adhesion of hydrophobic fractions (droplets, WAF/CEWAF) to particles from naturally occurring sedimentation processes or by exposure from a subsea plume. During the DWH incident, the majority of the sedimented oil is believed to have originated from the subsea plume of oil droplets (James R. Payne, pers. comm. (IOSC 2017)) that directly hit the affected areas at the seafloor. Oil can be dispersed either naturally or chemically. Organic matter is primarily brought to the sediments by processes described in Figure 5, which includes a simplified schematics of the modes of transport within the sediments.

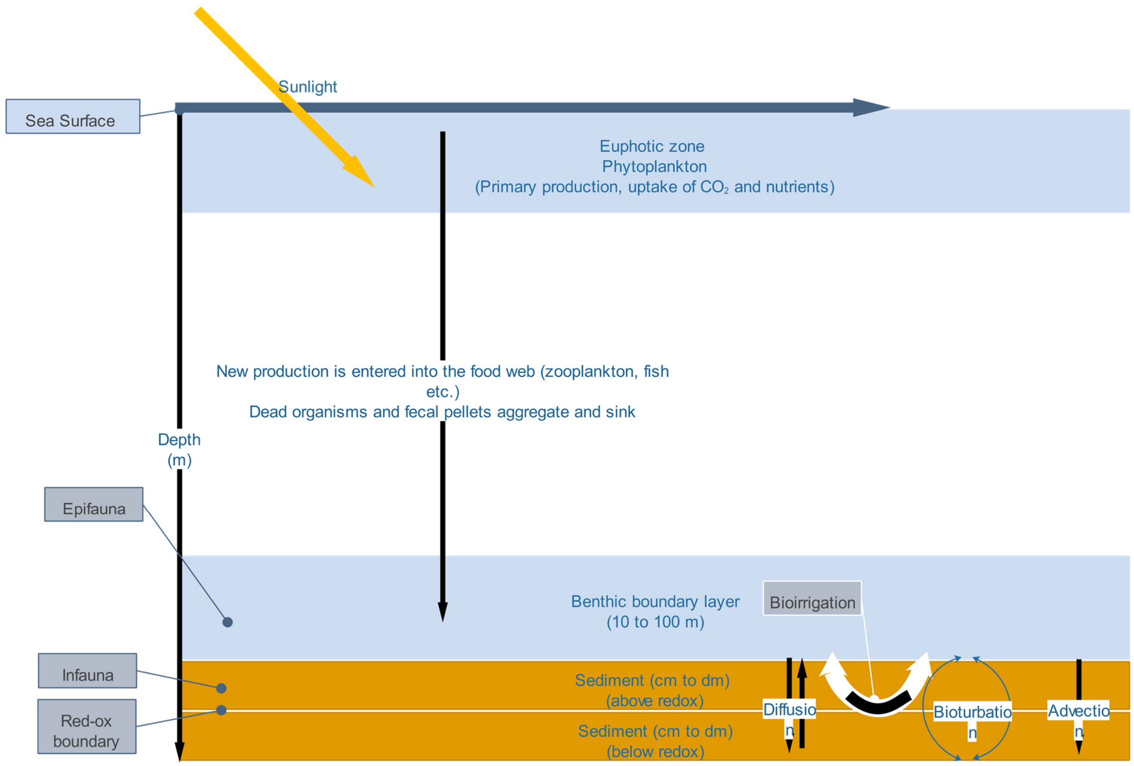

Figure 5 Organic matter flux to the sediments, including simplification of modes of transport of matter in the sediment: Molecular diffusion, bioirrigation, bioturbation and advection. (Figure adapted from two figures in Marine Geochemistry, 2. ed. 2006).

3.1 Purpose and approach of the test of EqP parameters

Testing the parameters necessary for calculating the concentration serves to

1. Test reference values for (1) DryDens, (2) WatC and (3) BDepth for typical sediment types (if possible) as basis for evaluating uncertainty and information for the guideline and best practise documents
2. Become more familiar with the first step of the model; calculation of sediment THC concentration and to provide information about how variation in input parameter affects model results
3. Within the scope and budget of the tests, provide information about the uncertainty associated with lack of knowledge about these three parameters
4. Determine how sensitive selected output of the models (intermediate result C_{THC} and endpoints; T_{res} as well as the size of the potential affected area if relevant for the test set-up) is and which parameter is most important. The goal is to provide information to the user about which parameters to place research efforts on, and which can be set as general or default values for the relevant substrate type.

The test is carried out by varying one parameter at a time and investigating the effect on the oil concentration in the sediment, while the other parameters are kept at one average value based on the findings of the literature study.

The calculation used to determine the $C_{THCsed,cell,sim}$ (ppb) (dry weight) is:

Equation 1

$C_{THCsed,cell,sim}$ [ppb)] (dry) = ($C_{THCsed,cell,sim}$ [kg/m^2] × 10^9 [mg/kg] × 1/BDepth [m)] × (1-WatC))× 1/DryDens [kg/m^3]

$$C_{THC,sed,cell,sim}(ppb, dry) = \frac{\text{SdMas\_kg\_m2} \times 10^9 \times \frac{1}{BDepth} \times (1 - \text{WatC})}{DryDens}$$

3.2 Test 1a Mixed depth (bioturbation depth)

Due to the feeding by benthic invertebrates and to the mixing of sediment by their burrowing activity (bioturbation) the deposited organic particles and associated THC contamination are buried into the sediment and become an integral part of the sedimentary organic matter (Marine Geochemistry, 2. ed. 2006) (Figure 6). The activity is largely restricted to a narrow surficial zone of marine sediments (Boudreau, 1998) making up the mixing depth (bioturbation depth), denoted BDepth in ERA Acute.

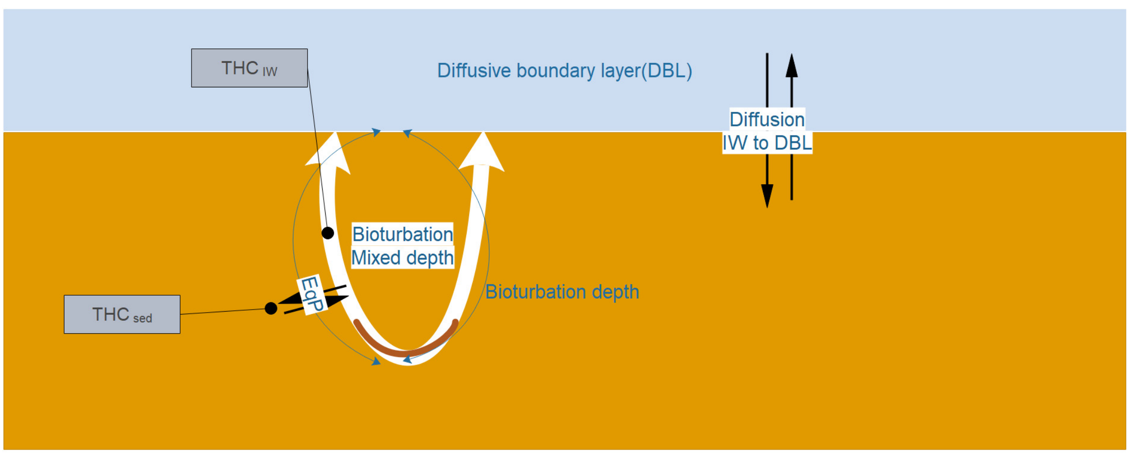

Figure 6 Illustration simplified and adapted from Marine Geochemistry (2. ed. 2006), showing the exchange of components in the bioturbation zone.

3.2.1 Choosing the range of BDepth values

Teal et al. (2009) determined global patterns of the mixing depth (BDepth) from bioturbation, citing a global mean of 0.0575 m (+- 0.0567m). Boudreau (1998) states a worldwide, environmentally invariant mean of 0.098 m with a standard deviation of 0.045 m.

Although the literature search did not reveal any quantified relationships given in open literature, the general trend is that the degree of bioturbation decreases with increasing water depth. Diversity and density of biogenic sedimentary structures decrease across the shelf when the *infauna* become less diverse and dense as the substrate becomes finer grained as depth increases. Mean grain size is a significant factor in the correlation between bioturbation depth and water depth. Sand-to-mud ratio is also significant (Geological Survey Professional Paper 1238 (Year unknown)). Bioturbation is denser in relatively sandy areas, indicating that a deeper bioturbation depth can be used for sands and coarse sands/gravels.

Based on the work by Teal and co-workers (2009), the first step calculations were tested using BDepth varying between 0 and an extreme value of 0.35 meters (see Table 4 and Figure 7). The results of the testing is seen in Figure 8. When BDepth was set at one defined value for testing one of the other values in the first equation, it was set at 0.0575 m, cited as the global mean by Teal *et al.* (2009). This is a more conservative value than Boudreau's value of 0.098 m, resulting in a higher concentration calculated for the bioturbated layer.

Table 4. Mixing depths of sediments in different regions and seas (Teal *et al.* 2009). The mixing depths found in the studies vary between 32 cm (maximum value in one of the Gulf of Maine samples) and 2 mm (minimum in one of the Baltic Sea samples).

Region	Sea	Mixing depth (mean) (BDepth) (m)	Standard dev. (SD)	No. of samples (n)	Mixing depth (high value) (m)	Mixing depth (low value) (m)
North Atlantic temperate	Gulf of Maine	0.24	0.0822	5	0.3222	0.1578
North Atlantic temperate	Baltic Sea	0.009	0.007	40	0.016	0.002
North Atlantic temperate	North Sea	0.027	0.023	135	0.05	0.004
Temperate South America	Temperate South America	0.064	0.027	10	0.091	0.037
Temperate	Temperate	0.008	0.018	5	0.026	-0.01
Polar	Polar	0.023	0.003	6	0.026	0.02
Southern Ocean	Southern Ocean	0.028	0.013	12	0.041	0.015
	Global	**0.0575**	**0.0567**	**791**	**0.1142**	**0.0008**

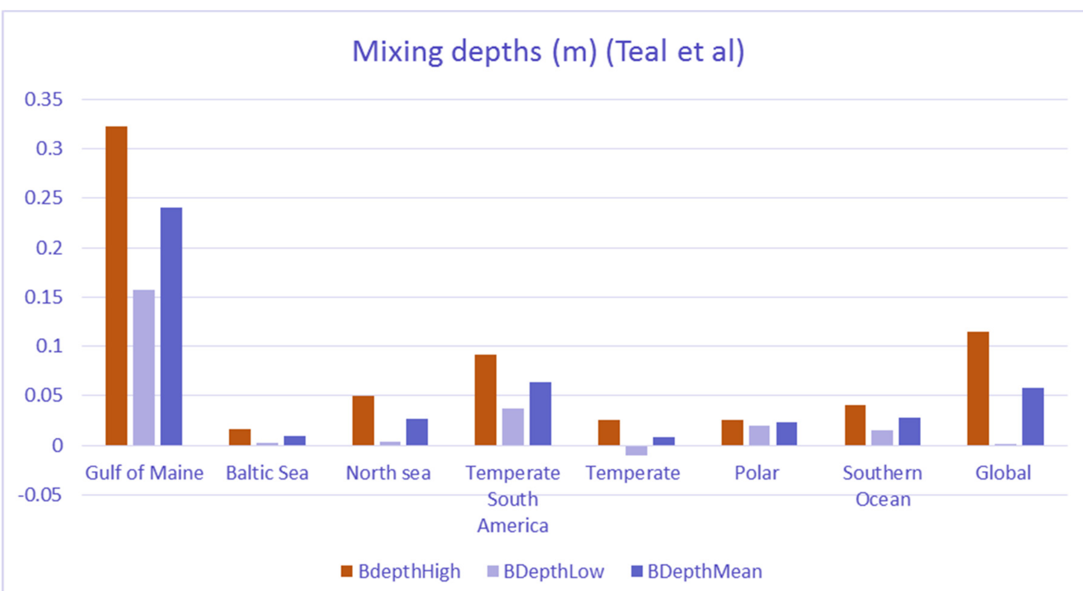

Figure 7. Mean, maximum and minimum values of measured mixing depths of sediments in different sea regions (Teal *et al.*, 2009).

3.2.2 Result of the value range sensitivity testing for mixing depth

Variations in mixing depths are high in the literature, indicating both regional differences, depth differences and difference due to substrates, but also representing the uncertainty of this value. The parameter is highly significant in the calculation of oil amounts in the sediment. By simple mathematical design, the concentration doubles when the mixing depth is halved, therefore this input parameter is a value that is relevant to research local values for. The mixing depths found in the studies vary between 32 cm (maximum value in one of the Gulf of Maine samples) and 2 mm (minimum in one of the Baltic Sea samples). The articles say nothing about which depths and substrates that were involved in the sites, therefore a separate search into databases with the BDepth in mind would further reduce the uncertainty, if the data are available.

Figure 8 shows how the concentration is reduced when mixing depth is increased between 1mm and 35 cm. For this test, the water content fraction was held constant at 0.25 (25 %) and the dry density was held constant at 2.1 g/cm^3 (See recommended values in Table 5). Holding these two parameters constant at the same values, Figure 9 shows a narrower range of the results from the calculations, varying between the lower and higher values of the SD around the global mean value. The results show, as expected, that the mixing depth is a highly significant parameter to select a verified value for. However, when such local values are lacking, a global mean of 0.0575 m could be used as a default value for most coarse low-TOC substrates. For Nordic conditions, a value of 0.026 m could be more relevant for coarse sand, based on mean values for the North Sea which has a lot of sandy bottoms. (Teal *et al.* 2008). For muds (deeper waters) a smaller value still may be relevant.

In the Deepwater Horizon (DWH) Incident it was found that the top centimetre was significantly different than the rest of the sediment layers (http://gulfresearchinitiative.org/study-examines-sediment-east-deepwater-horizon-oil-associated-marine-snow/). The incident, which occurred during the spring algal bloom, had a significant portion of the oil deposited to the seabed through marine snow. Based on this information, the deep-sea muddy seafloor can therefore be assumed to in the short run to have a mixing depth in the impact phase of 1 cm when there is heavy deposition of particles. Conservatively, based on the literature searches and the testing, the values used for each of the substrate types when specific values are missing are: Coarse sand and bioclastic coarse sand: 5 cm; sand: 2 cm; sandy mud: 1cm and mud: 0.5 cm. Very low mixing depths would indicate absence of organisms in the soft substrate and the high lethality calculated would have little relevance. 5 mm for mud is low, half of what was found to be the contaminated layer in DWH. However, the 1 cm contaminated layer depth in DWH was also due to the large amounts of marine snow deposited. As a starting point for ERA Acute calculations, 5 mm is considered sufficiently conservative for a mud substrate with burrowing fauna present. This assumption also takes into consideration that it takes some time for the sedimented oil to become fully mixed within the bioturbated layer, and the concentration at the top layer would initially be higher.

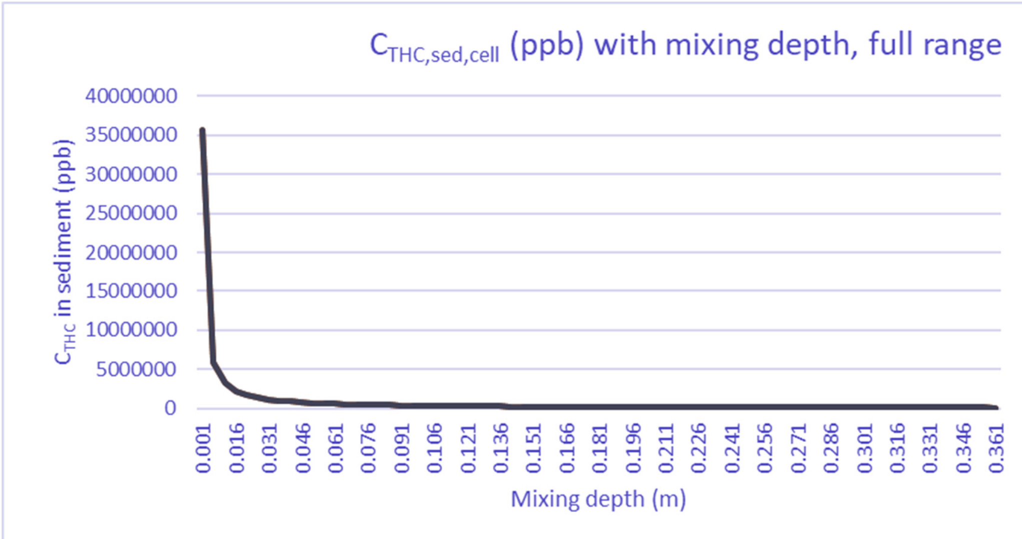

Figure 8. By simple mathematical design, the C_{THC}-value in the sediment halves if the mixing depth doubles, the value should therefore be selected with care. The figure shows the values calculated at the full range of the values found.

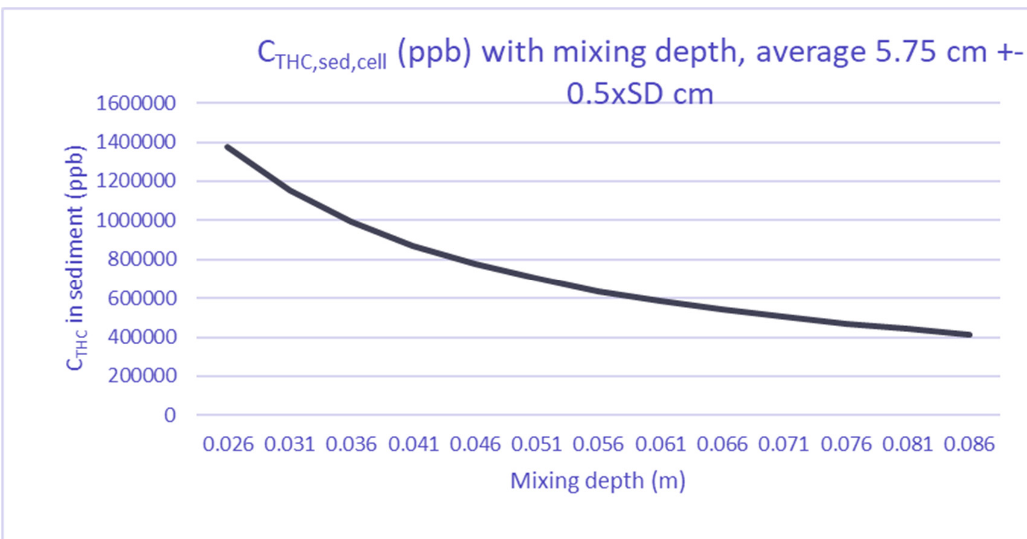

Figure 9. Change in C_{THC} in the sediment with mixing depth varying at the global average mixing depth, ± 0.5x SD (global).

3.3 Test 1b Dry density

3.3.1 Choosing the range of DryDens Values - Dry density (grain density)

Dry densities are not readily available in the literature searches carried out, and is not available in the MOD database. Grain density of the non-water fraction of the sediment will vary with the density of the mineral, as well as the amount of organic material, which has a lower density. We were able to obtain ranges of values from surveys of sediments from drilling samples, (http://www-odp.tamu.edu/publications/188_IR/chap_04/c4_) with an average value of 2.70 g/cm^3, with a range of 2.60-2.75 g/cm^3. Marine Geochemistry, (2. ed. 2006) states typical grain densities as being 2.65 g/cm^3 for calcareous sediment ($CaCO_3$-rich) (bioclastic sediments), 2.75 g/cm^3 for terrigenous (formed by land erosion) (siliclastic) and 2.1 g/cm^3 for diatomaceous sediments (sediments formed by algal matter). A range between 1.8 g/cm^3 and 2.8 g/cm^3 is tested deterministically in the Excel-model, keeping the other parameters constant. These three types of sediments may have grain sizes from fine to coarse. The value for diatomaceous sediments is conservatively but realistically chosen as the value for when dry density is held constant to test other parameters (2.1 g/cm^3). It is important to note that the lower density of a diatomaceous sediment is not only due to a higher organic carbon content, but also due to the lower density of biogenous silica.

3.3.2 Result of the value range sensitivity testing for dry density

Holding mixing depth constant at 5.75 cm (global mean, Teal *et al.* 2008) and the water content fraction constant at 0.25, the $C_{THC,sed}$ (THC-concentration in sediment) variation with the dry density is shown in Figure 10 for a wider range of test values, and in Figure 11 for values between diatomaceous and terrigenous sediment types. The results show that the value of 2.75 g/cm^3 results in a $C_{THC,sed}$ -concentration which is 75 % of the $C_{THC,sed}$ at 2.1 g/cm^3 dry density. If specific values are not found and used, a conservative value of DryWeight at 2.1 g/cm^3 can be used and is expected to be realistically conservative, especially in deeper waters where a more muddy sediment may be expected. The value is entered as kg/m^2 in the model.

Based on the literature values and testing, the densities recommended for the substrates are: 2.1 g/cm^3 for mud and sandy mud, 2.65 g/cm^3 for bioclastic sand, which is a little lighter than sand and coarse sands at 2.7 g/cm^3 .

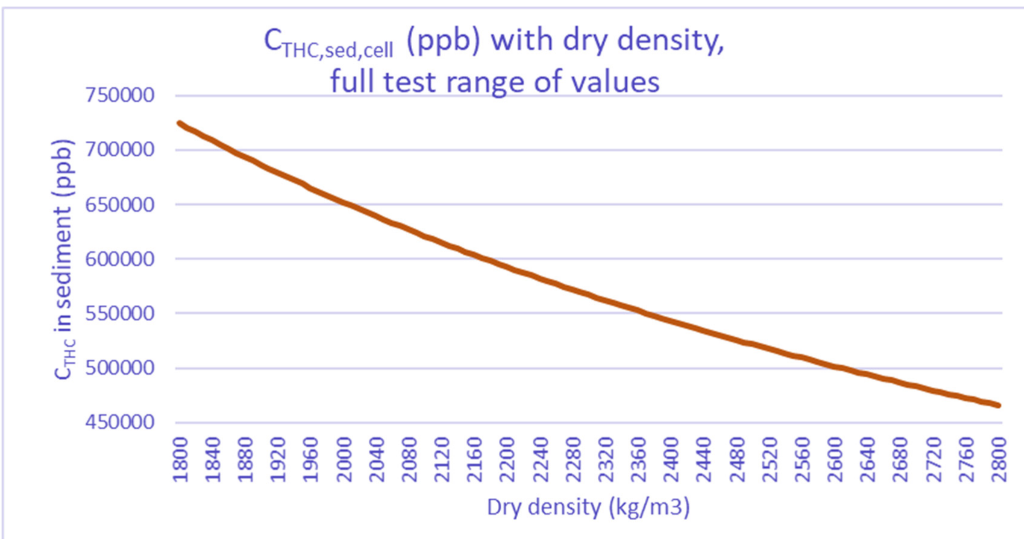

Figure 10. Variation in C_{THC} with dry density in kg/m^3 , values varying in the experimental range.

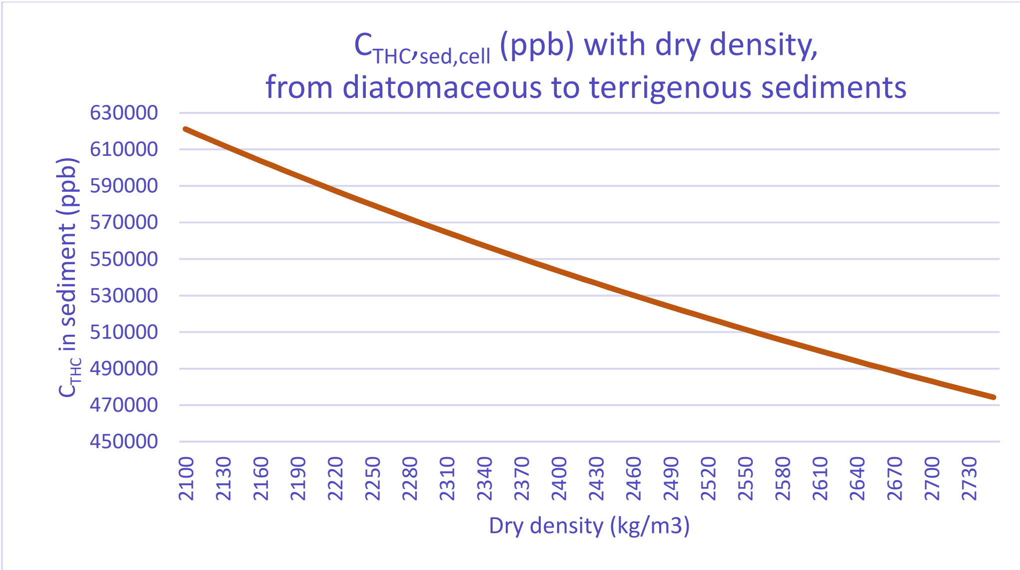

Figure 11. Variation in $C_{THC,sed}$ with dry density in kg/m^3, values varying in the range found relevant for marine sediments (2.1-2.75 g/cm^3).

3.4 Test 1c Water content

Benthic fauna may actively transport bottom water through their habitats, a process which is known as bioirrigation. Interstitial water (IW) fills the void spaces between particles, and the porosity of the sediment depends on wet bulk density of the sediment as well as the wet water content as in the function:

Wet-water content (%) = porosity (%)/wet-bulk density (g/cm^3)

3.4.1 Choosing the range of Water Content values

Water content ranges vary between 20-90 % in the tests performed on the calculation formula. When held constant to test the other parameters, a value of 25 % is chosen, as a conservative choice, although bioirrigation is expected to be higher in the upper sediment (bioturbated layers) than in lower, more compacted layers. For the substrate types described in the Mareano database, the water contents vary between 25 and 65 % (Table 5). The $C_{THC,sed}$ -values when the water content is 65% (mud) is 47 % of what it is when the water content is 25% (e.g. sand).

3.4.2 Result of the value range sensitivity testing for water content

As expected from the formula, the lower the water content, the higher the concentration. The dry density was held constant at 2.1 g/cm^3 and mixing depth was 0.0575 m for the sensitivity test of the formula, and the initial input sediment THC-concentration (Sd_Mass from OSCAR) 0.1 kg/m^2. The results of the deterministic tests show that the choice of water content significantly influences the $C_{THC,sed}$ value, and it is therefore recommended to use a substrate-specific water content value, using a lower concentration conservatively if a range of values are found for the substrate in question.

Following literature searches and testing, the values of water content were set at 25 % for bioclastic coarse sand and coarse sand, 30 % for sand, 50 % for sandy mud and 65 % for mud.

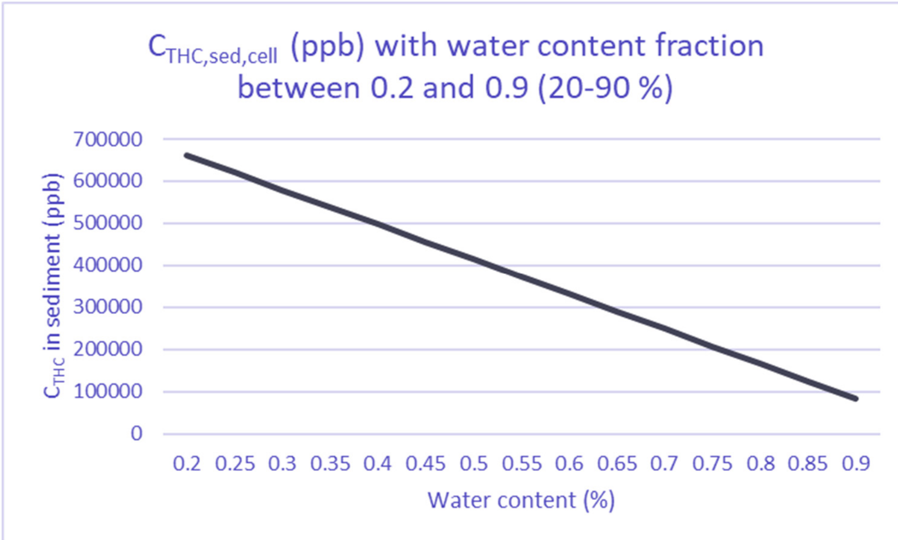

Figure 12. Variation in $C_{THC,sed}$-values in sediment with varying water content – full range of tested values (%).

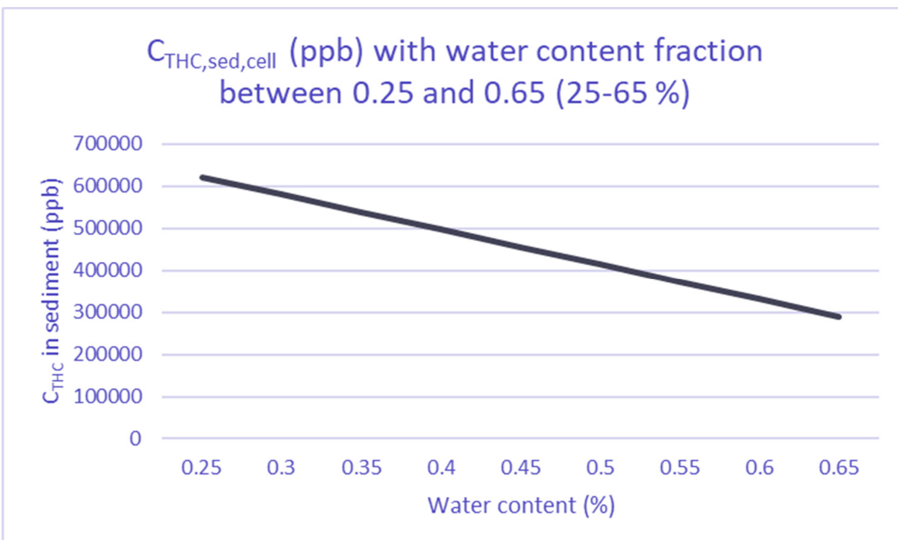

Figure 13. Variation in $C_{THC,sed}$-values in sediment with water content varying between that of sand (25%) and mud (65%).

4 Test 2: EqP parameters: Total carbon content in sediment (TOC = f_{OC})

Test 2 studies the sensitivity of the parameters related to partitioning of THC between carbon-rich sediment particles and water phase(s), used in the Equilibrium Partitioning (EqP)-based calculations. Total organic carbon (TOC) in the sediment is used together with hydrocarbon content in the sediment ($C_{THC,sed}$) (the refined HC-content in sediment as described above) and the organic carbon water partition coefficient (K_{OC}) to derive the interstitial (pore) water concentrations ($C_{THC,IW}$) of oil for the toxicity calculation in the second step of the modelling. In this calculation, the TOC concentration or fraction (foc) is used to derive the p_{let} values (p_{let}WC) from a Species Sensitivity Distribution (SSD) curve for organisms exposed only by interstitial (pore) water. The K_{OC} value used in the equation is derived from octanol-water partitioning coefficient (K_{OW}) (see Test 3).

TOC and K_{OW} both influence this formula significantly after the initial sediment concentration ($C_{THC,sed}$) has been calculated in the previous step (tested in tests 1a-c).

Globally, TOC values range from 0.01 % to more than 10 % TOC in a few cases near shore and where upwelling is intense (Marine Geochemistry, 2. ed. 2006). Typical hemipelagic sediments on outer shelves and continental slopes range between 0.3 and 1 % TOC. The total organic carbon content (TOC from LECO combustion) varies from 0.2 to 2.74 wt % for the whole investigated area in a study for MAREANO (Barents Sea) (Knies *et al.,* 2006). In the Gulf of Mexico, Escobar-Briones and Garcia-Villalobos (2009) found an average of 0.9 % TOC+- 0.3 % and cite Seiter *et al.* (2004), that at the global scale, the storage of organic matter as TOC mirrors the distribution pattern of phytoplankton biomass. This could be particularly important in areas with high biological production.

Test 2 is also run with the Microsoft Excel ERA Acute Calculator, which was used for analyses of the following:

1) Endpoints of concentration in interstitial water, ($C_{THC,IW}$) (= THC_{IW})

2) Lethality calculations $plet_{IW}$

Test 2 serves to provide information on:

1. Reference values for typical substrates as basis for the guideline and best practise documents
2. Are “default” or recommended values possible for various substrates?
3. Is it worth the effort to gather real TOC values for input to ERA Acute?
4. Getting to know the model
    a. Information about the calculation step, calculation of $C_{THC,IW}$ and subsequent p_{let}
    b. Information about how variation in input parameter affects model results

The calculation step to be tested is:

Equation 2

$$C_{THC,IW,cell,sim} = C_{THCsed,cell,sim} /(foc \times Koc)$$

Equation 3

$$Log_{10}KOC = 0.00028 + 0.983 \times (Log_{10} K_{OW})$$

Equation 4

Foc = TOC (approximation)

4.1 K_{OW} value for testing

SINTEF have calculated an expected representative value of Kow at 891994.66 ($LogK_{OW}$=5.95), based on the K_{OW} values of hydrocarbons typically associated with (i.e. with affinity to) sediments in OSCAR simulations (Ute Brönner, *pers. comm.* 2017). The assessment is made based on the chemical properties of the groups of “pseudo-components” in the database of crude oil types available for OSCAR, using a single simulation and the fractions between the pseudo-component groups to calculate the expected “weighted” K_{OW}.

4.2 Total Organic Carbon (TOC) vs. Total Organic Matter (TOM)

Total organic matter has been measured for all stations in the MOD database in the more recent years, while fewer TOC-measurements are available. TOM increases with the amount of pelite (silt/clay) in the substrate (Trannum *et al.,* 2006).

Schumacher (2002) states that: "a conversion factor of 1.724 has been used to convert organic matter to organic carbon *in terrestrial soils*, based on the assumption that organic matter contains 58% organic carbon", citing Nelson and Sommers (1996). For *marine sediments*, the factor varies from sediment to sediment, depending upon the type of organic matter present in the sample. Conversion factors range from 1.724 to as high as 2.5 (Nelson and Sommers, 1996; Soil Survey Laboratory Methods Manual, 1992). Schumacher also cites Broadbent (1953), that recommended the use of 1.9 and 2.5 to convert organic matter to total organic carbon for surface and subsurface (terrestrial) *soils*, respectively.

Searching the MOD database (May 2017), we compared the TOC values from the few samples of measurements of TOC in substrates classified by grain size and pelite content, with the TOM-values from the far more abundant and more recent samples. The number of samples were not enough to derive a conversion factor for each of the substrate types. Based on all samples of all substrate types, a TOM/TOC conversion factor of 3.27 was estimated for the samples in the MOD database. This is higher than found for terrestrial soils in the above cited work. Using a lower conversion factor would lower the TOC-estimate in the sediment type and increase bioavailable $C_{THC,IW}$ and thereby also the *plet*. However, it is important to remember that although we may be erring on the less conservative side using a higher conversion factor (although based on limited MOD data) the sedimentation of oil is through deposits of carbon-rich material in many cases, as well as by direct plume encounter. How much $C_{THC,IW}$ is increased with lowered TOC can be seen from the individual tests below, holding other parameters constant.

Carbon/nitrogen (C/N)-ratios vary with the source of the organic matter; C/N ratios of phytoplankton and zooplankton are around 6, freshly deposited marine organic matter ranges around 10, whereas terrigenous organic matter has C/N ratios of 20 and above (Marine Geochemistry, 2. ed. 2006). Based on the findings in the MOD data base, the average TOC and estimated TOC-values were as given in Table 5 below. This table also gives the values found for other substrates for which there are data for in the Mareano database, that are used as reference values for VEC-data for the Norwegian Sea case study later in this document (section 8.4).

The factor TOC has high uncertainty, and great variation between sediment sampling sites. This is discussed in section 6.

4.3 Static parameters in the test of TOC-sensitivity

Testing TOC-sensitivity values using a range was carried out individually for the substrate types: Mud, coarse sand, bioclastic coarse sand, and (finer and higher TOC average than coarse sand), and sandy mud, using different and substrate-specific parameters for the static values as given in Table 5, which contain values based on literature search (see also section 8.4).

For the purpose of testing the effect that varying TOC-values has on the THC_{IW}-values and the corresponding p_{let}, the BDepth was held constant at 0.0575 m for all substrates for the initial testing. The effect of mixing depth on $C_{THC,sed}$ (and thereby on the $C_{THC,IW}$ -values and corresponding p_{let}-values) was tested when going back and testing the effect of BDepth again using substrate-specific values. Although actual mixing depths will differ between the different substrates, especially dependent on grain size, and with a smaller mixing depth with finer grain size (Section 3.2.1), no quantifiable relationship was found in the limited literature search. For finer-grained substrates, a smaller mixing depth value would be recommended as a conservative approach.

The K_{OW} was held constant at 891994.7 ($LogK_{OW}$=5.95). The other constant values are, as mentioned, different for each substrate type.

Table 5. Summary of the VEC data parameters applied in the Norwegian Sea data set adapted from Mareano substrate data. The compilation of substrate types uses Mareano sediment groups and grouping with fractions of silt/clay (~pelite), sand and/or gravel (Mareano), with TOC-values estimated from TOM/TOC-ratio in the MOD database, dry densities and water contents. (ND= No Data)

English term for Mareano data	VEC name	Fraction silt:clay	Fraction Sand	Fraction gravel	TOC (%)	DryDens	Water C	BDepth	Algorithm
Biological material	Bioclastic coarse sand	ND	ND	ND	0.4	2650	0.25	0.05	SOFT
Sand with gravel	Coarse sand	0-0.1	0.9-1	0.02-0.3	0.4	2750	0.25	0.05	SOFT
Muddy, sandy gravel	Coarse sand	0-0.1	0.2-0.7	0.3-0.8	0.4	2750	0.25	0.05	SOFT
Sandy gravel	Coarse sand	0-0.1	0.2-0.7	0.3-0.8	0.4	2750	0.25	0.05	SOFT
Sand, gravel and stones	Coarse sand				0.4	2750	0.25	0.05	SOFT
Sand	Sand	0-0.1	0.9-1	0-0.02	1	2750	0.3	0.02	SOFT
Sandy mud	Sandy mud	0.5-1	0-0.5	0-0.02	1.2	2100	0.5	0.01	SOFT
Muddy sand	Sandy mud	0-0.5	0.5-1	0-0.02	1.2	2100	0.5	0.01	SOFT
Gravel-containing muddy sand Gravel-containing sandy mud	Sandy mud	0.1-0.5	0.5-0.9	0.02-0.3	1.2	2100	0.5	0.01	SOFT
Mud	Mud	0.9-1	0-0.1	0-0.02	2.4	2100	0.65	0.005	SOFT
Thin, discontinuous layer of sediment on rock	Hard substrate							N/A	HARD
Bare rock	Hard substrate							N/A	HARD
Gravel, stones and boulders	Hard substrate							N/A	HARD
Hard sediments (sedimentary rock)	Hard substrate							N/A	HARD

4.4 Results and graphs for the different substrate types- TOC

4.4.1 Overall variation with TOC

The variation of $C_{THC,IW}$ -values with TOC between 0.4 % (typical for sand) and 2.4 % (typical for mud) is shown in Figure 14, using a water content value of 0.65 (65%), dry density of 2100 g/cm^3, mixing depth of 0.0575 m and a starting value of 0.1 kg/m^2 $C_{THC,sed}$ in sediment (proxy from "ODS").

The ERA Acute project is carried out by a consortium of industry partners (Statoil, Total, Norwegian Oil and Gas Association) and experts in environmental risk analysis (Acona, Akvaplan-niva (Project Manager), DNV-GL and SINTEF), supported also by the Research Council of Norway.

ERA Acute is developed to provide a globally applicable, transparent method for quantitative environmental risk assessment of oil spills in four compartments: Sea surface, shoreline, water column and sea floor.

4.4.2 Substrate mud

In this case (Figure 14), the typical TOC of 2.4 % for mud would result in a lower rate of THC leaching into the interstitial water, and thereby lower $C_{THC,IW}$ (Figure 14) and corresponding toxicity (Figure 15).

As the substrate mud, with its higher content of finer particles, is a candidate for searching for more specific mixing depths (expected to be less deep), the sensitivity test was repeated. This time, fixed values relevant for mud were used; Water content: 0.65, dry density: 2100 g/cm^3, and TOC: 2.4 % and the mixing depth was varied between 0.001 and 0.0575 m. As in all tests, the starting value of oil contamination was $C_{THC,sed}$ = 0.1 kg/m^2 in sediment. As can be seen from Figure 16 and Figure 17, using specific TOC-values and mixing depths are important to calculations of lethal effects.

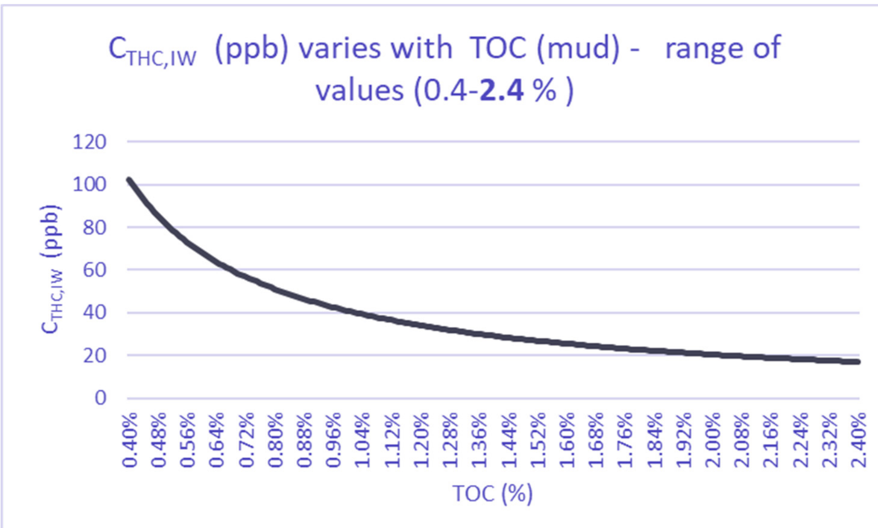

Figure 14. The variation of $C_{THC,IW}$ with TOC when water content and dry density are typical for mud, and mixing depth and K_{OW} are held constant. Mud has a typical TOC concentration of 2.4 % (MOD database) leading to a $C_{THC,IW}$ of <20 ppb when the starting value is $C_{THC,sed}$= 0.1 kg/m^2 in sediment.

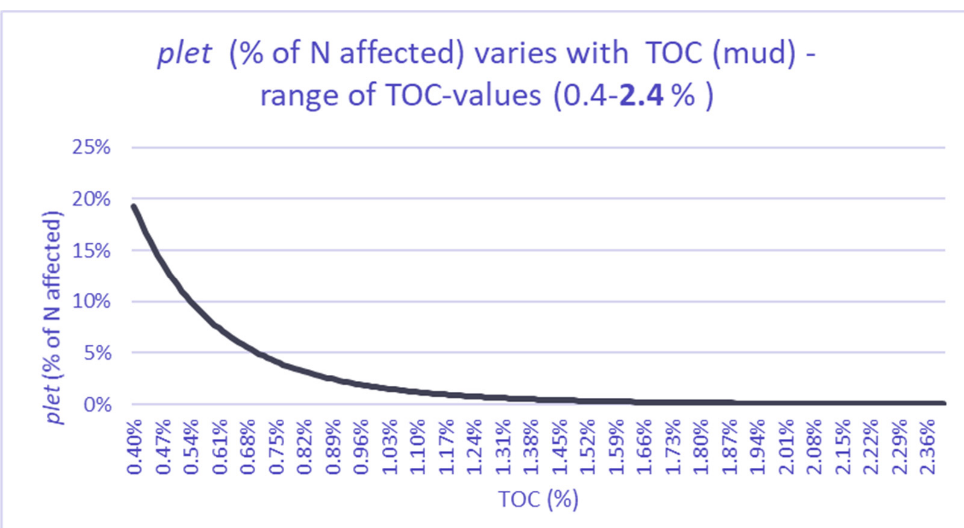

Figure 15. The variation of p_{let} with TOC when water content and dry density are typical for mud, and mixing depth and KOW are held constant. Mud has a typical TOC concentration of 2.4 % (MOD database) leading to a p_{let} = 0.045 % lethality to resources in the cell.

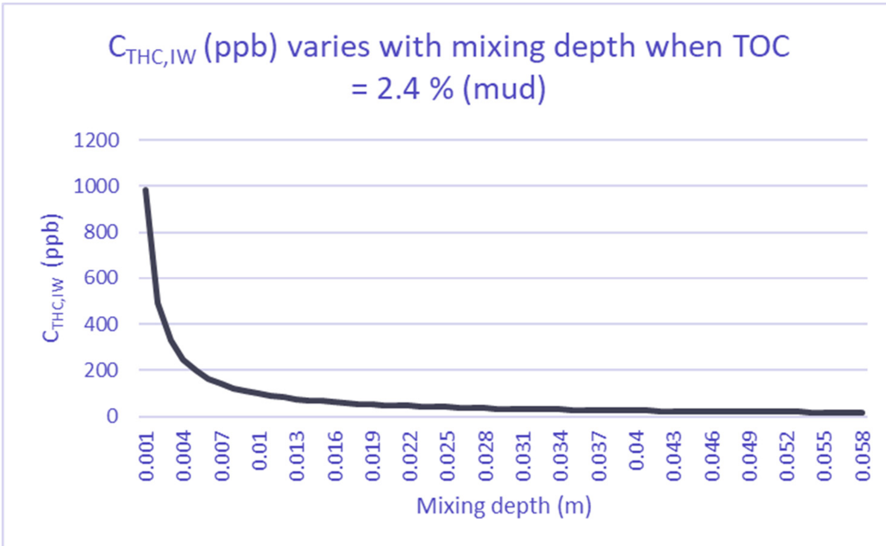

Figure 16. The variation of $C_{THC,IW}$ (ppb) with mixing depth (re-test when TOC, water content and dry density are typical for mud, and K_{OW} is held constant).

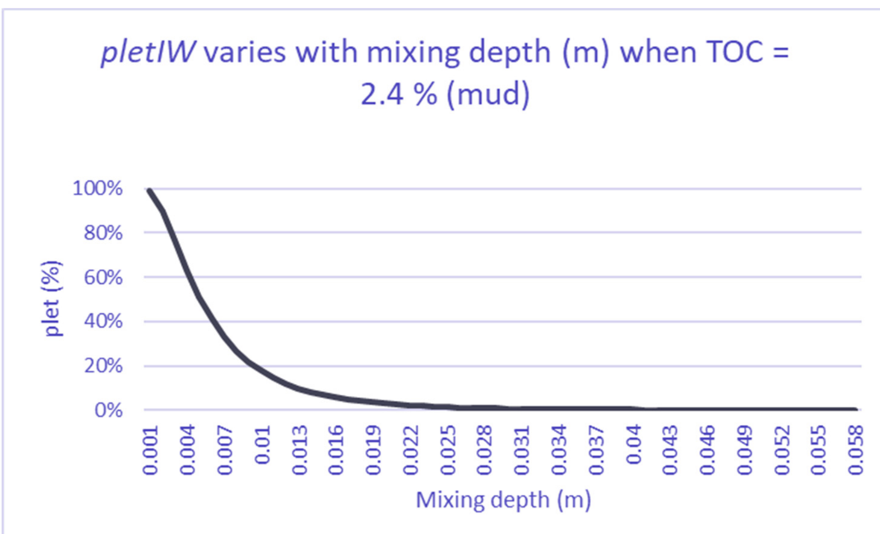

Figure 17. The variation of p_{let} with mixing depth when TOC, water content and dry density are typical for mud, and K_{OW} is held constant. Mixing depth is important for calculation of lethal effect.

4.4.3 Substrates sand, coarse sand and bioclastic coarse sand

These three substrates are fairly similar with respect to water content, a finer sand is found to have slightly more interstitial water (30 % is used), the coarser grains somewhat less (25 % is used), noting that all values are variable and in ranges. Dry weight of the grains is relatively high, we use 2750 g/l (2.75 g/cm^3) for sand and coarse sand, bioclastic sands are slightly less dense (2.65 g/cm^3). The main difference between them is that the TOC-content is usually higher when the current conditions allow for a smaller particle size, i.e. finer sand was found to average at 1 % TOC, the coarser sand and bioclastic sand have 0.4 % in our tests (testing and results for finer sand is described in the next section). A lower TOC leads to a higher proportion of THC in the interstitial water, and thereby higher toxicity when other factors are held constant. In the tests of variation with TOC, the mixing depth was held constant at the global mean 5.75 cm, whereas in the repeated test with substrate-typical TOC, the mixing depth was varied. The results of $C_{THC,IW}$ in coarse sand with the variation of TOC (other parameters held constant for coarse sand), is shown in Figure 18, corresponding lethality is shown in Figure 19. Coarse sand values are 0.4 % giving a $C_{THC,IW}$ of 167 ppb. The similarity between coarse sand and bioclastic coarse sand is high, in our setup, only the density differentiates them. It should be noted, however, that this is a simplification. Figure 20 and Figure 21 show that as expected, the small difference in grain dry weight density does not lead to a large difference in IW-concentrations of oil, or corresponding toxicity. When in doubt, the user would be conservative to choose the lower density.

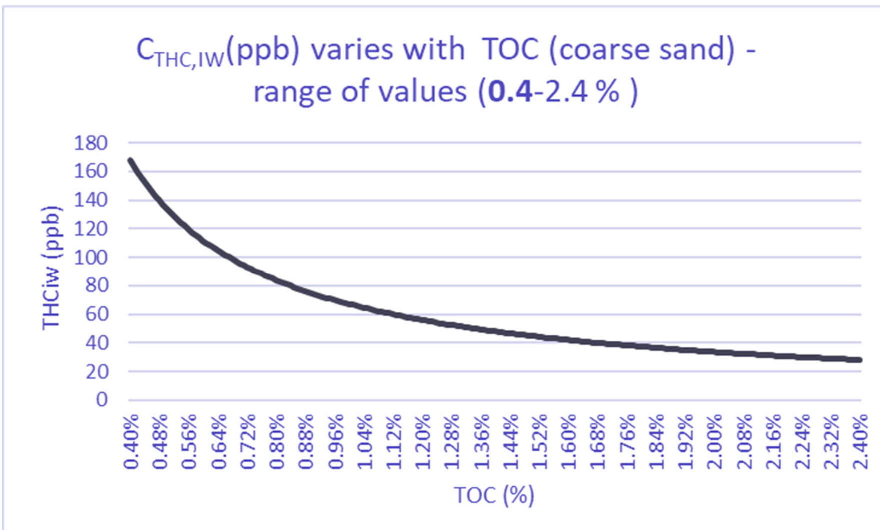

Figure 18. The variation of $C_{THC,IW}$ with TOC when water content and dry density are typical for coarse sand, and mixing depth and K_{OW} are held constant. Coarse sand has a typical TOC concentration of 0.4 % (MOD database) leading to a $C_{THC,IW}$ of 167 ppb when the starting value is 0.1 kg/m^2 THC in sediment.

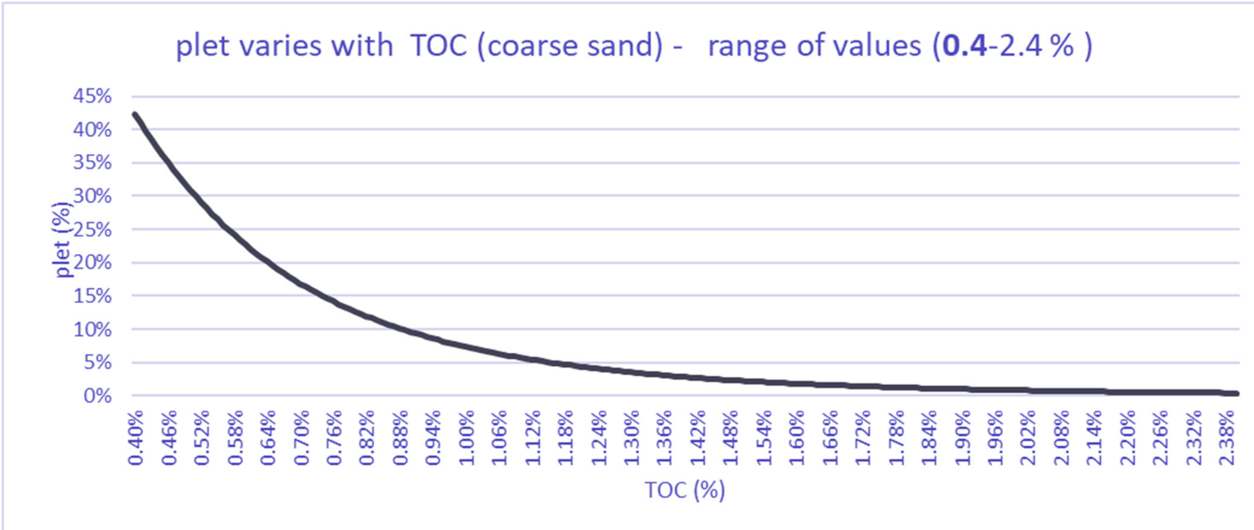

Figure 19. The variation of p_{let} with TOC when water content and dry density are typical for coarse sand, and mixing depth and K_{OW} are held constant. Coarse sand has a typical TOC concentration of 0.4 % (MOD database) leading to a p_{let} of 42 % lethality to resources in the cell.

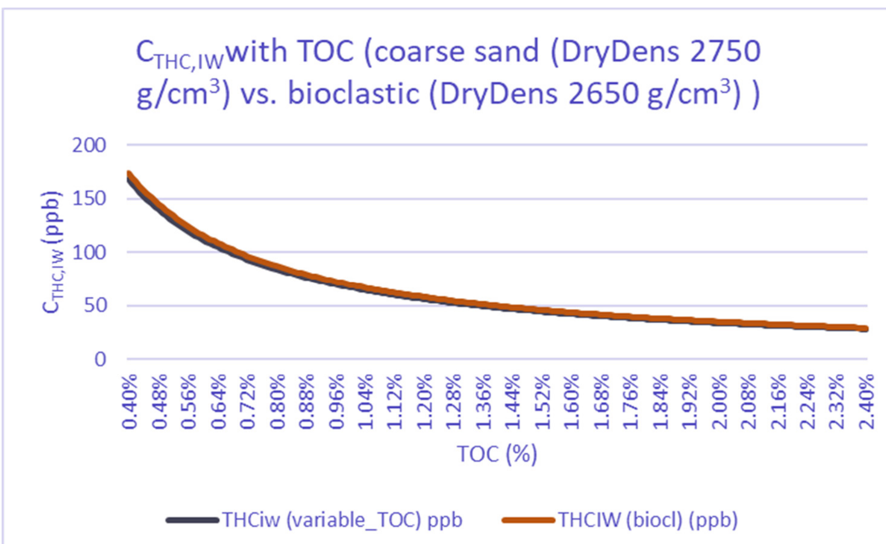

Figure 20. Comparison between coarse sand and bioclastic coarse sand, the only difference is the small difference in dry weight. Mixing depth and K_{OW} are held constant, TOC concentration is 0.4 % (MOD database) for both, water content 25 %. The difference is small, leading to a slightly higher $C_{THC,IW}$ for the lighter dry weight.

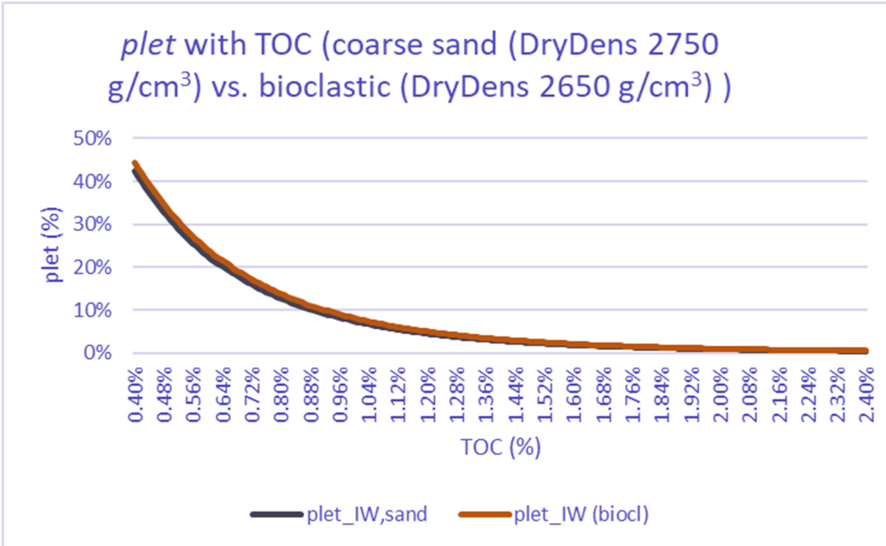

Figure 21. Comparison between coarse sand and bioclastic coarse sand with respect to lethality, the only difference is the small difference in dry weight. Mixing depth and K_{OW} are held constant, TOC concentration is 0.4 % (MOD database) for both, water content 25 %. The difference is small, leading to a slightly higher toxicity for the lighter dry weight.

Holding the TOC constant at the relevant values for coarse sand (and bioclastic) (0.4 %), the effect of variation in mixing depth on $C_{THC,IW}$ (Figure 22) and $p_{let,IW}$ (Figure 23) was tested again (1mm-15 cm). Mixing depths in sand substrates are usually higher in sandy substrates than in muddy substrates. A global mean of 0.0575m is considered sufficiently conservative, noting that the concentration of oil in the sediment in these tests are high and N=1 for the cell.

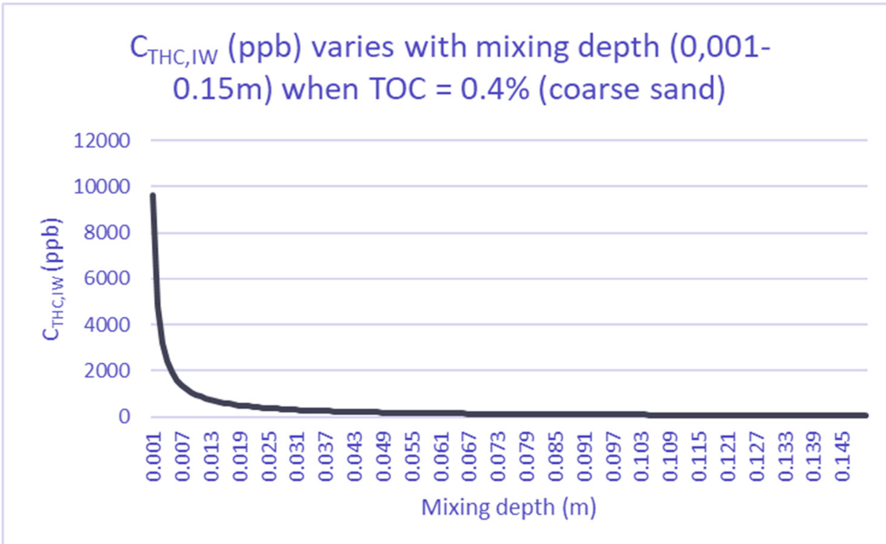

Figure 22. The variation of $C_{THC,IW}$ (ppb) with mixing depth (re-test when TOC, water content and dry density are typical for coarse sand, and K_{OW} is held constant).

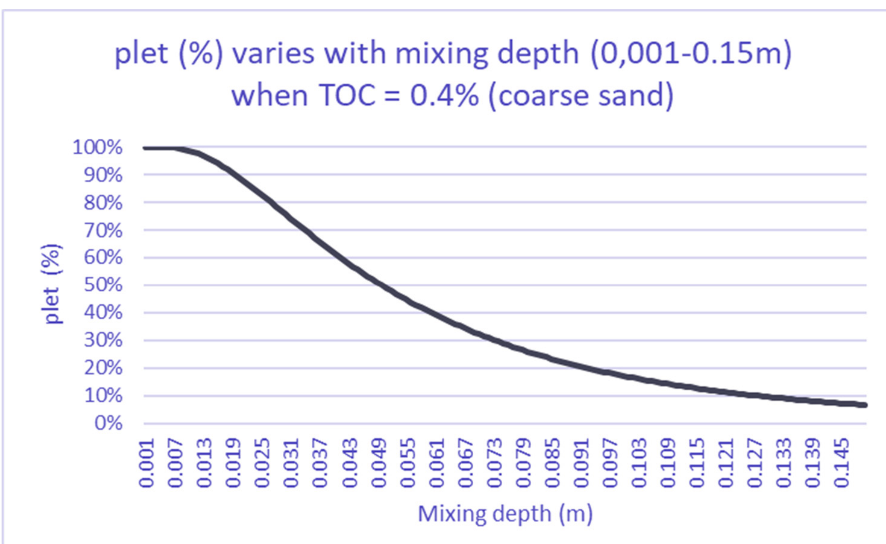

Figure 23. The variation of $plet_{IW}$ (% lethality) with mixing depth (re-test when TOC, water content and dry density are typical for coarse sand, and K_{OW} is held constant).

4.4.4 Substrate sand

Finer sand usually has a higher TOC than coarser sand and a water content of 30 %. Concentration of $C_{THC,IW}$ with varying TOC is shown in Figure 24 and lethality $plet_{IW}$ in Figure 25, when other factors are held constant and relevant for sand (Dry density 2.75 g/cm3). Water content is 30 %, mixing depth 5.75 cm, and oil amount in sediment is 0.1 kg/m^2. The red dot shows the point where TOC is 1 % which is an approximated relevant value for sand. Holding TOC constant at 1 % and investigating the variation of mixing depth with all other parameters held constant at sand-relevant values, it can be seen that $C_{THC,IW}$ (Figure 26) and corresponding $plet_{IW}$-value (Figure 27) vary greatly with mixing depth as expected, smaller depths by design leading to higher concentrations and lethality. Using a global mean value of 0.0575 m is less conservative for sands with a higher TOC-content than for coarser sands with a lower TOC-content.

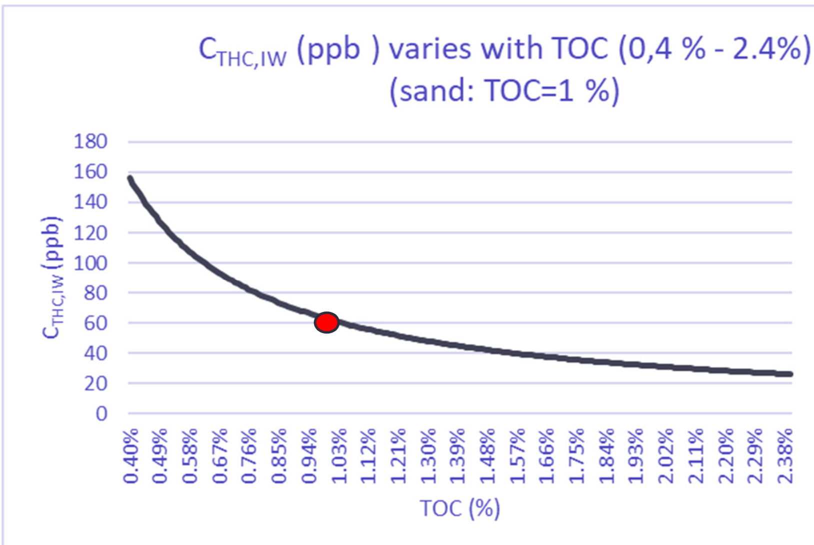

Figure 24. The variation of $C_{THC,IW}$ with TOC when water content and dry density are typical for sand, and mixing depth and K_{OW} are held constant. Sand has a typical TOC concentration of 1 % (MOD database) leading to a $C_{THC,IW}$ of 63 ppb when the starting value is 0.1 kg/m^2 THC in sediment.

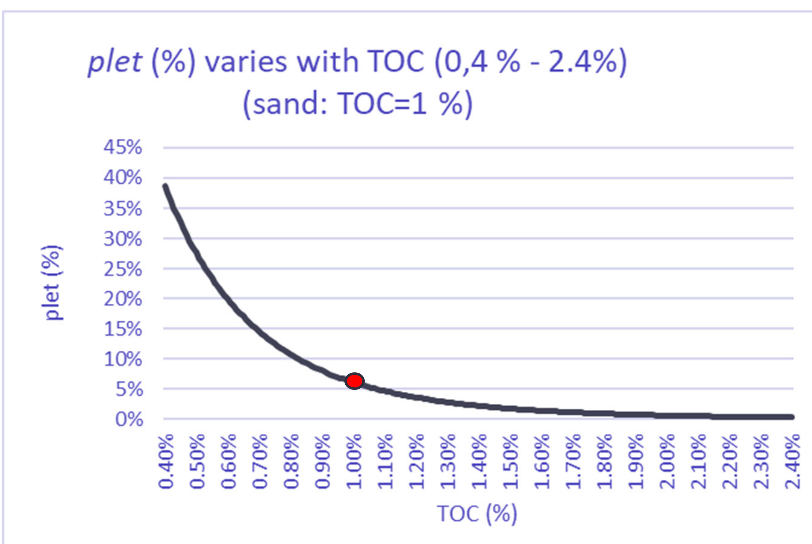

Figure 25. The variation of *plet*$_{IW}$ with TOC when water content and dry density are typical for sand, and mixing depth and K_{OW} are held constant. Sand has a typical TOC concentration of 1 % (MOD database) leading to a *plet*$_{IW}$ of 6,1 % when the starting value is $C_{THC,sed}$ =0.1 kg/m^2 in sediment.

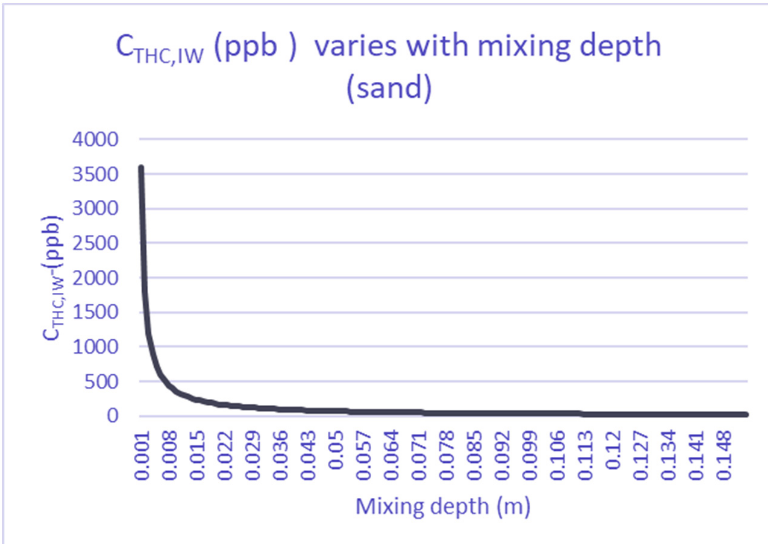

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Figure 26. The variation of $C_{THC,IW}$ (ppb) with mixing depth (re-test when TOC, water content and dry density are typical for sand, and K_{OW} is held constant).

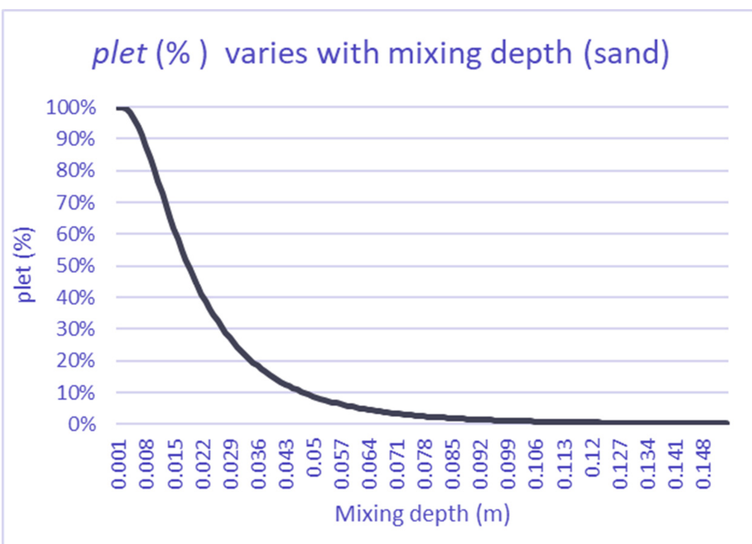


Figure 27. The variation of *plet*$_{IW}$ (% lethality) with mixing depth (re-test when TOC, water content and dry density are typical for coarse sand, and K_{OW} is held constant).

4.4.5 Substrate muddy sand

In areas with less currents, sandy and gravelly substrates may collect more organic matter and finer particles. Collating the results of the literature studies and MOD database entries, it was found that relevant values for the gravels and sands with a significant proportion of mud would be ascribed the following relevant parameters: TOC: 1.2 % Dry Density 2.1 g/cm^3 and 50 % water content, i.e.

parameters between mud and sand. $C_{THC,IW}$ variation with the TOC-content, when the latter is varied between typical values for sand (0.4 %) and mud (2.4 %), is shown in Figure 28, and the corresponding variation in $plet_{IW}$ is shown in Figure 29.

How $C_{THC,IW}$ varies with the mixing depth with typical sandy mud parameters is shown in Figure 30, and corresponding $plet_{IW}$-values in Figure 31. The latter figure which shows that at high values of THC in the sediment in a cell, if the bioturbation depths are lower than the global mean found by Teal *et al.* (1988), lethality could be significant. Finding specific values of bioturbation depths increases accuracy.

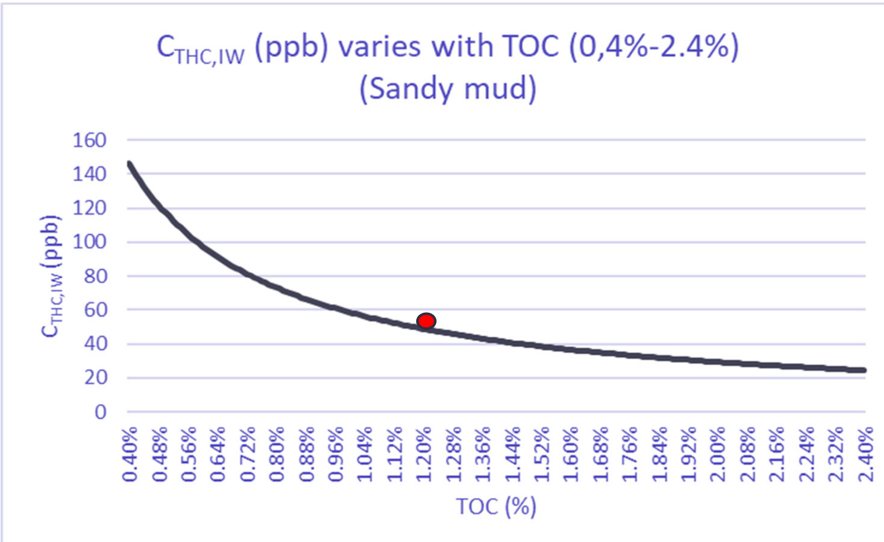


Figure 28. The variation of $C_{THC,IW}$ with TOC when water content and dry density are typical for muddy sand, and mixing depth and K_{OW} are held constant. Muddy sand has a typical TOC concentration of 1.2 % (red dot) (MOD database) leading to a $C_{THC,IW}$ of 49 ppb when the starting value is $C_{THC,sed}$ =0.1 kg/m^2 in sediment.

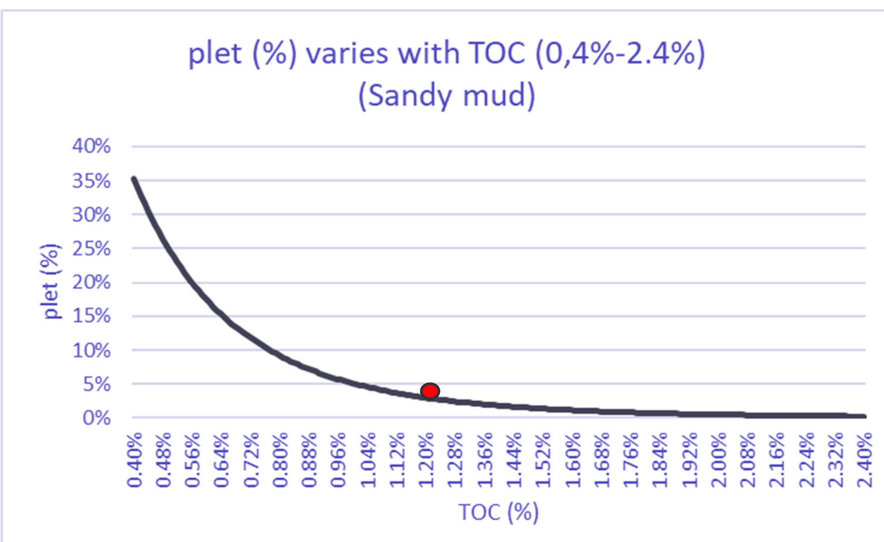


Figure 29. The variation of *plet*$_{IW}$ (%) with TOC when water content and dry density are typical for muddy sand, and mixing depth and K_{OW} are held constant. Muddy sand has a typical TOC concentration of 1.2 % (red dot) (MOD database) leading to a *plet*$_{IW}$ of 3 % when the starting value is $C_{THC,sed}$ =0.1 kg/m^2 in sediment.

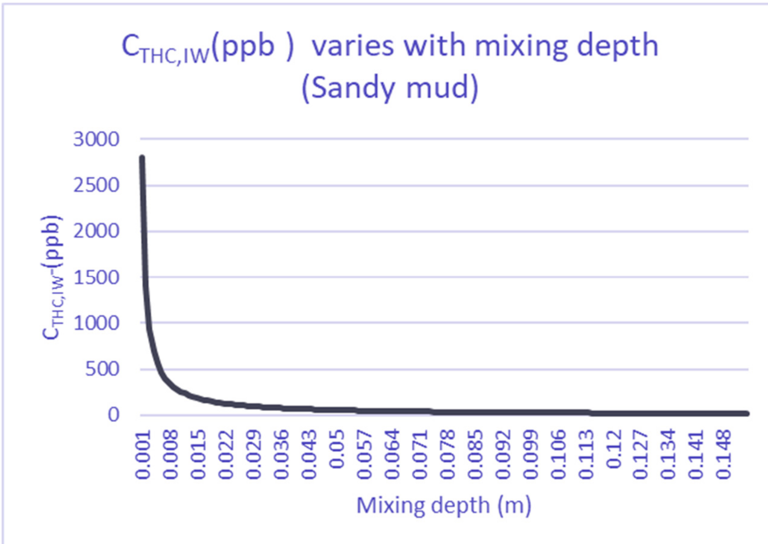


Figure 30. The variation of $C_{THC,IW}$ (ppb) with mixing depth (re-test when TOC, water content and dry density are typical for sandy mud, and K_{OW} is held constant).

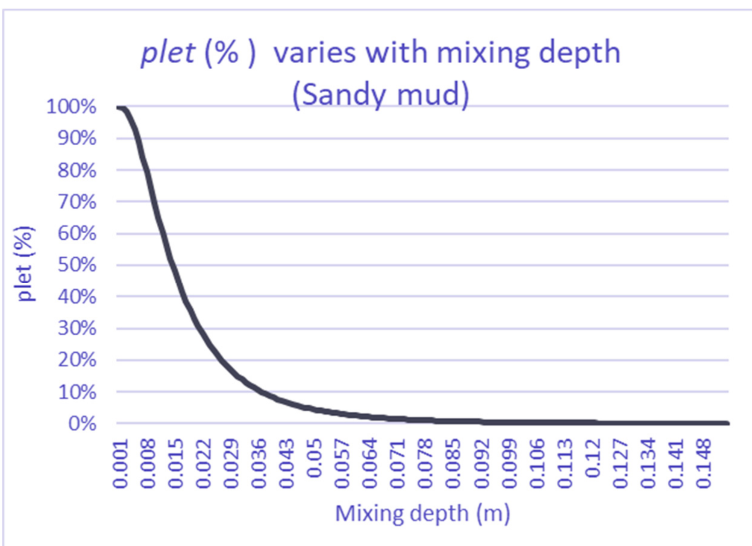


Figure 31. The variation of *plet*$_{IW}$ (%) with mixing depth (re-test when TOC, water content and dry density are typical for sandy mud, and K_{OW} is held constant).

4.5 Most conservative values of the substrate-specific values

As a form of positive control, calculations using the most conservative set of values (regardless of substrate type) has been used as a proxy for all substrate types, calculating the effect on plet$_{IW}$-values, using variation of input sediment THC from oil drift and a constant K_{OW}. The most conservative values are BDepth 0.005m (mud), DryDens 2100 kg/m^3 (mud), Water content of 25 %

(coarse sands). The input value of oil amount in the sediment is varied between 0.001 kg/m^2 which is a relevant value from oil drift simulations (see Table 3) and 0.15 kg/m^2, which is a very high value, but not unrealistic (section 2.2). The results are shown in Figure 32. This combination of input values is not realistic, but the test serves to show that the lethality approaches 100 % at 0.04 kg/m^2.

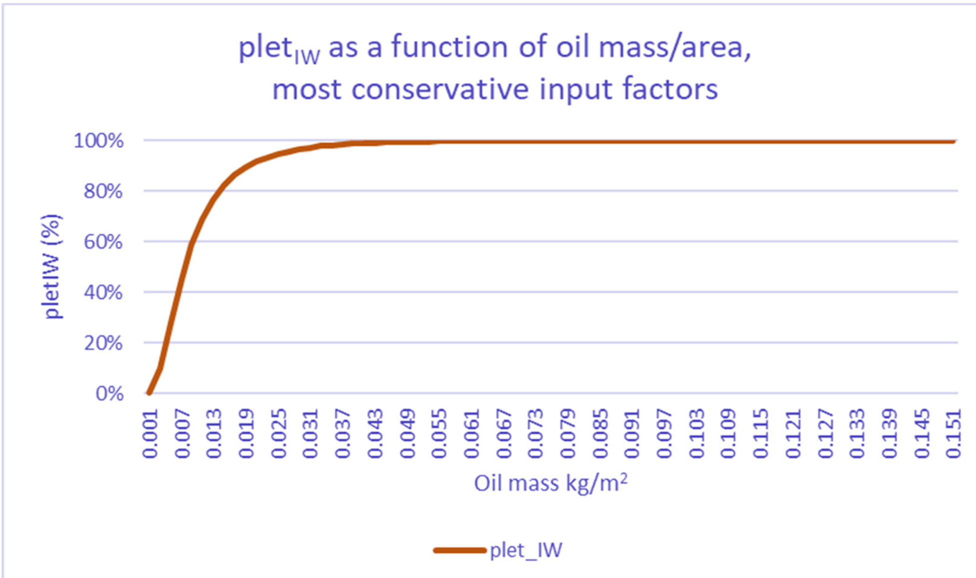


Figure 32. pletIW as a function of oil mass/area given use of the most conservative values to the EqP-functions, regardless of substrate.

5 Test 3 – EqP parameters: K_{OW}

5.1 Octanol-water partitioning coefficient and pseudo-components in OSCAR

By physical chemistry definition, the octanol-water partitioning coefficient (K_{OW}) defines the affinity of a chemical substance to organic carbon or water, I.e. whether it is (predominantly) hydrophobic or hydrophilic. How much organic carbon (TOC) there is in the sediment also determines how much substance the sediment can hold (see previous chapters). K_{OW} is almost the same as the K_{OC}, i.e. the partitioning of an organic substance between organic carbon in the sediment and water surrounding the sediment particle. K_{OW} and thereby K_{OC} are unique for each organic component and different crude oils will have different mean K_{OW} values depending on the composition of the crude. Regional differences could potentially influence model results. E.g. ambient sea temperature influences by default the reaction rate of all chemical processes towards equilibrium. Colder temperatures will change the rate of partitioning between THC adhered to the organic carbon fraction of the sediment and THC in pore water. When K_{OW} changes, interstitial water concentration and thereby potential toxicity changes with it. This variability is tested by a simple test of the variation with varying K_{OW} (Test 3), and the importance of KOW is tested in the stochastic tests (section 6).

Oil drift models use K_{OW} as an important factor in determining the partitioning between the compartments, and importantly for this work – the amount of the oil and the nature of the components that reaches the sediment. Compounds with a high water solubility will not reach the sediment in the first place, heavier and hydrophobic compounds will dominate the fractions present in the sediment. So, by the time the oil has reached the sediment, not all ranges of K_{OW} are relevant to the equation. In Phase 3 of the project, SINTEF carried out a study of the most relevant values of K_{OW} based on the K_{OW} mean values of the pseudocomponent groups that were most likely to reach the sediment. Based on this, by calculating the component-averaged value from the sediment grid from a single simulation, SINTEF recommended a K_{OW} value of 891994.66 (Log K_{OW} = 5.95) to be used as a general default value for testing of the calculator, and as a relevant input factor for use in analyses.

Using a specific KOW value based on the actual fractions of the various pseudocomponent-groups would lead to reduction in uncertainty of this input value. How much the impact varies with K_{OW} is the endpoint of test No. 3.

Pseudo-components are grouped based on molecular weight ranges and similar chemical properties, relevant to their distribution, fate and weathering properties, and K_{OW} is one of these factors that could be similar between chemicals in groups. Using OSCAR as an example, which pseudo-component groups that are actually present in the sediment after a simulation in OSCAR can be viewed in the layer "sediment" (Figure 33). However, pseudo-components generalisations. The actual chemical compounds within the pseudo-component group that are in the sediment after a simulation, are not known to the general user. Using OSCAR, finding the exact mean K_{OW} values based on the in-going components and their relative contribution is not expected to be a viable option for ERA Acute users. The value may be changed if using oil drift models that calculate a mean KOW value of the components present in the sediment. Note also that the groups contain both saturated and aromatic compounds with similar molecular weights.

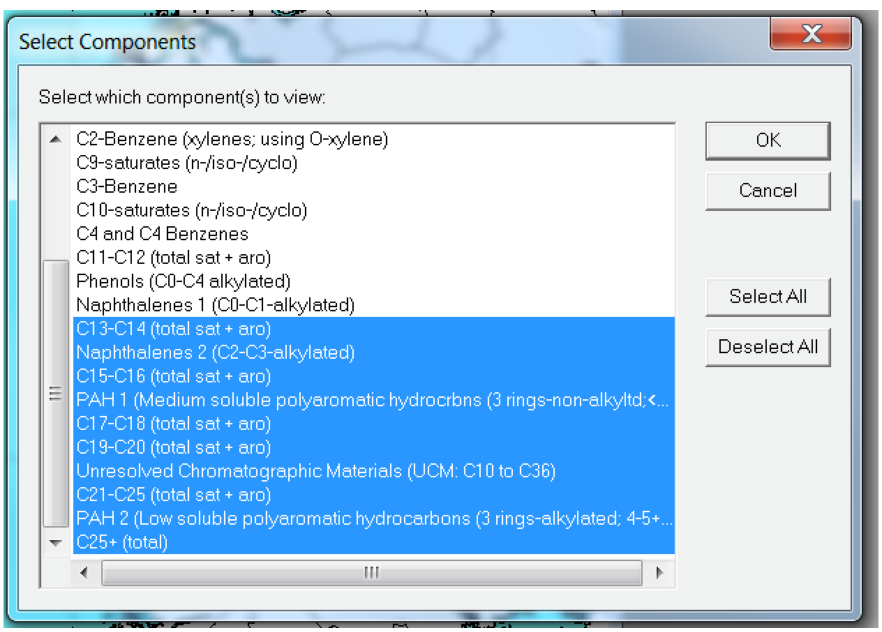


Figure 33. Selection of the components that comprise the sediment THC mass.

Generally, solubility decreases with molecular weight, and aliphatic hydrocarbons are less water-soluble than aromatic. Various side chains, alkyl-groups or other chemical structures further complicate the water solubility of the higher molecular-weight hydrocarbons that may be present in crude oils.

Two-ring PAHs (e.g naphthalene, LogKow=3.3), and to a lesser extent three-ring PAHs (e.g. anthracene, LogK_{OW}= 4.45), dissolve in water, making them more available for biological uptake and degradation. Compounds with five or more rings have low solubility in water and low volatility; they are therefore predominantly found in solid state, bound to particulates, such as e.g. in sediments. In solid state, these compounds are less accessible for biological uptake or degradation, increasing their persistence in the environment. From C_{17} and up, n-alkanes are generally in the solid state at standard conditions (sea water temperatures at the sea floor are below Standard temperature of 25 °C).

LogK_{OW}-values found in the open database PubChem for a few examples of compounds from C_{10}-aromatic naphthalene to tricontane (C_{30} n-alkane) are shown in Table 6.

Table 6. Examples of hydrocarbons from C10-aromatic naphthalene to C30-n-alkane tricontane, their LogK_{OW}-values (PubChem) and corresponding KOW values. Reference K_{OW}-value provided by SINTEF included.

	log K_{OW}	K_{OW}	Structure	Reference
Naphthalene ($C_{10}H_8$)	3.30	1995	Two-ring aromatic	https://pubchem.ncbi.nlm.nih.gov/compound/931#section=LogP
Anthracene $C_{14}H_{10}$	4.45	28184	Three-ring aromatic	https://pubchem.ncbi.nlm.nih.gov/compound/8418#section=LogP
SINTEF reference value for ERA Acute	***5.95***	***891994,66***	***Several***	
Benzo[a]pyrene $C_{20}H_{12}$	6.13	1348963	Five-ring aromatic	https://pubchem.ncbi.nlm.nih.gov/compound/2336#section=LogP
Tridecane ($C_{13}H_{28}$)	6.73	5623413	C-13 Aliphatic (straight-chain)	https://pubchem.ncbi.nlm.nih.gov/compound/12388#section=LogP
Tetradecane ($C_{14}H_{30}$)	7.20	15848932	C-14 Aliphatic (straight-chain)	https://pubchem.ncbi.nlm.nih.gov/compound/12389#section=LogP
Pentocosane $C_{25}H_{52}$	12.62	4.16869×10^{12}	C25 aliphatic	https://pubchem.ncbi.nlm.nih.gov/compound/12406#section=LogP
Tricontane $C_{30}H_{62}$	15.07	1.1749×10^{15}	C30 aliphatic	https://pubchem.ncbi.nlm.nih.gov/compound/12535#section=LogP

For species exposed through interstitial water, $C_{THC,IW}$ is calculated by the formula tested in tests 1 and 2:

$C_{THCIW,cell,sim} = C_{THCsed,cell,sim} /(foc \times Koc)$

$\text{Log}_{10KOC} = 0.00028 + 0.983 \times (\text{Log}_{10} K_{OW})$

Testing the effects on partitioning and thereby $C_{THC,IW}$ and $plet_{IW}$ with the variation of K_{OW} is therefore important.

For species that ingest sediment particles that are contaminated with oil, the partitioning of oil from the sediment particle to the gut water is an important possible route of exposure. The calculation of BSAF (Biota to sediment Accumulation Factor) is calculated by the equations given in:

Equation 5

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

Where:

f_{OC} can be set = TOC

$Log_{10}K_{OC} = 0.00028 + 0.983 \times (Log_{10}K_{OW})$

$Log\ BCF = 0.85 Log\ K_{OW} - 0.70$

The THC- concentration in the gut of biota (internal bioavailable fraction) THC_{biota} or $C_{THC,Ing}$ = BSAF × $C_{THC,IW}$ and the added lethality from ingestion, $plet_{Ing}$ can be calculated, varying also with the $LogK_{OW}$ values chosen (entered into ERA Acute as K_{OW}).

Probability of lethal effect from either THC in water column (hard substrates) or for soft substrates from exposure through interstitial water or gut water is calculated by entering the THC-concentration into the equation, as implemented in the calculator:

plet = Cumulative normal distribution with μ= 0 and σ= 1 of the expression: $((\ln C_{THC} - \ln 193)/0.73)$

Expressed in excel as: =NORMDIST((LN(**C_{THC}**)-LN(193))/0.73),0,1,TRUE)

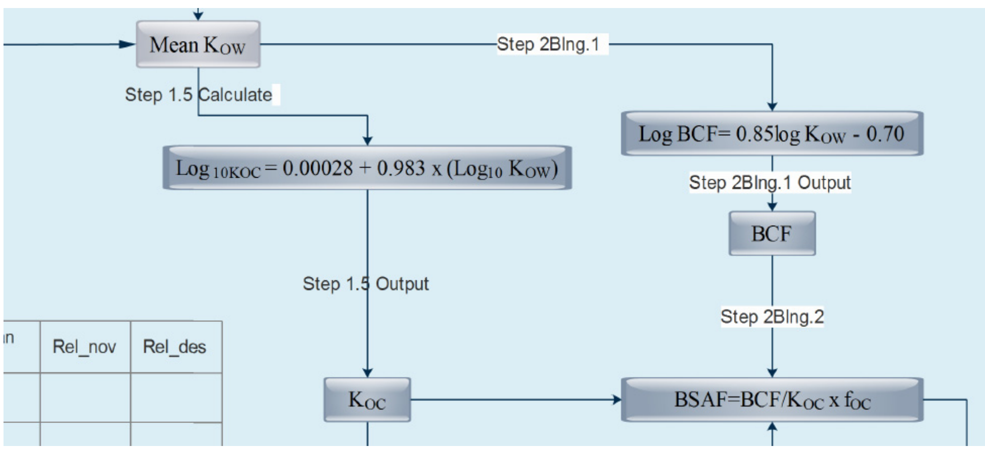


Figure 34. The equations that use the K_{OW} values in calculations of internal exposure from ingestion. K_{ow} is used to calculate the K_{oc} and the bio-concentration factor BCF, which are used together with TOC (= foc) to calculate the Biota to Sediment Accumulation Factor BSAF.

5.2 Results and graphs for the different substrate types – KOW

For the test of variation with K_{OW}, the previously tested input values were held constant as shown in Table 7, and the effect of varying the $LogK_{OW}$-value was tested.

Table 7. Parameters used in the tests of variation with K_{OW}

Substrate	Mixing Depth (m)	TOC (%)	Water content (%)	Dry Density g/cm^3
Mud	0.05 (global mean)	2.4	65	2.1
Sandy mud	0.05	1.2	50	2.1
Sand	0.05	1	30	2.75
Coarse sand	0.05	0.4	25	2.75

Using the range of the $LogK_{OW}$-values from 3.3 (K_{OW}= 1995) to 7.8 (K_{OW}= 63095734), the lethality for *infauna* exposed through interstitial water ($plet_{IW}$) varies as shown in Figure 35, when holding all other parameters constant for the substrate in question (see above, and tests 1 and 2) and the sediment THC-concentration initially is $C_{THC,sed}$=0.1 kg/m^2. The red line marks lethality at the LogK_{OW}-value found by SINTEF for the components in the sediment following simulations. Figure 36 shows the values of lethality due to ingestion of contaminated sediment and partitioning of THC to gut water ($plet_{Ing}$) varying with the LogK_{OW}-values tested for each of the four substrate types. The red line shows the value of LogK_{OW} found by SINTEF to be the mean of the LogK_{OW}-values for components in the sediment in the single simulations they performed. The range 3.3 -7.8 was chosen based on the numerical results behind the figure. However, as can be seen from the figure, the changes are infinitesimal between 4.0 and 6.8 (range including all substrates tested), this range is therefore used as a narrower range for the stochastic sensitivity testing.

When the TOC-content is low, a higher fraction of the total THC in the sediment will be present in the interstitial water if the compounds present have some water solubility (Lower LogK_{OW}). For mud, a Log K_{OW}=5.95 would lead to a low toxicity in interstitial water, as would be expected. With a much lower TOC-content, the toxicity is higher, as less organic carbon means less bound hydrocarbon. Additional $plet_{Ing}$ for species that ingest contaminated sediment (Figure 36) would be higher also for species in sandy substrates, given the same starting sediment concentration of $C_{THC,sed}$ per m^2.

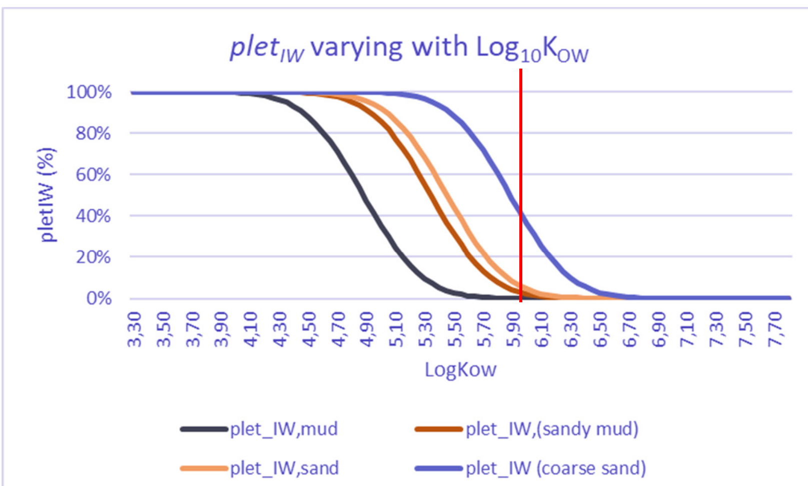


Figure 35. Variation of lethal effect through interstitial water ($plet_{IW}$) with LogK_{OW} for the range of LogKOW-values between 3.3-7.8 when the other parameters are held constant for four substrates mud, sandy mud, sand and coarse sand. The red line shows the lethality when the LogK_{OW}-value corresponds to the mean value of K_{OW} found by SINTEF in single simulations (LogK_{OW}=5.95).

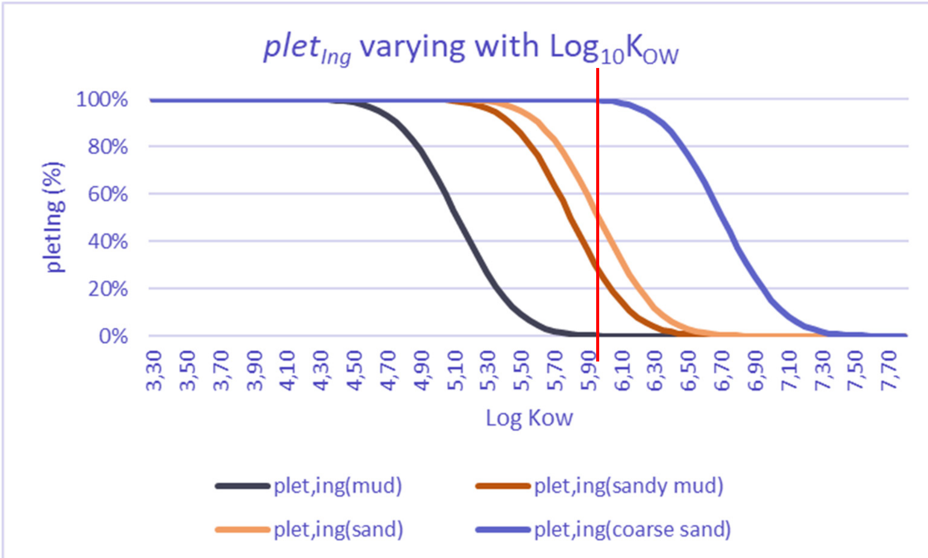


Figure 36. Variation of lethal effect through ingestion of contaminated sediment and partitioning of THC into gut water ($plet_{Ing}$) with Log K_{OW} for the range of Log KOW-values between 3.3-7.8 when the other parameters are held constant for four substrates mud, sandy mud, sand and coarse sand. The red line shows the lethality when the $LogK_{OW}$-value corresponds to the mean value of K_{OW} found by SINTEF in single simulations ($LogK_{OW}$=5.95).

Finally, holding K_{OW} constant at the value found by SINTEF to be a relevant mean value for the pseudo-components, K_{OW} = 891994.66 (Log K_{OW} = 5.95), the calculations were carried out using all the recommended values for the four substrates, using varying starting values for $C_{THC,sed}$ in sediment as "input" from oil drift modelling. Note that the values used range from 1/10 of the value used in the previous tests to 5 times the value. The result is shown in Figure 37, illustrating that the parameters used for coarse sand substrates lead to higher concentrations in interstitial water and thereby higher $plet_{IW}$. The lowest $plet_{IW}$ value is found for mud. Mixing depth was constant at 5.75 cm for all substrates in this test. Most of the values used in this test are more than 5 times higher than the values in single cells from the simulations carried out. In the case of the 21 simulations, only very few cells exceeded the lowest value used in this test (0.01 kg/m^2).

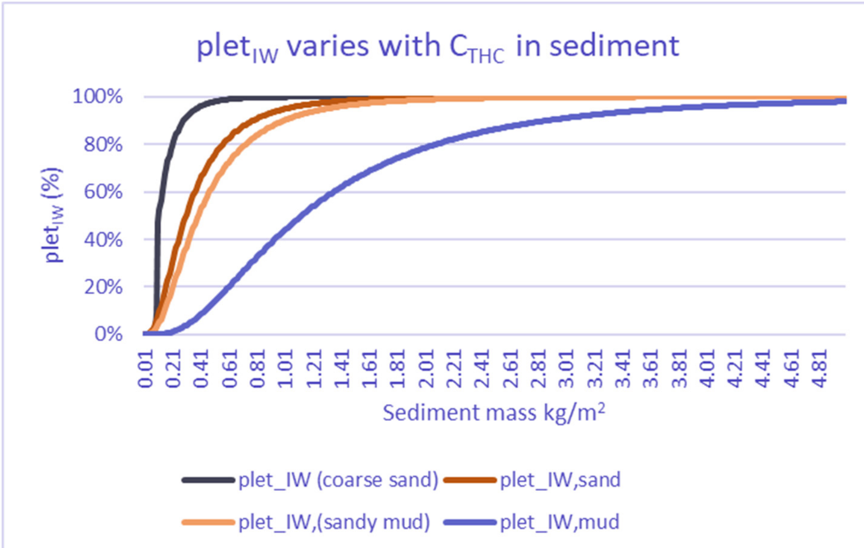


Figure 37. Variation of $plet_{Ing}$ with $C_{THC,sed}$ (kg/m^2) between 0.01 kg and up when the other parameters are held constant for four substrates mud, sandy mud, sand and coarse sand. The LogK_{OW} value was held constant at LogK_{OW}=5.95.

6 Stochastic tests - $C_{THC,sed}$ and $C_{THC,IW}$

6.1 Effect of different input values on resulting *plet*-value

The above tests 1a-1c investigate the result of the initial input values on the conversion of the $C_{THC,sed,cell}$ from kg/m^2 to ppb, test 2 the effect of carbon-content of the sediment, one of the factors involved in the partitioning of THC from carbon-phase to interstitial ($C_{THC,IW}$) and gut water ($C_{THC,Ing}$). These two are directly related to the *plet*-value, and especially the IW-concentration is subject to stochastic testing of the significance of the parameters.

6.2 Combined formula

From the above deterministic tests, it is intuitive that all the parameters tested above may be important to the calculation of oil in sediment. Effort was therefore placed on finding the most relevant values for the default files to provide with ERA Acute.

To test the effect of the input parameters together on the final value of the calculated concentration in sediment $C_{THCsed,cell,sim}$ as ppb (from input as kg/m^2) and following $C_{THC,IW}$, Monte Carlo simulations have been carried out to test which parameter has highest influence on calculation of $C_{THC,sed}$ (ppb) and the resulting bioavailable concentration, $C_{THC,IW}$; Mixing depth (BDepth), Water content (WatC), Dry density (DryDens) or TOC. The equations 1-4 were combined into:

Equation 6

$C_{THC,IW,cell,sim}$ [ppb] = (($C_{THCsed,cell,sim}$ [kg/m^2] × 10^9 [mg/kg] × 1/BDepth [m)] × (1-WatC))× 1/DryDens [kg/m^3])/(TOC ×$10^{(0.00028 + 0.983 \times (\text{Log10 KOW}))}$))

(In OSCAR, $C_{THCsed,cell,sim}$ is called SdMas). Following calculation of $C_{THC,IW,cell,sim}$ the calculation of the final endpoint for sensitivity testing *plet* is carried out by:

plet = Cumulative normal distribution with μ= 0 and σ= 1 of the expression: ((lnC_{THC}-ln 193)/0.73)

Expressed in Excel as: =NORMDIST((LN(**C_{THC}**)-LN(193))/0.73),0,1,TRUE)

6.3 Setup

Input parameters were as given in Table 8. Choosing ranges to test should reflect uncertainty, as the wider the range, the more the parameter will influence the result. It is therefore important to choose the ranges carefully.

6.3.1 TOC

The factor TOC has high uncertainty, and great variation between sediment sampling sites. Using the factor 3.27, the SD for the TOM-measurements converted into TOC-measurements were 2,4 % for mud, 1.2% for muddy sand, 1 % for sand and 0.4% for coarse sand. TOC is an uncertain value for which finding high quality real values would not be expected to be readily available. The range of TOC to test in the stochastic tests are 0.1 (Average TOC for coarse sand – SD, to 3.2 (Average TOC for mud +SD) (converted from TOM).

6.3.2 KOW

KOW is another highly uncertain factor for which we know will have a high influence on all models based on EqP. In Figure 35, which shows how p_{let} in interstitial water varies with KOW for four substrates, the range for visualization 3.3 -7.8 was chosen based on the numerical results behind the figure. However, as can be seen from the figure, the changes are infinitesimal between 4.0 and 6.8 (range including all substrates tested), this range is therefore used as a narrower range for the stochastic sensitivity testing.

6.3.3 Mixing depth (bioturbation depth)

As mentioned, by definition, the mixing depth has high influence on the lethality, as it directly correlates with the calculated concentration in sediment. The global mean is 5.75 cm, and the mean values of all regions given by Teal et al. (2009) range between 2 mm and 32 cm. To use this as the range for BDepth in the stochastic test will confirm its importance. However, we find it more interesting to use the mean value ± SD for a specific region, for one where the number of samples is larger, meaning that the actual range in itself is less uncertain, improving the value of the stochastic sensitivity testing. In the North Sea the mean BDepth (Teal *et al.* 2009) was 2.7 cm, the SD 2.3 cm and the number of samples 135. The range tested is therefore 0.003 m to 5 cm.

6.3.4 Water content

Water content was entered using 25% as the lower limit and 65 % as the high.

6.3.5 Input oil amount in sediment from OSCAR

The input value from “oil drift” was held at 0.1 kg/m^2, as in previous tests.

Table 8. Input parameter values to the stochastic Monte Carlo simulations (#1000) carried out for the endpoints used to calculate initial concentration of oil in the sediment, $C_{THC,sed}$ and the calculated $C_{THC,IW}$ (based on values given in Table 3 and modified by the experiments from the deterministic tests.

Parameter	SdMas (uniform)	BDepth (uniform) global	WatC (uniform)	DryDens (uniform)	TOC	K_{OW}
Minimum (a)	0.1 kg/m^2	0.003 m	0.25	2100 g/l	0.1	4.0
Maximum (b)	0.1 kg/m^2	0.050 m	0.65	2750 g/l	3.2	6.8

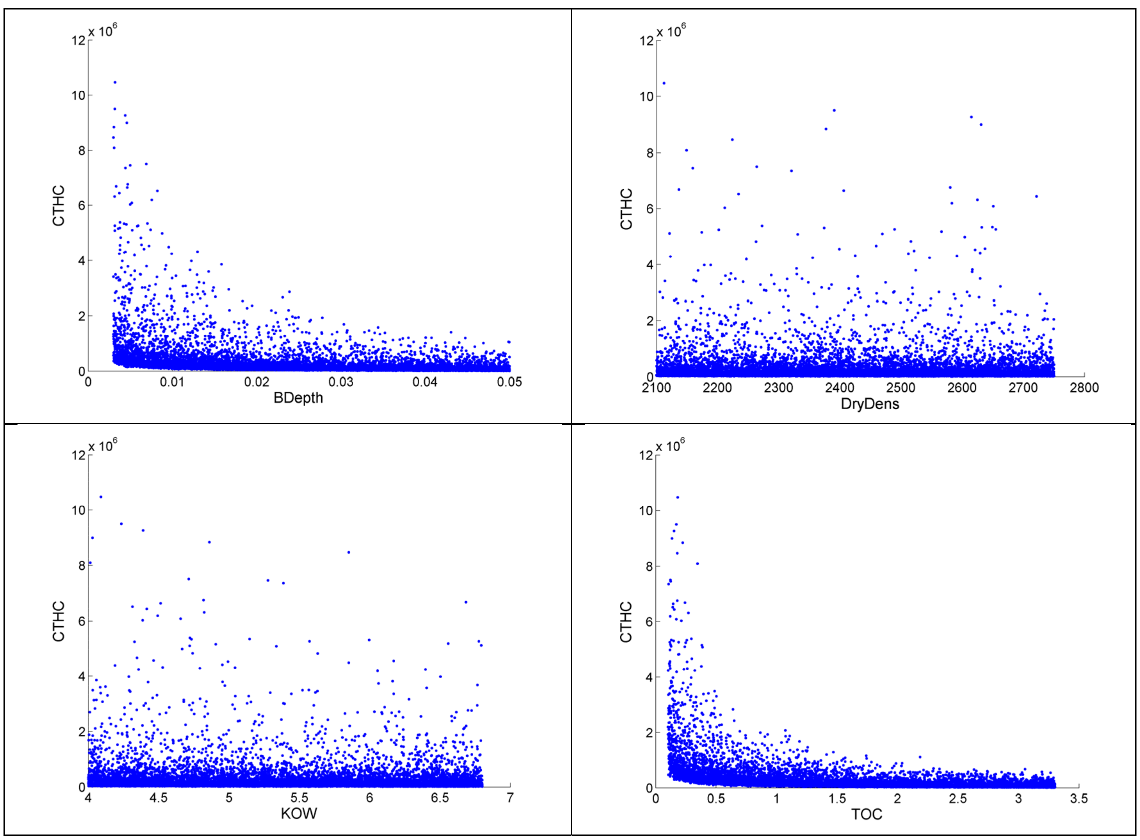
6.4 Testing

In the first step. the Monte Carlo simulation sampled all the values from the range provided for each parameter, stochastically and with equal probability (uniform distribution), using a fixed value of input oil amount in the sediment (OSCAR-proxy). Ten thousand simulations were carried out using these parameters shown in Table 8, resulting in as many combinations of the input parameters in a file as shown for the ten first resulting combinations in Table 9.

Table 9 Example of the resulting file from the first step; the ten first combinations (of 10 000) of values drawn stochastically using a uniform distribution from the input ranges for each parameter, resulting in a unique combination of the input parameters.

CTHCsed	BDepth	WattC	DryDens	TOC	KOW
0.1	0.032166	0.273866	2200.312	2.368409	6.725539
0.1	0.042258	0.391359	2625.602	0.927712	6.472358
0.1	0.046887	0.302093	2533.494	3.084638	5.421758
0.1	0.00535	0.274718	2585.601	1.169181	4.225257
0.1	0.024882	0.414989	2582.164	0.734512	6.512439
0.1	0.036765	0.533048	2531.71	1.490371	6.477848
0.1	0.031898	0.551603	2311.978	2.479723	5.503459
0.1	0.011432	0.51349	2648.694	1.40273	4.202372
0.1	0.038233	0.367777	2411.71	2.767519	6.571094

Scatter plots of the distribution of $C_{THC,IW}$ vs. each of the five input parameters from the monte Carlo simulations are shown in Figure 38.



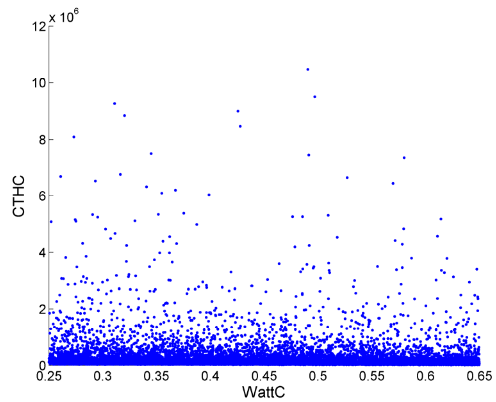


Figure 38. Scatter plots of the calculated value of $C_{THC,IW}$ vs. each of the input parameters to the calculation that were varied in the Monte Carlo simulations. Units: BDepth (m), DryDens (kg/m^3) KOW is a factor without unit, TOC (%), WatC (fraction).

This file (example Table 9) is then entered into the combined formula (Equation 6), and the concentration of THC in interstitial water, $C_{THC,IW}$ Is calculated for each combination, resulting in 10 000 values. The central statistics of the results of these 10 000 values are shown in Table 10.

Table 10 Result of the Monte-Carlo simulations (first step), showing mean values, variance, upper and lower confidence limits of the random draws of values from a uniform distribution of each parameter. All variables random, except C_{THC_sed} / SdMas = 0.1 kg/m^2

Sim01			
End Product & input parameters	Mean	Lower 95%-confidence limit (P2.5)	Upper 95 %-confidence limit (P97.5)
$C_{THC,IW}$ (ppb)	2.93E+05	2.80E+04	1.68E+06
C_{THCsed} (kg/m^2)	1.00E-01	1.00E-01	1.00E-01
BDepth	2.66E-02	4.12E-03	4.88E-02
WattC	4.50E-01	2.61E-01	6.40E-01
DryDens	2425.95	2117.42	2733.11
TOC	1.70E+00	1.73E-01	3.22E+00
KOW	5.40E+00	4.06E+00	6.73E+00

The results from the Monte Carlo simulations are then used in a sensitivity analysis which was carried out in a second step, to find out which variable parameter that has the largest influence on the resulting endpoint of the combined formula.

This is done in a FPRV sensitivity analysis (Factor Prioritization by Reduction of Variance), where the resulting sensitivity index for each input parameter to the combined formula from calculation of $C_{THC,IW}$ from $C_{THC,sed}$ (kg/m^2), is the fraction of the variation in $C_{THC,IW}$ that can be ascribed to the different parameters (Figure 39). Note that this is given the uncertainty defined by the range of natural variation and the weight of each value given by the distribution (uniform – equal weight). If a different distribution for the initial random drawing of values had been used, the result would have been different. However – given the nature of the parameters, a uniform distribution was assumed.

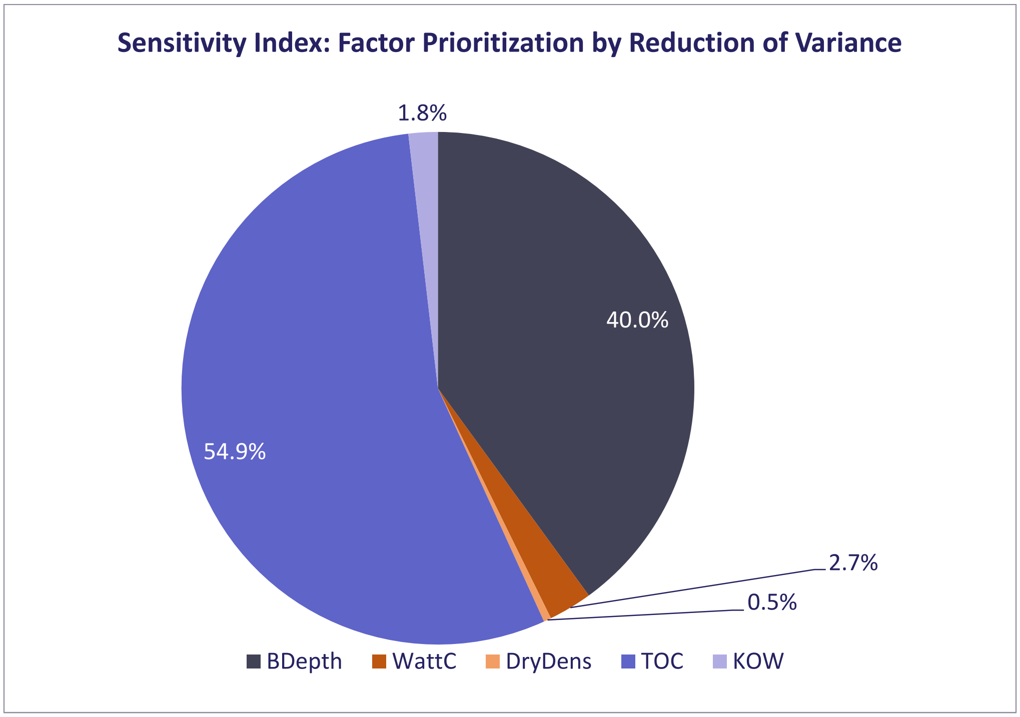


Figure 39. The result of the sensitivity analysis (Factor Prioritization by Reduction of Variance), where the sensitivity index shows the fraction of the variation in CTHC,IW that can be ascribed to the different parameters in the combined formula from calculation of CTHC,IW from CTHC,sed (kg/m2), given the uncertainty defined by the range of natural variation and the weight of each value given by the distribution (uniform – equal weight).

6.5 Interpretation of the stochastic results

A higher percentage value in the sensitivity index (Figure 39), the more sensitive the calculation is for this parameter, i.e. the parameter explains X% of the variation in the result. It is therefore as mentioned, important to have relevant values as the upper and lower limits of the range that is tested, as the larger the range (larger uncertainty), the larger influence the parameter will have on the result. A narrower range reduces the number and one also has higher certainty of the value. This inherent property of the test is important to have in mind when interpreting the results. Effort was therefore placed on finding relevant ranges of values from field studies. From the deterministic testing and the ranges found, it was expected that mixing depth (BDepth) is both a sensitive (impact on result) and an uncertain factor (high range of natural values). The sensitivity analysis using natural ranges of variation of mixing depths confirms the sensitivity of the calculations to this factor. Erring on the side of conservativity, it should be noted that a lower mixing depth gives a higher sediment concentration (amount is divided by a lower volume), but an extremely low value would indicate also a lower abundance of burrowing fauna that could be exposed. Choice of the value is important for the resulting value of bioavailable $C_{THC,IW}$ calculated, in the sensitivity analysis, with the ranges and probability distribution used, mixing depth accounts for 40 % of the *variation* in $C_{THC,IW}$ calculated. Uncertainty of the value is relatively low. KOW accounts for 1.8% of the variation, Dry density for only 0.5 %. Water content is ascribed 2.7 % of the variation in calculated $C_{THC,IW}$ value. The factor which has the highest influence on the variation of the $C_{THC,IW}$ value is the organic carbon content of the substrate, which accounts for 55 % of the variation, this is supported by the distribution shown in the scatter plots.

It is well known that local values of TOC may vary between regions, depending on substrate type and influxes of organic carbon. TOC may therefore be an input parameter worth finding local values for to reduce uncertainty in the analysis.

6.6 Discussion of the parameters relating to the EqP calculations

From the first deterministic tests of the sensitivity analysis we see that all parameters directly influence the outcome in $C_{THC,IW}$ –values and corresponding toxicity to *infauna (plet$_{IW}$)*. For the four (five including bioclastic coarse sand) soft substrate (groups) that were defined based on the literature study, MOD-database and grouping of MAREANO-data, general recommended values have been proposed for dry density, water content, total carbon content and bioturbation (mixing) depths for the substrates.

However, leaching of hydrocarbons and corresponding toxicity varies greatly with all these factors. Temperature variation of the equilibrium partitioning (K_{OW}-values) has not been taken into account within the scope of this study. However, lower temperatures lead to less leaching of THC into interstitial water, and therefore lower bioavailability.

Not all the ranges of the curves are relevant for each substrate, and it is relevant to note that the input value of oil in the sediment of 0.1 kg/m^2 was a very high value found only in a few cells in some simulations.

A summary of the recommended values based on literature study and tests is given in in Table 20, section 9.4.

7 Test 4: Sensitivity to feeding mode distributions

7.1 Feeding modes in ERA Acute – a recap

The soft substrate (sediment) part of the seafloor compartment calculates impact based on contribution from three different exposure routes (1) water column, (2) interstitial (pore) water and (3) ingestion of sediment. The equilibrium partitioning approach cannot account for exposure via ingestion of sediment and a separate equation to calculate the Biota to Sediment Accumulation Factor (BSAF) is derived to account for this important exposure route for organisms that ingest particles (cf. Stephansen *et al.* 2015 for details). The observant reader of the full seafloor compartment documentation will notice that the algorithms only contain four *different* alternative combinations of these exposure routes: Exposure by water column (*epifauna*) or interstitial water (*infauna*), either alone - for animals that do not feed on deposits that could contain HC – or combined with exposure from *ingestion* of contaminated deposits. The division into seven feeding modes has been done so that it is easier for a biologically oriented user to recognise and place relevant species into the correct group when assigning data for VECs. See Table 12 for a summary of the feeding modes, exposure routes and substrates they are associated with. Corals and sponges are assigned FM 4 (epifaunal suspension/filter feeders) and their impact depends on water column exposure for calculation of *plet* WC. Hard substrate carnivores (e.g. molluscs feeding on corals or sponges) are assigned to FM1, resulting in equal lethality as species with FM4. Hard substrate organisms are therefore either FM1 or FM (both WC-exposure).

7.2 Parameters related to feeding modes – deterministic test

Test 4: Using the Excel spreadsheet the effect of ingestion of oil-contaminated sediment particles for feeding modes 6 (surface deposit feeders) and 7 (sub-surface deposit feeders) was investigated deterministically. How much does the additional toxicity from ingestion of particles add to the lethality?

Based on the variation in K_{ow} there will be a range of K_{oc} values and thereby BSAF. It is necessary to test the sensitivity of the additional impact to feeding modes 6 and 7 based on variation in BSAF with K_{ow} (and thereby Koc). This was tested on a range of relevant K_{ow} values in test 3. The variation of $plet_{Ing}$ with K_{OW} is shown in Figure 36.

For a range of relevant K_{ow} values for sedimentation of oil, we will investigate the difference between feeding modes (Difference is whether Exp_Ing is "True" or "False") for sediment infauna.

Feeding modes FM1/FM3/FM4 are exposed *only* in the water column and FM6 are exposed *also* in the water column in addition to ingestion. Exposure in the water column is determined solely by $C_{THC,WC}$ with input directly from the oil drift simulations (THC_{max}) and lethality is calculated using the water column impact function, with no relation to input parameters from the sediment soft substrate characteristics. These FMs have therefore been omitted from the deterministic Excel sheet testing as bringing the $plet_{WC}$ into the test complicates the picture. They are included in the tests using the ERA Acute tool (section 7.3) which shows the additional risk.

How the effect of ingestion changes with K_{OW} can be seen in Figure 36 which shows the effect of $plet_{,Ing}$ alone, valid for both FM6 and 7.

When setting up the test protocol, it was originally planned to carry out the test of sensitivity to feeding modes using available data of feeding mode distributions to construct a dataset that designates the feeding mode for the most common benthic species on the Norwegian Continental Shelf into the seven different feeding modes. As mentioned in the introduction, this also proved too complex for deterministic testing at this first point, as literature and databases did not provide real fractions of the feeding modes for each substrate, nor ranges suitable for uncertainty testing by statistical methods. This lack of FM distribution data availability has led to a calibration in recommended approach in the use of VEC data sets, which was used when adapting the final data sets for the Norwegian Sea case in Phase 2. (See chapter 8.4).

The test, relevant to show the variation in lethality to feeding modes FM2/5 and FM 7 with changes in K_{OW}, was therefore simplified to better isolate the difference. For FM2/FM5 and FM7, the test has been carried out in Excel for the two substrates mud and muddy sand where these FMs are relevant. (Figure 40). The *additional* lethality to FM7 relative to FM2/5 due to ingestion will be identical for FM 6 given the same substrate.

Note: The values for K_{OW} are extremes, and the input $C_{THC,sed}$ amount in sediment is high, the result shows, however that it would be correct to insert a check of the resulting collective lethality that it does not exceed 100 %, as this is a mathematical artefact of the model, although this result is not expected with realistic K_{OW}-values.

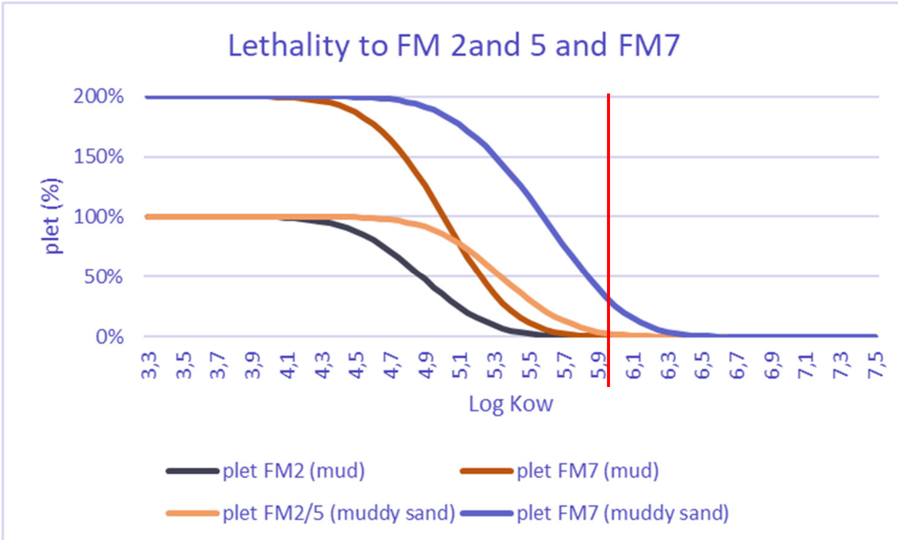


Figure 40. Lethality of feeding modes 2/5 and 7 when K_{OW}-values vary (extreme ranges). The red line indicates Log KOW = 5.95.

Holding K_{OW} constant at the value found by SINTEF to be a relevant mean value for the pseudo-components, Log K_{OW} = 5.95, the values for *plet(IW+Ing)* for each of FM2/5 and FM7, are shown in Table 11. The calculations were carried out using all the recommended values for the four substrates, using $C_{THC,sed}$ in sediment= 0.1 kg/m^2 as "input" from oil drift modelling.

Table 11 Values of *plet* (%) for feeding modes FM2 and FM5 by exposure in interstitial water and for FM 7 by both interstitial water and ingestion when logK_{OW} is 5.95, in the two relevant substrates mud and muddy sand. $C_{THC,sed}$ = 0.1 kg/m^2.

Log10(Kow)	*plet* FM2/5 (mud)	*plet* FM7 (mud)	*plet* FM2/5 (muddy sand)	*plet* FM7 (muddy sand)
5.95	0.045 %	00.22 %	3 %	33 %

Finally, again holding K_{OW} constant at the value found by SINTEF to be a relevant mean value for the pseudo-components, K_{OW} = 891994.66 (Log K_{OW} = 5.95), the calculations were carried out using all the recommended values for the four substrates, using *varying starting values* for $C_{THC,sed}$ in sediment as proxy "input" from oil drift modelling. Note that the values used are from 1/10 of the value used in the previous tests to 5 times the value. The result is shown in Figure 41, illustrating how ingestion adds exposure, and so more when TOC in the sediment is lower. This is because the lower TOC in the ingested contaminated particle, the higher the proportion of the THC is released to gut water, and made available. Also in such substrates, the concentrations in the surrounding interstitial water are also higher. Note that Mixing depth was constant at 5.75 cm for all substrates in this test. It could be argued, however, that substrates lower in TOC will have lower affinity to THC, and therefore sequester less than in substrates with higher TOC in the first place and thereby providing a deposit with lower THC. On the other hand, the deposits themselves that are ingested would be expected to be of high organic carbon content, otherwise there would be no nutritional value for the organism to ingest them. It is the ratio of organic deposit-to non-organic grain that is different in the sediments, not the “quality” of the actual deposit particle. Organic pollution will increase the TOC in the deposits.

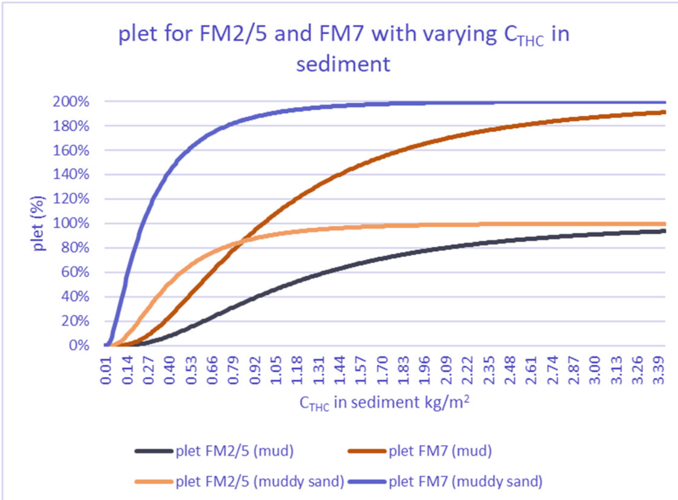


Figure 41. Additive effect and lethality of feeding modes 2/5 and 7 when starting value of THC in sediment-values varies (extreme maximum values.)

Table 12 Combination of impact functions based on primary route of exposure for the different feeding modes. Exposure and Impact reflects whether Exp_WC/IW/Ing = True/False in the column in the VEC file. Presence of expected *dominant* feeding modes per substrate habitat type. Organisms with other FMs may be present in substrates.

Feeding mode #	Description (biological)	Exposure & Impact		Mud	Sandy mud	Sand	Coarse sand	Bioclastic Coarse sand	Hard substrate
FM1	Carnivores, *epifauna*	WC	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.	x	x	x	x	x	x
FM2	Carnivores, *infauna*	IW		x	x	x	x	x	
FM3	Herbivores*	WC	Organisms that consume plant material in the benthic assemblage.						x
FM4	Suspension feeders, *epifauna*	WC	Capture food particles from the water (i.e. removes them from suspension) using for example stinging tentacles. (E.g. *Anthozoa* class, including scleractinian corals and octocorals.). Sub-group Filter feeders filter dissolved and suspended matter from the water by pumping water through filtration structures. (e.g., some tunicates, bivalves and sponges). Areas with high currents tend to see more species of suspension feeders.	x	x	x	x	x	x
FM5	Suspension feeders, *infauna*	IW		x	x	x	x	x	
FM6	Surface deposit feeders (*epifauna*)	WC + Ing	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).	x	x				
FM7	Sub-surface deposit feeders (*infauna*)	IW + Ing	Organisms that consume organic material below the surface of seafloor sediments (e.g., some bivalves and polychaetes).	x	x				

* Herbivores are omitted from the relevant datasets, as they are present in shallow waters where there is plant material present.

Mud

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.

Sand

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.

Sandy mud

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

Hard substrate habitat types:

The ERA Acute project is carried out by a consortium of industry partners (Statoil, Total, Norwegian Oil and Gas Association) and experts in environmental risk analysis (Acona, Akvaplan-niva (Project Manager), DNV-GL and SINTEF), supported also by the Research Council of Norway.

ERA Acute is developed to provide a globally applicable, transparent method for quantitative environmental risk assessment of oil spills in four compartments: Sea surface, shoreline, water column and sea floor.

	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 (on hard substrates).

7.2.1 The effect of using a fixed Mixing Depth in these tests

The mixing depth was held constant at 5.75 cm in the experiments, resulting in an initially calculated value of $C_{THC,sed}$ (ppm) that is dependent on the other characteristics of the substrate. However, typical mixing depths vary among the substrates and regions, adding to the complexity of testing. Further testing, using the ERA Acute Core Calculator (CC) was therefore carried out in a second set of sensitivity analyses of feeding modes vs. substrate properties, using the full set of 21 simulations from OSCAR as input (see chapter 7.3).

7.3 Sensitivity test of feeding modes and substrate properties – ERA Acute CC

7.3.1 Feeding mode distributions – data availability and adaption of model use

To obtain an exact as possible result for VECs that are multi-FM communities, the algorithms are currently designed so that one either can use fractions in the feeding mode distributions, assuming a community has x % of a certain FM etc. As discussed in more detail in section 9.1.1, finding reliable data for the distribution of feeding modes between the species in a substrate community was not readily available within the scope of testing. The algorithms are currently designed so that using a fraction of each feeding mode in the resource setup file will lead to a total impact with a proportionate contribution from each feeding mode.

If the distribution between the feeding modes is unavailable, *one* approach would be to calculate exposure to each of the exposure modes assuming 100 % of each. This would mean calculating the *sum of impacts* (contributions adding up to #FMs x 100 %) to all "FM-populations" in the substrate, not the *sum of their contributions*, (contributions adding up to 100 %) to which the ERA Acute model is designed. To investigate the hypothesis that this approach is erroneously conservative relative to the design of the impact calculations, a test was carried out using the input parameters

As a practical approach to testing the sensitivity of the feeding modes, ERA Acute with CC 0.55 was run using "dummy" data covering the Norwegian Sea and Barents Sea in two ways, and using the 21 oil drift simulations from the Norwegian Sea case. The VEC presence data are evenly distributed between the months (N= 100 km^2 in all months), so monthly differences are ascribed to variation between simulations. Using the 21 single simulations carried out for the Norwegian sea case (9000 Sm^3/day for 65 days) the ERA Acute CC was run. There are 1-2 simulations starting per month, and contributions from all simulations covering a month contribute to the impact that month. This way the FMs are tested against the variation of oil input from actual oil drift simulations.

Under Test 4 – feeding modes, three setups were used.

A. A setup with 5 soft substrates and hard substrate: Using all *dominant* FMs (Table 12) (excluding FM3) set to 100 %. The results of all feeding modes will be summarized to a total impact for the substrate community.
B. A setup with 5 soft substrates, hard substrate: Using all FMs (excluding FM3) set to 100 %. The results of all feeding modes will be summarized to a total impact for the substrate community.

C. A setup with 5 soft substrates, hard substrate: Using single VEC data sets for each *dominant* FM (Table 12) (excluding FM3) for each substrate, using 100% of that FM and all other FM at 0%. The results are calculated as separate for each feeding mode.

The ERA Acute CC cannot (in CC0.55) use the same resource data set for two different VECs. Individual dummy datasets, assuming that N= 100 km^2 of the substrate, was prepared for each of the five soft substrates and hard bottom.

Feeding mode 3 (herbivores) is not relevant at a depth of several hundred meters, as it is too deep for plant growth. Herbivores are therefore omitted, but the results would be the same as for FM1, carnivores.

7.3.2 Test 4.A Dominant FMs set to 100 % in all soft substrates

7.3.2.1 Setup

Using the *dominant* feeding modes in Table 12 for each substrate, the dummy data were prepared for using the recommended input values for each substrate and 100 % presence of each of the dominant FMs for a large area covering the Norwegian and Barents Seas.

The setup is shown in Table 13.

Table 13. Setup for Test 4.A Dominant feeding modes in five soft substrates and hard substrate. FM 3 (herbivores are omitted due to depths.

Species	Hard or soft	FM1	FM2	FM4	FM5	FM6	FM7	SF	Dry dens.	Wat. cont.	Mix. depth	TOC	THC max	Rest. thres.
Dummy mud	SOFT	1	1	1	1	1	1	2.4	2100	0.65	0.005	0.024	1000	50
Dummy hard	HARD	1	0	1	0	0	0	1	0	0	0	0	0	0
Dummy sandy mud	SOFT	1	1	1	1	1	1	1.2	2100	0.5	0.01	0.012	1000	50
Dummy sand	SOFT	1	1	1	1	0	0	1	2750	0.3	0.02	0.01	1000	50
Dummy coarse sand	SOFT	1	1	1	1	0	0	0.4	2750	0.25	0.05	0.004	1000	50
Dummy bioclastic coarse sand	SOFT	1	1	1	1	0	0	0.4	2650	0.25	0.05	0.004	1000	50

7.3.2.2 Results

Figure 42 shows the average impacted area for each of the five soft substrates and hard substrate, using feeding modes that are *dominant* in each substrate, i.e. that not all FMs are included in all substrates. Within a substrate, the results show the variation between the oil drift simulations, leading to different impacts per month (monthly distribution of VEC is constant). Note that the approach used (100 % for each FM is overly conservative and the impacts correspondingly high.

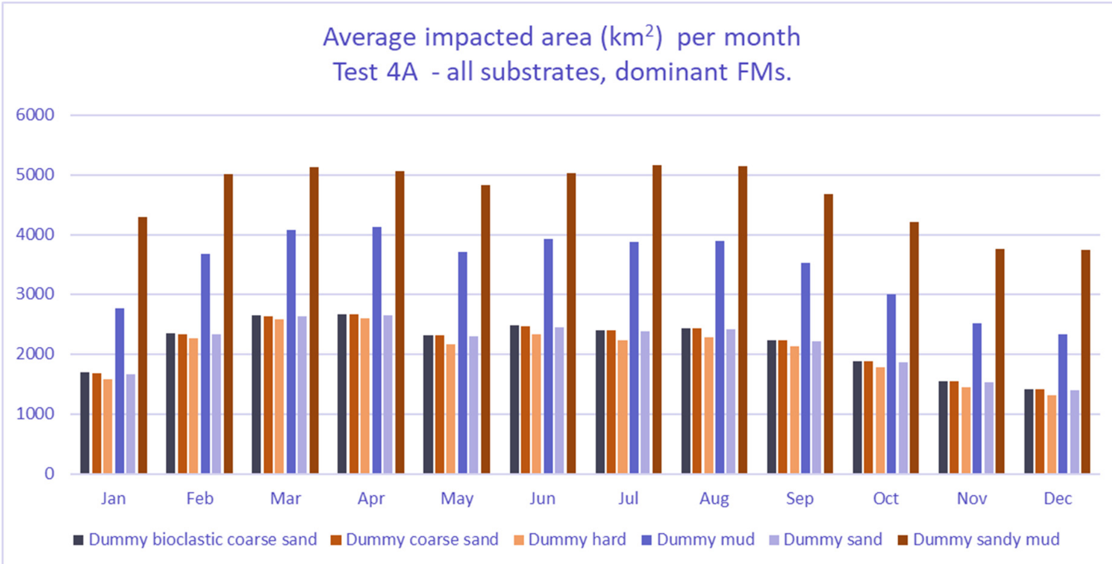


Figure 42. Average impacted areas (km^2) for each of the 5 soft substrates and hard substrates, using each of the dominant feeding modes in each substrate set at 100 % contribution, i.e. the sum of contributions can be more than 100 %, as FM contributions are added up to a habitat community impact.

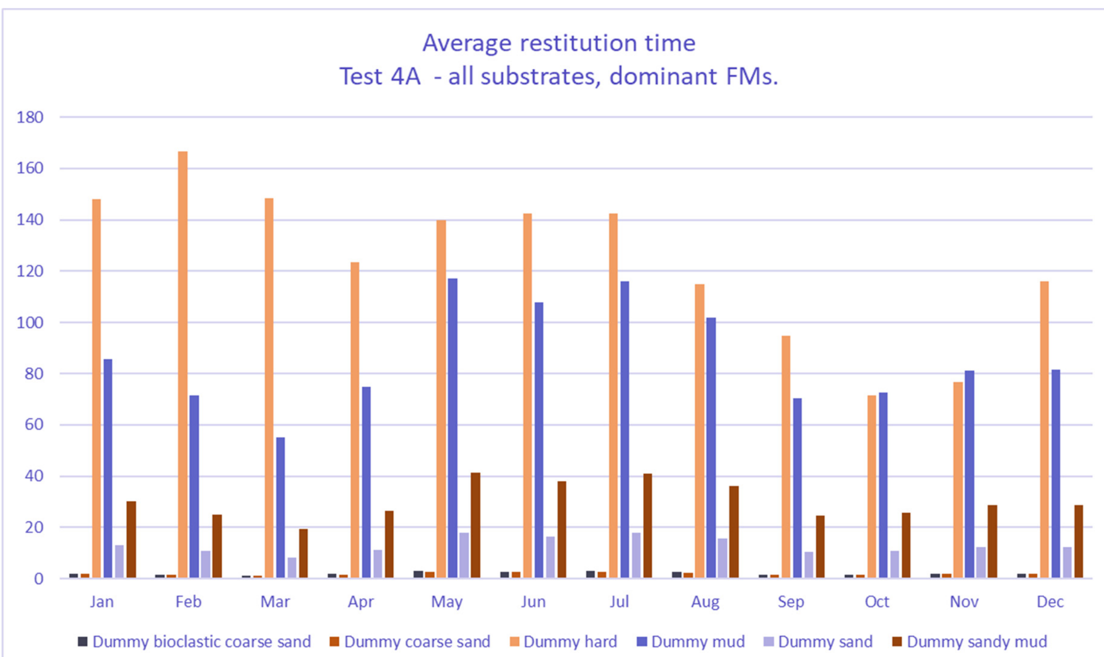


Figure 43. Average restitution time (years) for each of the 5 soft substrates and hard substrates, using each of the dominant feeding modes in each substrate set at 100 % contribution, i.e. the sum of contributions can be more than 100 %, as FM contributions are added up to a habitat community impact. Note that the restitution time in hard and soft substrates are based on different restitution functions.

RDF-values as monthly averages for hard substrate is shown in Figure 44. Hard substrate uses a different lag- and restitution time calculation, based on impact magnitude, not THC-content in sediment. See Stephansen & Sørnes (2015).

RDF values as monthly averages for the soft substrates are shown in Figure 45 for mud and sandy mud, which give much higher and more long-lasting impacts than the other substrates. Sand, coarse sand and bioclastic coarse sand are shown separately as their values are much lower (Figure 46).

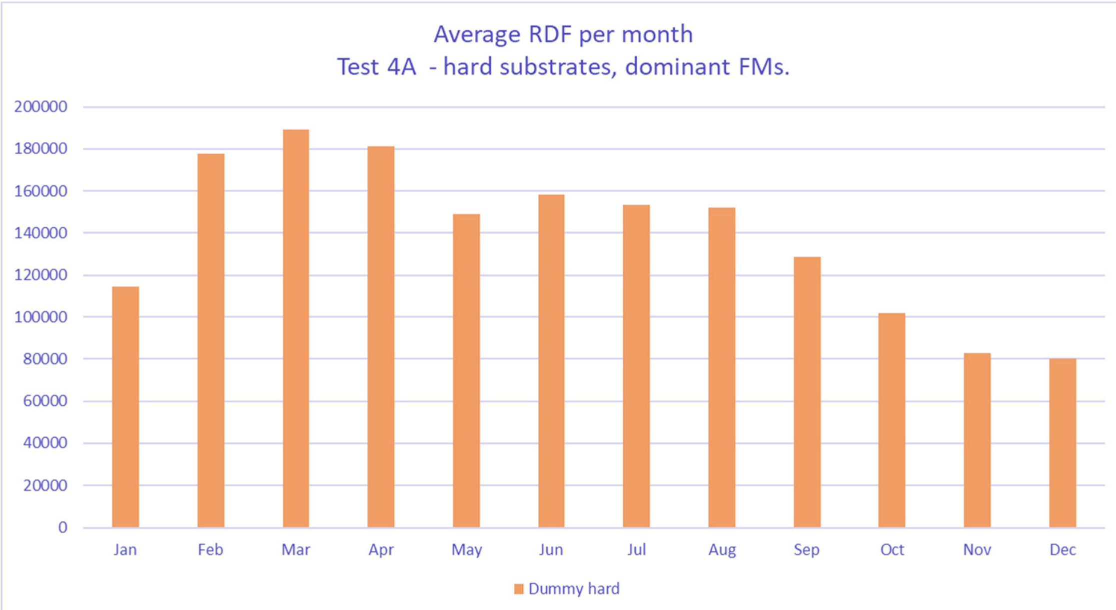


Figure 44. Average Resource Damage Factors (km^2years) for hard substrate (FM4) and using the restitution algorithm for hard substrate.

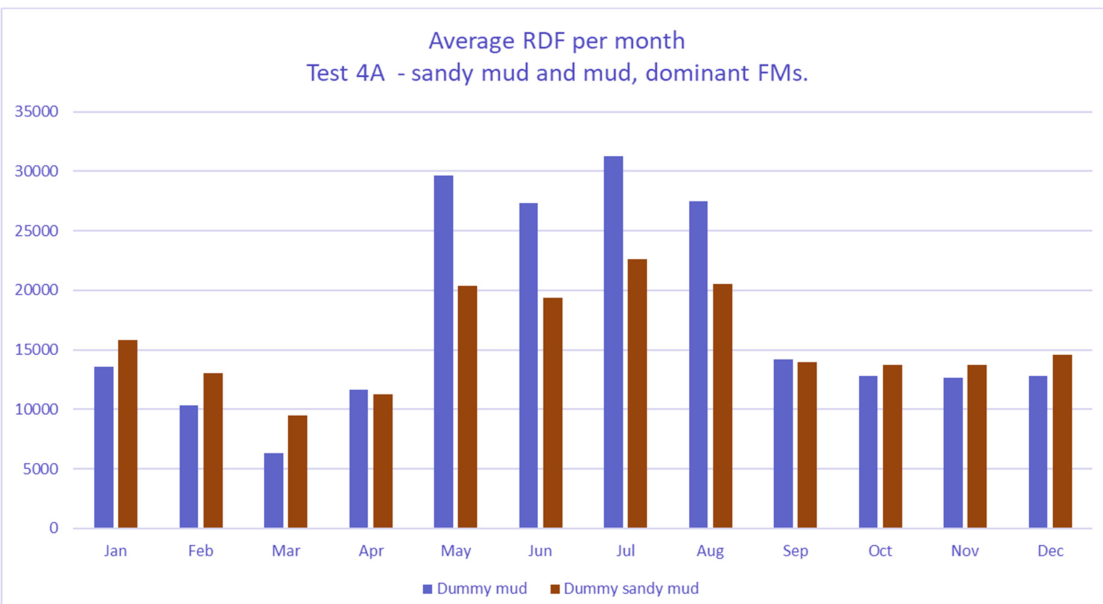


Figure 45. Average Resource Damage Factors (km^2years) for soft substrates sandy mud and mud, using each of the dominant feeding modes in each substrate set at 100 % contribution.

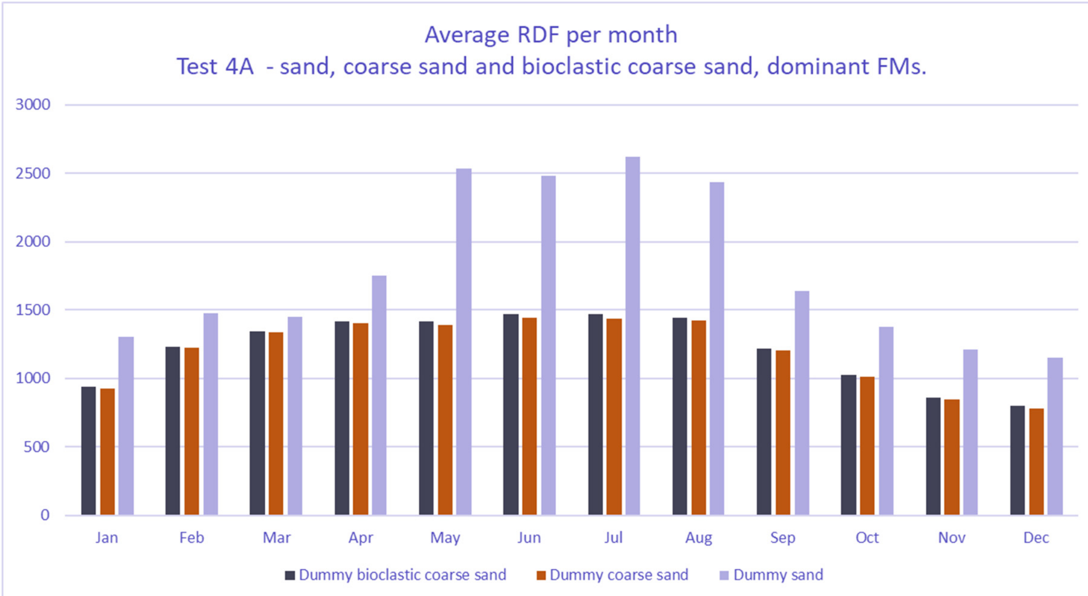


Figure 46. Average Resource Damage Factors (km²years) for soft substrates sand, coarse sand and bioclastic coarse sand, using each of the dominant feeding modes in each substrate set at 100 % contribution.

7.3.3 Test 4.B Impacts to substrate-based VEC data with 100 % presence of all FMs

7.3.3.1 Setup

In test 4.B, the dummy data were prepared for using the recommended input values for each substrate and 100 % presence of all FMs (except for hard substrate) for a large area covering the Norwegian and Barents Seas.

The setup is shown in Table 13. The difference between the two tests 4.A and 4.B is that feeding modes 6 and 7, which include ingestion of THC by deposit feeding are included for all substrates, not only mud and sandy mud.

Table 14. Setup for Test 4.B All feeding modes in five soft substrates and FM 4 in hard substrate.

Species	Hard or soft	FM1	FM2	FM4	FM5	FM6	FM7	SF	Dry dens.	Wat. cont.	Mix. depth	TOC	THC max	Rest. thres.
Dummy mud	SOFT	1	1	1	1	1	1	2.4	2100	0.65	0.005	0.024	1000	50
Dummy hard	HARD	1	0	1	0	0	0	1	0	0	0	0	0	0
Dummy sandy mud	SOFT	1	1	1	1	1	1	1.2	2100	0.5	0.01	0.012	1000	50
Dummy sand	SOFT	1	1	1	1	1	1	1	2750	0.3	0.02	0.01	1000	50
Dummy coarse sand	SOFT	1	1	1	1	1	1	0.4	2750	0.25	0.05	0.004	1000	50
Dummy bioclastic coarse sand	SOFT	1	1	1	1	1	1	0.4	2650	0.25	0.05	0.004	1000	50

7.3.3.2 Results

For the soft-bottom substrates, each with an equal area, and having all FMs at 100 % presence in all of the FMs, the resulting areas impacted in each month are shown in Figure 47. The inclusion of FMs

6 and 7 (ingestion) increases impact a great deal for the two low-TOC substrates, coarse sand and bioclastic coarse sand. However, the TOC is low in these two substrates which indicates a low rate of sedimentation of carbon-rich particles. This in turn leads to the detritus-feeding organisms being less likely to be dominant in these two substrates and therefore not relevant. The results are included to illustrate the sensitivity of the functions to FMs. As expected, the restitution times (Figure 48) are not changed from test 4A, as the restitution time does not depend on the FM.

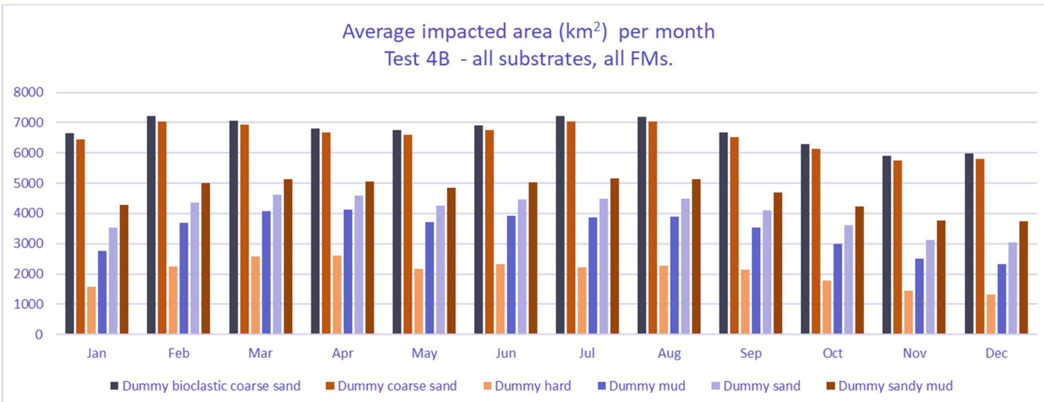


Figure 47 . Average impacted areas (km^2) for each of the 5 soft substrates and hard substrate, using all feeding modes in each substrate set at 100 % contribution, i.e. the sum of contributions can be more than 100 %, as FM contributions are added up to a habitat community impact.

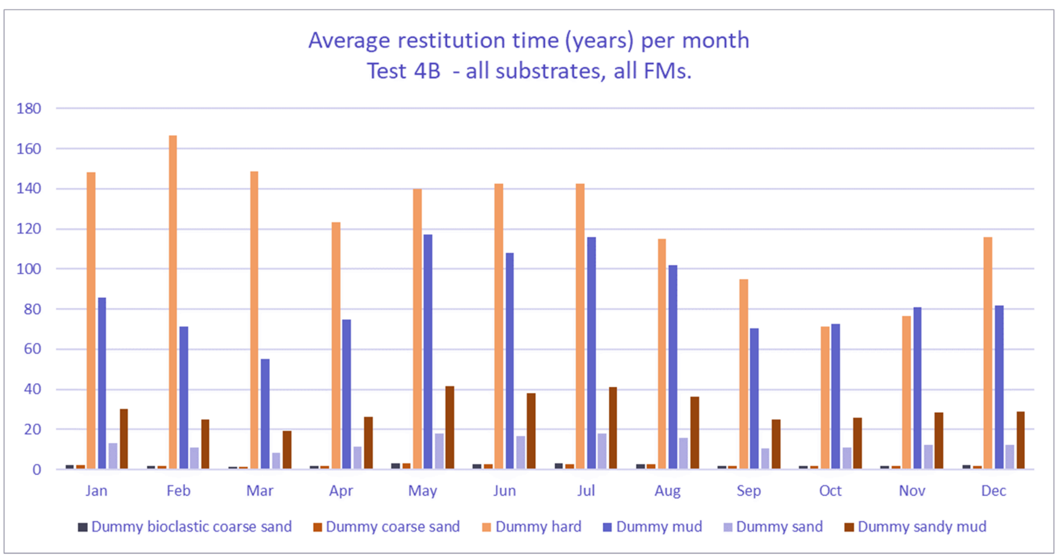


Figure 48 . Average restitution time (years) for each of the 5 soft substrates and hard substrate, using all feeding modes in each substrate set at 100 % contribution, i.e. the sum of contributions can be more than 100 %, as FM contributions are added up to a habitat community impact.

RDFs, also as expected, increase for the substrate VECs where the impact increases. (Figure 49 and Figure 50).

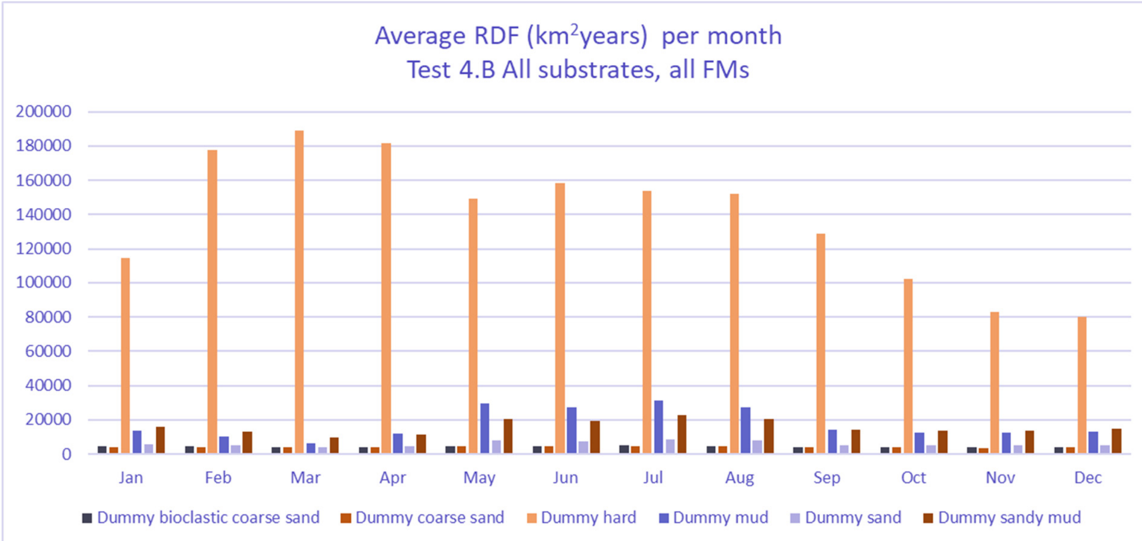


Figure 49 . Average RDF (km^{2}years) for each of the 5 soft substrates and hard substrate, using all feeding modes in each substrate set at 100 % contribution, i.e. the sum of contributions can be more than 100 %, as FM contributions are added up to a habitat community impact.

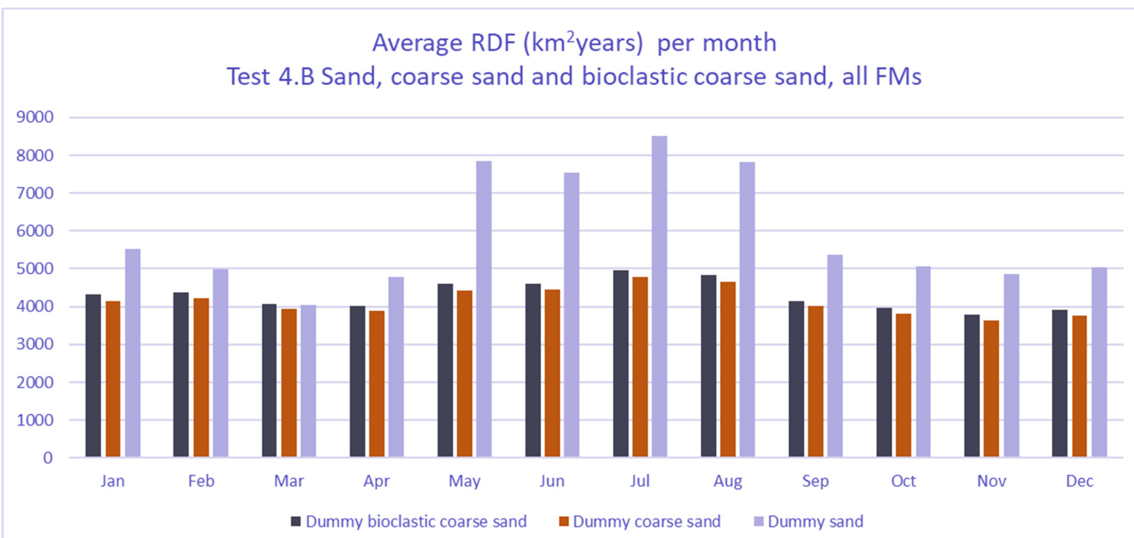


Figure 50 . Average RDF (km^{2}years) for sand, coarse sand and bioclastic coarse sand substrates, using all feeding modes in each substrate set at 100 % contribution, i.e. the sum of contributions can be more than 100 %, as FM contributions are added up to a habitat community impact.

The relative impact contribution between the months varies very little between the months, this may be due to the few simulations (1-2) per month. Note that this impacted area is based on dummy data for testing purposes, where the same 10x10 km cell within the influence area has 100 km^2 of each of the substrate types, an obviously artificial situation. Also, again using a 100 % presence of each feeding mode, the results are pushed to the extreme. Using these results, the relative distribution of the contributions to total impact from each substrate if the total were 100 % of the impacted area is very similar between the months. Two examples are shown for January and March in Figure 51.

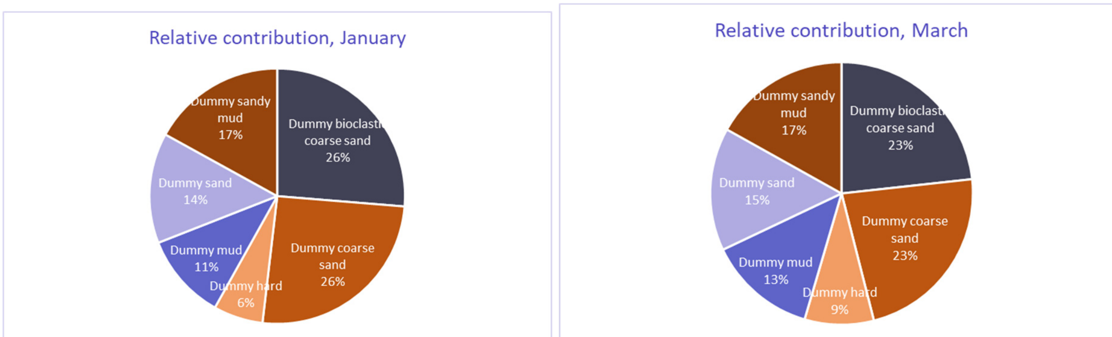


Figure 51 Relative contributions to the total impacted area for January and March, assuming all substrates are present with 100 % in all cells (artificial) and all FMs are 100% in each substrate. The differences are due to differences between the oil drift simulations.

7.3.4 Test 4.C Using separate VEC data for dummy data sets

Using the *dominant* feeding modes in Table 12 for each substrate, the dummy data were prepared for each substrate and feeding mode in **separate** data sets for each VEC instance, for a large area covering the Norwegian and Barents Seas.

The data sets are identical except for the species name, all have 100 km^2 of the area with the habitat/species in each cell. This was done to test whether splitting the datasets and calculating risk for each FM separately will provide a more feasible solution for use of the method, given that the distribution data are not as readily available as initially anticipated. It is important to remember that exposure via water column (all on hard substrates (FM1 and 4) and FM 1,4 and 6 in soft substrates) and *infaunal* exposure in sediment (IW and Ing) (soft substrates) are based on different inputs from the oil drift modelling. Initial tests were carried out to verify that the splitting of data sets into individual FMs was a feasible solution, and this approach was thereafter used in the Norwegian Sea case model runs.

7.3.4.1 Impacts to substrate based VEC data with one FM per data set

The same data sets as used above were split into one data set for each relevant FM as described in Table 12. The input parameters used are given in Table 15.

Table 15. VEC data sets used in test 4C using dummy data for all substrates, individual data sets for each FM, and parameters used.

Species	Hard or soft	Deep or Shallow or empty	FM1	FM2	FM3	FM4	FM5	FM6	FM7	Sensitivity factor	Dry density	Water content	Mixing depth	TOC	THC max	Rest. threshold
FM 4 Dummy hard bottom coral garden	HARD	Deep	0	0	0	1	0	0	0	1	0	0	0	0	0	0
FM4 Dummy Glass sponges	HARD	Deep	0	0	0	1	0	0	0	1	0	0	0	0	0	0
FM4 Dummy Demospongia	HARD	Deep	0	0	0	1	0	0	0	1	0	0	0	0	0	0
FM7 Dummy burrowing w_seapens	SOFT		0	0	0	0	0	0	1	1.2	2100	0.5	0.01	0.012	1000	50
FM7 Dummy burrowing w_umbellula	SOFT		0	0	0	0	0	0	1	1.2	2100	0.5	0.01	0.012	1000	50
FM4 Dummy hard substrate	HARD	Deep	0	0	0	1	0	0	0	1	0	0	0	0	0	0
FM1 Dummy hard substrate	HARD	Deep	1	0	0	0	0	0	0	1	0	0	0	0	0	0
FM7 Dummy sandy mud	SOFT		0	0	0	0	0	0	1	1.2	2100	0.5	0.01	0.012	1000	50
FM6 Dummy sandy mud	SOFT		0	0	0	0	0	1	0	1.2	2100	0.5	0.01	0.012	1000	50
FM5 Dummy sandy mud	SOFT		0	0	0	0	1	0	0	1.2	2100	0.5	0.01	0.012	1000	50
FM4 Dummy sandy mud	SOFT		0	0	0	1	0	0	0	1.2	2100	0.5	0.01	0.012	1000	50
FM2 Dummy sandy mud	SOFT		0	1	0	0	0	0	0	1.2	2100	0.5	0.01	0.012	1000	50
FM1 Dummy sandy mud	SOFT		1	0	0	0	0	0	0	1.2	2100	0.5	0.01	0.012	1000	50
FM5 Dummy sand	SOFT		0	0	0	0	1	0	0	1	2750	0.3	0.02	0.01	1000	50
FM4 Dummy sand	SOFT		0	0	0	1	0	0	0	1	2750	0.3	0.02	0.01	1000	50
FM2 Dummy sand	SOFT		0	1	0	0	0	0	0	1	2750	0.3	0.02	0.01	1000	50
FM1 Dummy sand	SOFT		1	0	0	0	0	0	0	1	2750	0.3	0.02	0.01	1000	50
FM5 Dummy mud	SOFT		0	0	0	0	1	0	0	2.4	2100	0.65	0.005	0.024	1000	50
FM4 Dummy mud	SOFT		0	0	0	1	0	0	0	2.4	2100	0.65	0.005	0.024	1000	50
FM2 Dummy mud	SOFT		0	1	0	0	0	0	0	2.4	2100	0.65	0.005	0.024	1000	50
FM1 Dummy mud	SOFT		1	0	0	0	0	0	0	2.4	2100	0.65	0.005	0.024	1000	50
FM7 Dummy mud	SOFT		0	0	0	0	0	0	1	2.4	2100	0.65	0.005	0.024	1000	50
FM6 Dummy mud	SOFT		0	0	0	0	0	1	0	2.4	2100	0.65	0.005	0.024	1000	50
FM5 Dummy coarse sand	SOFT		0	0	0	0	1	0	0	0.4	2750	0.25	0.05	0.004	1000	50
FM4 Dummy coarse sand	SOFT		0	0	0	1	0	0	0	0.4	2750	0.25	0.05	0.004	1000	50
FM2 Dummy coarse sand	SOFT		0	1	0	0	0	0	0	0.4	2750	0.25	0.05	0.004	1000	50
FM1 Dummy coarse sand	SOFT		1	0	0	0	0	0	0	0.4	2750	0.25	0.05	0.004	1000	50
FM5 Dummy bioclastic coarse sand	SOFT		0	0	0	0	1	0	0	0.4	2650	0.25	0.05	0.004	1000	50
FM4 Dummy bioclastic coarse sand	SOFT		0	0	0	1	0	0	0	0.4	2650	0.25	0.05	0.004	1000	50
FM2 Dummy bioclastic coarse sand	SOFT		0	1	0	0	0	0	0	0.4	2650	0.25	0.05	0.004	1000	50
FM1 Dummy bioclastic coarse sand	SOFT		1	0	0	0	0	0	0	0.4	2650	0.25	0.05	0.004	1000	50
FM 4and5 Dummy soft bottom coral garden	SOFT		0	0	0	1	1	0	0	1.2	2100	0.5	0.01	0.012	1000	50
FM 4and5 Dummy seapens	SOFT		0	0	0	1	1	0	0	1.2	2100	0.5	0.01	0.012	1000	50
FM4and5 Dummy Umbellula	SOFT		0	0	0	1	1	0	0	1.2	2100	0.5	0.01	0.012	1000	50

7.3.4.2 Impacted area (km^2)

The dummy data represent the maximum impact level, assuming that all cells have 100 km^2 of all VEC substrates and FMs. This is over-conservative, and the results are therefore presented per substrate type. Figure 52 show the results for all substrates and FMs, as percentage of the 21 simulations that have impacts in categories of impacted areas. As expected, the results show clearly the identical results between FMs 1 and 4 as well as FMs 2 and 5. Results were then investigated for each FM, which were compared between the substrates, to investigate the overall effect of the recommended combination of input parameters used.

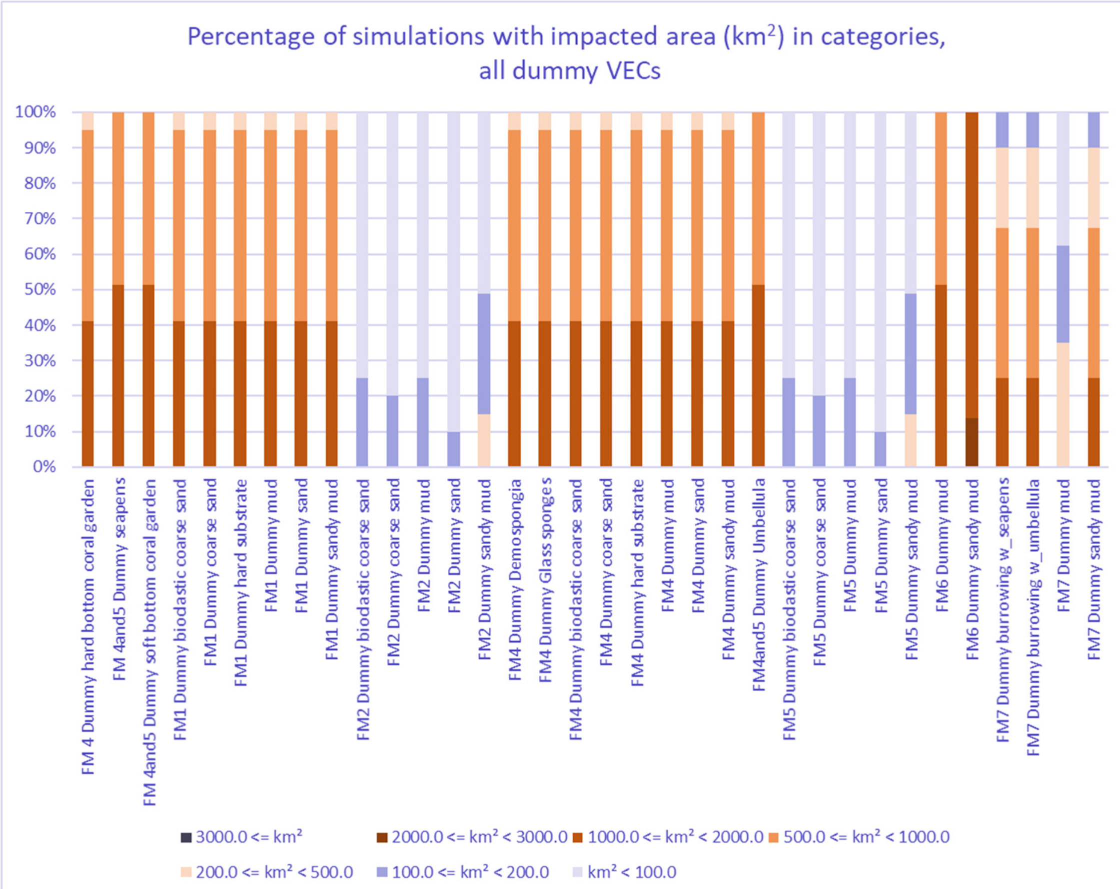


Figure 52. Cumulative probabilities as % of simulations that impact categories of areas. Dummy data are used, i.e the area shown is the maximum possible, and the impact is directly related to the oil contamination level and the differences in feeding modes and the substrate characteristics.

7.3.4.3 Feeding Modes 1 and 4 – Epifauna carnivores (and herbivores) and Epifauna suspension feeders

These organisms are only exposed through water column in the algorithms. As expected, the exposure is identical for all these, as water column exposure is independent of the substrate partitioning-defining parameters (Figure 53).

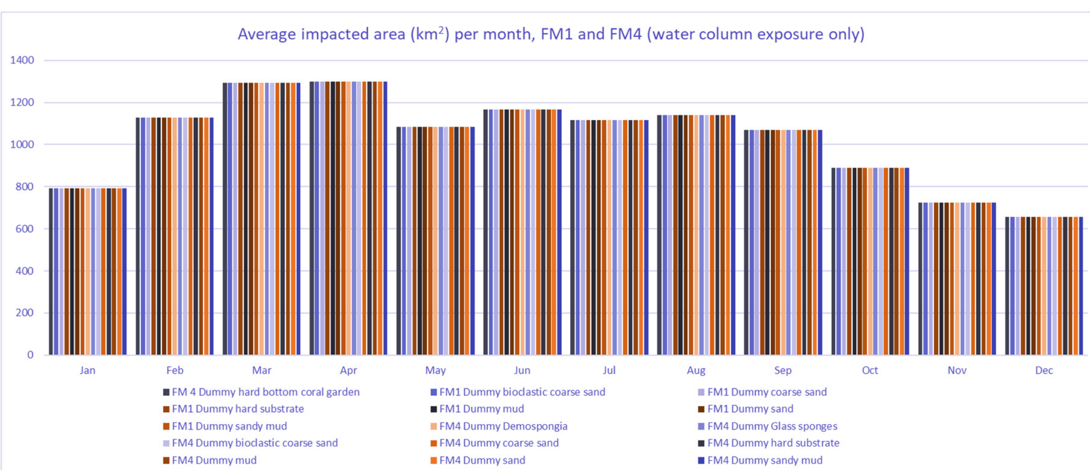


Figure 53. Result for FM1 and FM4 – water column exposure only for dummy datasets of 5 soft and 1 hard substrates.

7.3.4.4 Feeding Modes 2 and 5 – Infauna Carnivores and suspension feeders

These two feeding modes are exposed through interstitial water, but do not ingest THC-contaminated particles. Figure 54 shows the result of impacted areas calculated for FM2 and FM5 using the partitioning-defining parameters of each substrate type. The combination of a medium TOC-value (1.2 %), a lower mixing depth of 1 cm, and 50% water content leads to higher interstitial water in sandy mud, which correspondingly shows the highest impact.

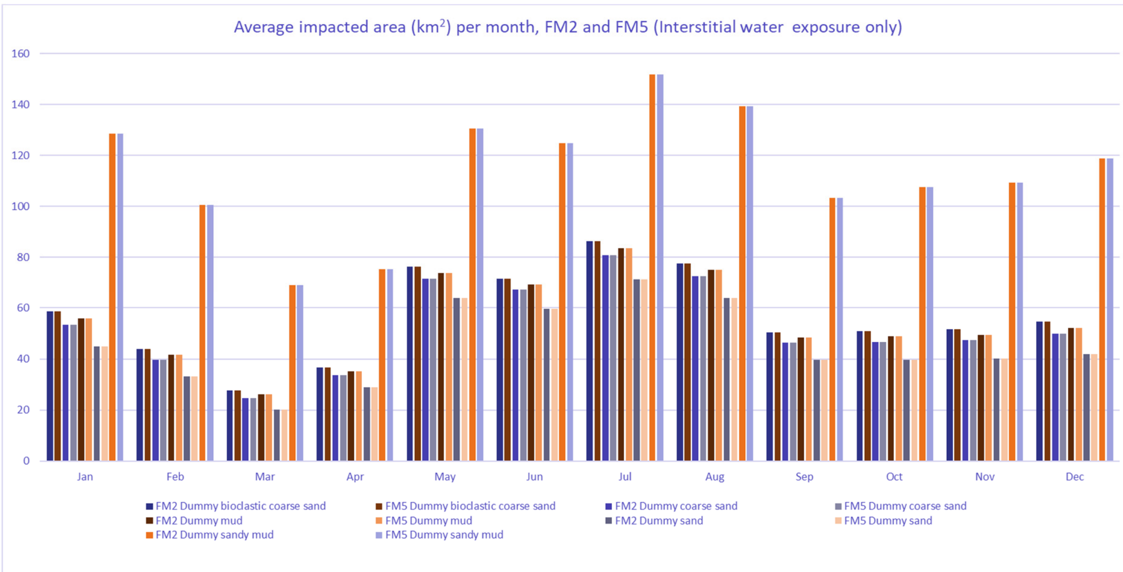


Figure 54. Result for FM2 and FM5 – interstitial water exposure only for dummy datasets of 5 soft substrate substrates (not relevant for hard substrates).

7.3.4.5 Organisms with both feeding modes 4 and 5 (Seapens, soft bottom corals and Umbellula)

Seapens, soft bottom corals and Umbellulas are exposed through both the water column as well as interstitial water. This leads to an additive effect of the two exposure routes. In Figure 55, the additive effect can be seen clearly. These organisms were ascribed to sandy mud in the data research, se section 9.2.

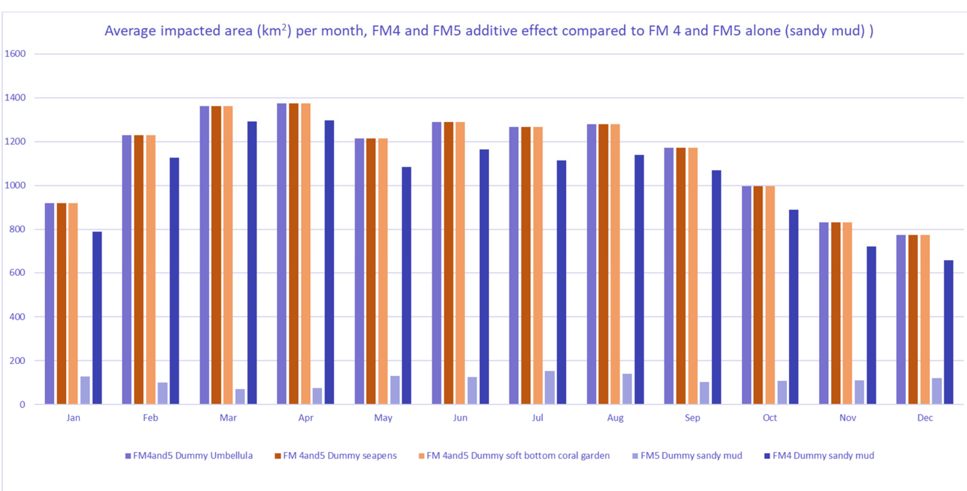


Figure 55. Result for FM4 (water column) and FM5 (Interstitial water) exposure individually, and the additive effect for organisms with exposure to both (seapens, soft bottom corals and *Umbellula*). The comparison is made to the two FMs individually on sandy mud.

7.3.4.6 Feeding modes 6 and 7 - Infauna and epifauna deposit feeders

The *epifaunal* FM6 organisms are exposed through interstitial water and through ingesting deposited sediment particles with THC. The *infaunal* FM7 organisms are exposed through interstitial water and ingestion. Figure 56 shows the result of impacted areas calculated for FM6 and FM7 using the partitioning-defining parameters of the two relevant substrate types mud and sandy mud. The combination of a medium TOC-value (1.2 %), a lower mixing depth of 1 cm, and 50% water content leads to higher interstitial water in sandy mud, which correspondingly shows the highest impact.

Looking at the figures for FM 1 and FM4 (water column only) (Figure 53) the overall impacted area is higher for organisms exposed through water column, than the impacted area calculated for exposure through interstitial water only (Figure 55). This difference is also reflected in the additive effect when including ingestion and exposure through gut water to either exposure route, FM6 organisms are more impacted than FM7 organisms. The difference is especially large for mud, which sequesters THC more than sandy mud (higher TOC-content), thereby releasing less to the bioavailable gut water.

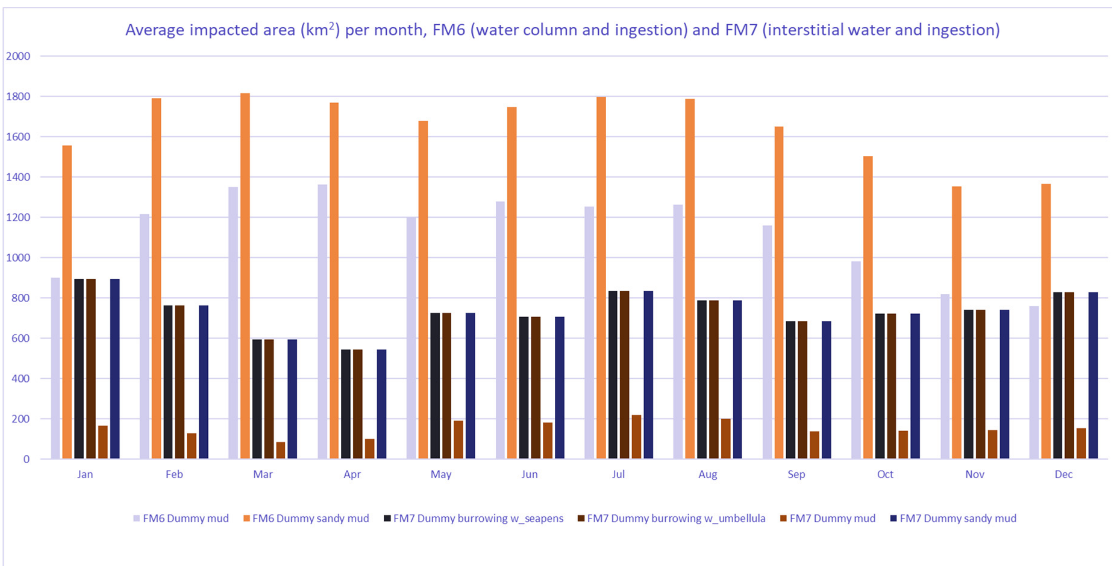


Figure 56. Results for FM6 and FM7 – interstitial water or water column exposure with the additional exposure through ingestion of contaminated deposited particles. Relevant mainly for mud and sandy mud. (The burrowing fauna associated with the seapen- and Umbellula-habitats have been assigned to sandy mud, as for seapens and Umbellulas.

Comparing the results for FM1 (=FM4) with FM6 shows the additional impact to epifaunal organisms when ingesting contaminated sediment deposits. Figure 57 shows how additive effect of ingestion increases the lethality of FM6 versus FM1 and FM4, and more so in sandy mud where the TOC-content is lower, and more THC is partitioned into the gut water. The difference between ingesting and not ingesting particles is also evident in Figure 58, where the difference between FM7 and FM2 is very large, again more so in sandy mud than in mud. Overall exposure is highest in organisms exposed in water column.

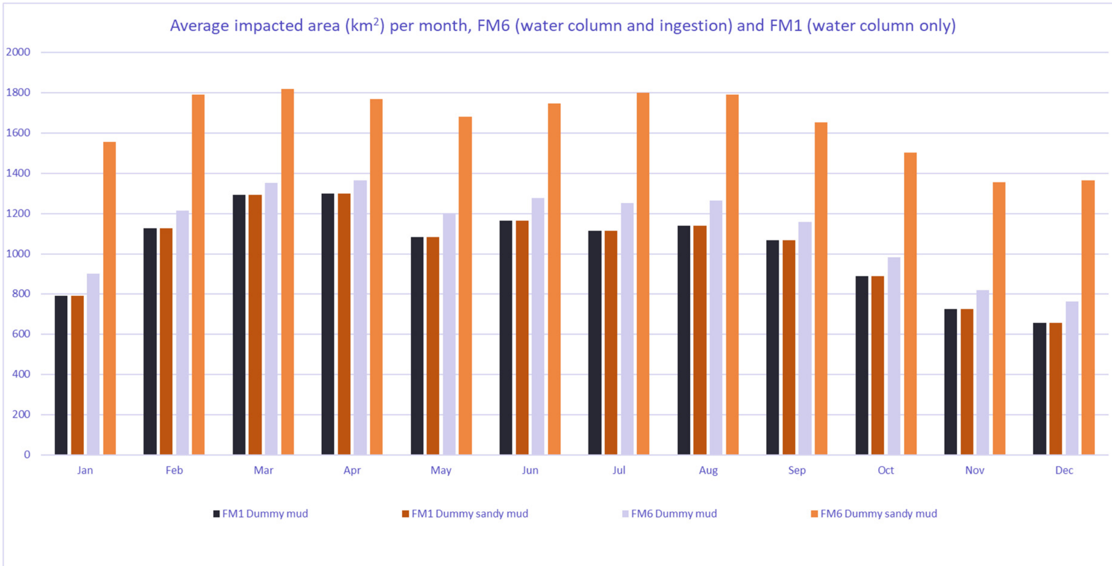


Figure 57. Results for FM1/4–water column only and FM6 water column exposure with the additional exposure through ingestion of contaminated deposited particles. Relevant mainly for mud and sandy mud.

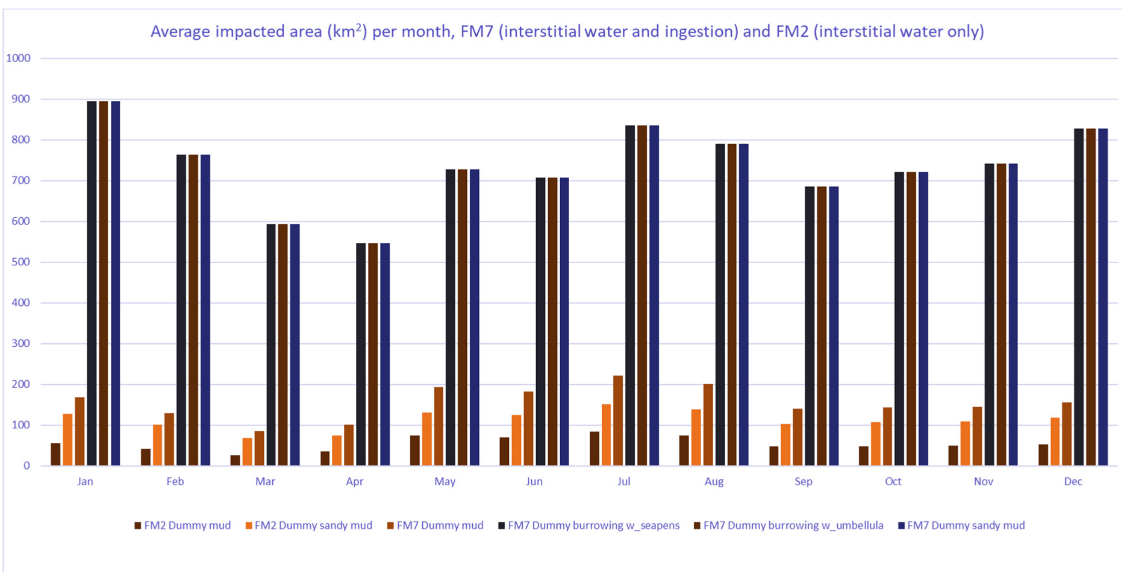


Figure 58. Results for FM2/5– interstitial water only and FM7 interstitial water exposure with the additional exposure through ingestion of contaminated deposited particles. Relevant mainly for mud and sandy mud.

7.3.5 Discussion of feeding mode sensitivity testing

Using 100 % presence of each of the FMs included is expected to be overly conservative relative to the way the model was designed, as there is no true additive effect (in toxicological terms) for each of the organisms representing a FM individually.

Regarding the large difference between 4A and 4B: As the areas of each substrate are the same for all datasets and the FM distribution is the same in all, the vastly different results between including the dominant FMs for each substrate (4.A) and including all (4.B), reflects the difference in exposure in interstitial water and gut water resulting from the differences in the substrate characteristics used as input parameters to the calculations of $C_{THC,IW}$ and $C_{THC,Ing}$. Ingestion is included in FMs 6 and 7. Note the differences in the results from coarse sand and bioclastic coarse sand when feeding modes with exposure from ingestion are included for especially these two substrates (in 4.B, as opposed to not including FM6 and 7 in 4.A. The TOC content is low in the two coarse sand types and any THC contained on ingested deposits will more easily be released into the gut water than when the substrates contain less TOC. However, it may be argued that the deposit particle itself is the fraction of the substrate that **does** contain the TOC, and therefore that the calculated “ready release” into the gut water is not really the case, but an artifact of calculation. Also, on substrates with less organic deposits to feed on (which as the particles containing the carbon) there is a lower abundance of organisms feeding on deposits. It is therefore assumed that the approach of including these FMs should be considered as overly conservative, and not relevant in use of ERA Acute.

For seapens and similar organisms (soft bottom corals and Umbellulas), on the other hand, the additive effect to an organism is reflected when FM modes 4 and 5 are used with 100 % exposure in both sub-compartments.

8 Test 5 Parameters related to restitution

8.1 Lag- and restitution in hard substrates

For hard-bottom species, T_{lag} and T_{res} have specific values determined in input files, based on literature values found in Phase 3 of the ERA Acute development project. T_{lag} and T_{res} are assumed to be long for corals. However, these parameters are not tested for sensitivity as the data are sparse, and the values are recommended standard values that are not calculated in an equation needing sensitivity testing. The preliminary lag- and restitution values for hard bottom substrates needs more research for ranges of values before a scientific testing of sensitivity and uncertainty can be carried out.

Corals and sponges are as mentioned, assigned FM 4 and their impact depends on water column exposure for calculation of *plet* WC. Hard substrate carnivores are assigned to FM1, resulting in equal lethality as species with FM4. Due to their being assigned to the same restitution calculation as other hard substrate organisms, which is designed for deep sea corals, their restitution time is currently assumed to be overly conservative for carnivores. Return of the carnivores is however dependent on the restitution of prey species (hydroids, sponges etc.) which will occur as soon as recolonization begins. In the future, if relevant it would result in better resolution for hard substrate communities if specific restitution tables were used for other species on hard substrates.

Hard substrate ***carnivores*** are in the current version of ERA Acute not assigned a specific recovery function based on their regeneration properties. The current version of ERA Acute estimates a recovery time for deep water coral reefs based on a *table* with estimates of recovery time related to the magnitude of impact, as mentioned above. The restitution time is *calculated* for soft substrates according to the amount of THC in the sediment, and this equation is not relevant for hard substrates. Therefore, in future work, a special restitution equation could be put in place for hard bottom carnivores (FM1 on HARD bottom) allowing them to recover more quickly than the coral reefs. However, considering that the carnivores on the reef are dependent on a healthy reef, it could be argued that their restitution time is closely tied to the reef restitution.

8.2 Test 5A. Restitution time in soft substrate sediments – adjustment method test

For sediment-dwelling organisms, restitution times are calculated using the concentration of THC in the sediments that is calculated in the Equation 1 and therefore varies with BDepth, Water Content and Dry Weight (See test 1a-c).

Based on experience data from monitoring studies after the use of oil-based drilling mud on the Norwegian Shelf, on literature and best judgement, a linear relationship between $C_{THC,sed}$ and $T_{res,sed}$ is currently used. For the few sample sites in the North Sea where information was available, restitution times were within the time frame of 20 years which gave the following restitution formula:

Equation 7

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

Threshold and benchmark values will be tested with varying input values of $C_{THC,sed}$ and using varying values of the currently static values of $C_{threshold,sed}$ and $C_{benchmark\text{-}max,sed}$. (NB! ppm is used in this formula, the equations for calculation of impact uses ppb).

$C_{threshold,sed}$: Threshold value for effect, NOEC - the concentration of THC at which effects on faunal communities in sediment cannot be detected in monitoring studies (Renaud *et al.* 2008) . 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 (Maximum at equilibrium).

Holding BDepth fixed for all substrates at 0.0575 cm, and using values for water content and dry weight at relevant values for the four soft substrate types, the results of the current implementation is shown in Figure 59 in using extreme values for $C_{THC,sed}$ in sediment in kg/m^2 (Excel spreadsheet). Figure 60 shows the same extreme input of $C_{THC,sed}$ values (kg/m^2), but using BDepths that are individual for the different substrates (Table 5). Using BDepths that are smallest for mud (0.005m) and largest for coarse sand (0.05m) the trends are turned the other way around, solely due to the calculation of $C_{THC,sed}$ in ppm which is different when the mixing depths are changed. This confirms the importance of mixing depths, which should be chosen with care also with respect to calculation of restitution times.

Figure 61 shows the restitution times with varying input of $C_{THC,sed}$ (kg/m^2) values from the cells in simulation 17 that gave $C_{THC,sed}$ exceeding 0.01 (kg/m^2) for the four soft substrates using their individual concentration-defining input parameters for each substrate (WaterContent, DryWeight and BDepth) proposed in Table 5.

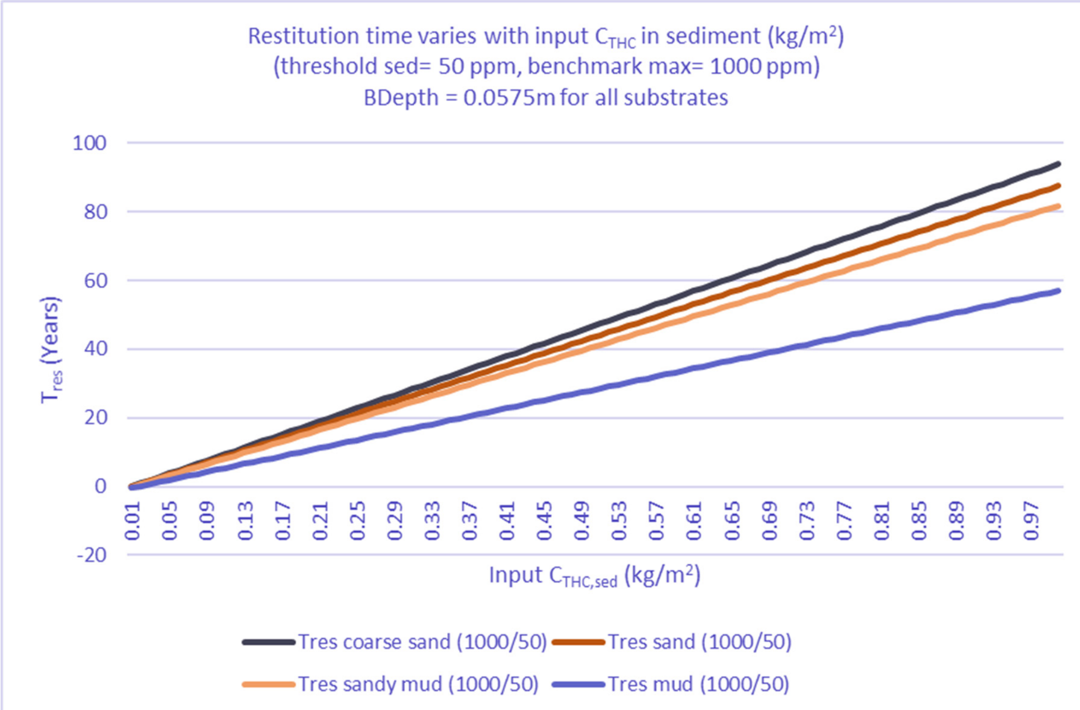


Figure 59. Restitution times with varying (high) input $C_{THC,sed}$ (kg/m^2) values for the four soft substrates using their concentration-defining input parameters for each substrate (WaterContent, DryWeight). BDepth is held the same for all substrates.

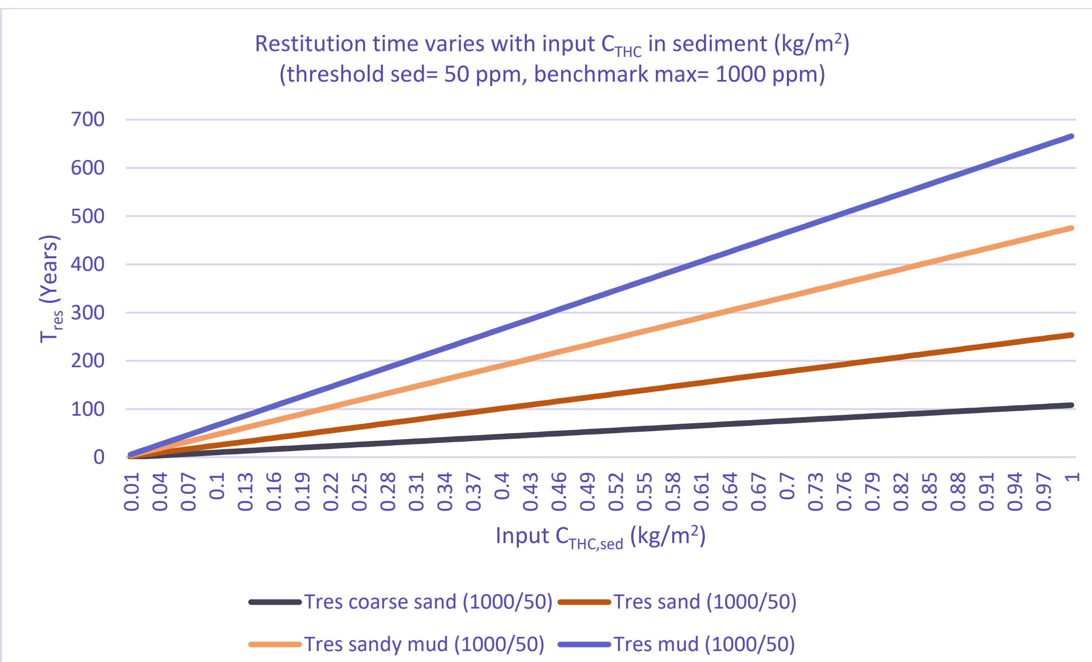


Figure 60. Restitution times with varying (extreme high) input $C_{THC,sed}$ (kg/m^2) values for the four soft substrates using their concentration-defining input parameters for each substrate (WaterContent, DryWeight and BDepth).

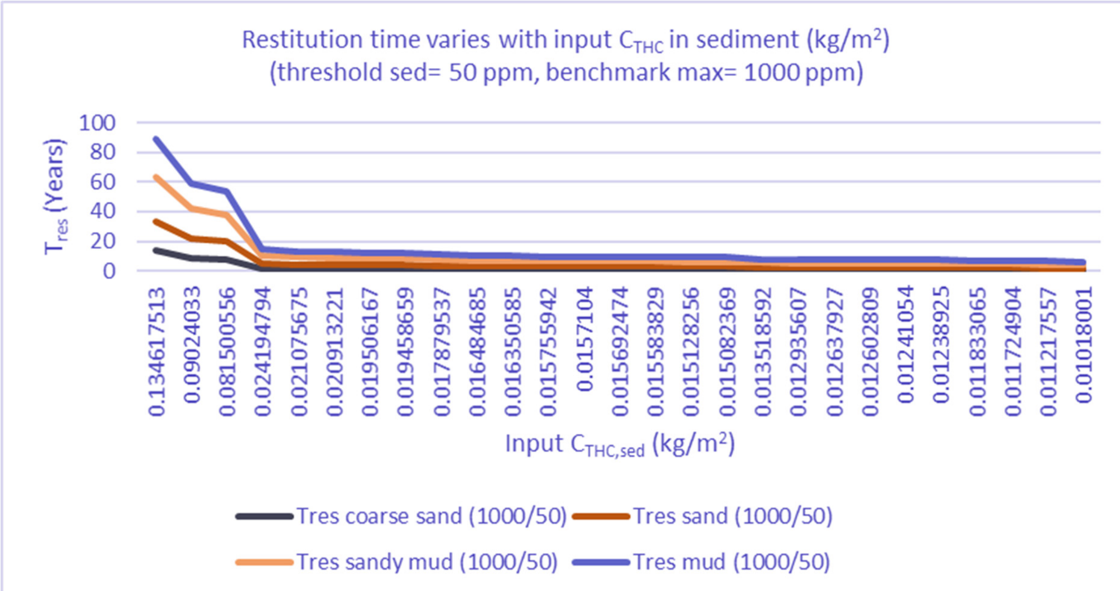


Figure 61. Restitution times with varying input $C_{THC,sed}$ (kg/m²) values from the cells in simulation 17 that gave $C_{THC,sed}$ exceeding 0.01 (kg/m²) for the four soft substrates using their concentration-defining input parameters for each substrate (WaterContent, DryWeight and BDepth) (sorted from highest to lowest input value!

8.2.1 Restitution times in the five substrates from the oil drift simulations

The 21 oil drift simulations were run through the core calculator. The exported file containing the original $C_{THC,sed}$ (kg/m²) values for each cell and simulation was used to calculate $C_{THC,sed}$ (ppm)-values for each substrate based on their bioturbation depths, water content and dry densities, as they have been found to be "most reasonable" in the preceding literature searches and sensitivity tests.

The results can be seen in Table 16, which shows the number of cells with $C_{THC,sed} > 0$ kg/m², maximum $C_{THC,sed}$ values (kg/m²) in a cell, and the corresponding calculated average and maximum restitution times t_{res} (years) and number of cells with $t_{res} > 0$ years for each of the five substrate types. Averages are calculated using only the cells with tres > 0, to be interpreted as average restitution times in cells where the restitution time is >0.

Some cells in the simulations receive a relatively high amount of oil whereas most cells are contaminated with levels of THC that are converted to less than 50 ppm oil, and therefore give tres<0 (negative values, which are disregarded). In the 21 simulations, the number of 10x10 km cells that are contaminated with more than 0 kg/m² THC vary between 413 (sim 15) and 1072 (sim 9) cells. As can be seen, the number of cells with $t_{res} > 0$ and both average and maximum restitution times vary between the substrates. In mud, the calculations lead to higher concentrations (given the same exposure) and thereby higher number of cells with $t_{res} > 0$, higher average t_{res}-values and higher maximum restitution time. The longest restitution time calculated for a cell in a single simulation is (88.7 years cell 30080 in sim17). Added together, 40 cells have more than 20 years restitution time (mud). Simulations 15, 18, 19, 20 and 21 have maximum restitution times in any cell below 20 years).

Table 16. Number of cells with $C_{THC,sed} > 0$ kg/m^2, maximum values in a cell, and the corresponding calculated average and maximum restitution times t_{res} (years) and number of cells with $t_{res} > 0$ years for each of the five substrate types. SF = 1 for all substrates.

					mud		Sandy mu		Sand		Coarse sand		Bioclastic coarse sand	
ID-Sim	# cells CTHC sed> 0	Ave CTHC,sed (kg/m2)	Max CTHC,sed (kg/m2)	Sum values in cells	#cells Tres >0	Ave tres in cells with tres>0 (t_resmax)	#cells Tres >0	Ave tres in cells with tres>0 (t_resmax)	#cells Tres>0	Ave tres in cells with tres>0 (t_resmax)	#cells Tres>0	Ave tres in cells with tres>0 (t_resmax)	#cells Tres>0	Ave tres in cells with tres>0 (t_resmax)
1	727	1.01E-03	0.045	0.734	105	2.8 (29.2)	74	2.5 (20.6)	45	1.6 (10.5)	15	1.1 (3.9)	17	1.0 (4.1)
2	559	9.97 E-04	0.037	0.556	84	2.8 (24.0)	63	2.3 (16.9)	35	1.7 (8.5)	16	0.7 (3.1)	16	0.8 (3.2)
3	449	1.26 E-03	0.044	0.568	87	2.8 (28.3)	63	2.4 (19.9)	38	1.5 (10.2)	12	0.9 (3.8)	12	1.0 (4.0)
4	504	1.22 E-05	0.065	0.614	81	3.3 (42.5)	63	2.7 (30.1)	40	1.7 (15.6)	18	0.8 (6.1)	18	0.9 (6.4)
5	549	1.53 E-03	0.095	0.841	110	3.5 (62.2)	84	3.0 (44.2)	44	2.4 (23.2)	22	1.3 (9.4)	23	1.3 (9.7)
6	645	1.41 E-03	0.082	0.912	106	4.0 (53.4)	93	3.0 (37.9)	53	2.2 (19.8)	22	1.4 (7.9)	23	1.5 (8.2)
7	749	1.8 E-03	0.088	1.35	158	4.1 (57.9)	130	3.2 (41.1)	84	2.1 (21.5)	30	1.6 (8.6)	31	1.6 (9.0)
8	815	1.33 E-03	0.061	1.09	148	3.2 (39.7)	113	2.7 (28.1)	73	1.7 (14.6)	23	1.2 (5.7)	26	1.1 (5.9)
9	1072	7.47 E-04	0.044	0.801	121	2.5 (28.5)	92	2.1 (20.1)	39	1.9 (10.3)	15	1.2 (3.8)	17	1.1 (4.0)
10	891	9.97 E-04	0.068	0.889	120	3.1 (44.5)	89	2.7 (31.5)	46	2.1 (16.4)	18	1.4 (6.5)	19	1.4 (6.7)
11	612	1.6 E-03	0.088	0.987	116	3.9 (57.5)	91	3.2 (40.8)	54	2.3 (21.3)	24	1.4 (8.6)	24	1.4 (8.9)
12	907	1.04 E-03	0.036	0.941	125	3.3 (23.1)	96	2.8 (16.2)	60	1.8 (8.2)	23	1.1 (2.9)	23	1.1 (3.1)
13	945	9.54 E-04	0.037	0.901	118	3.4 (23.8)	103	2.5 (16.7)	59	1.7 (8.5)	21	1.1 (3.1)	22	1.1 (3.2)
14	632	9.04 E-04	0.032	0.571	86	2.8 (20.7)	61	2.5 (14.5)	41	1.4 (7.3)	12	0.8 (2.6)	13	0.8 (2.7)
15	413	8.3 E-04	0.013	0.343	61	2.0 (11.9)	43	1.7 (8.2)	20	1.2 (3.9)	7	0.4 (1.1)	7	0.5 (1.2)
16	596	1.59 E-03	0.091	0.948	109	4.2 (59.3)	83	3.6 (42.1)	55	2.3 (22.0)	23	1.5 (8.9)	24	1.5 (9.2)
17	574	1.82 E-03	0.134	1.05	103	5.2 (88.7)	76	4.7 (63.1)	57	2.8 (33.3)	29	1.6 (13.7)	29	1.7 (14.2)
18	472	7.83 E-04	0.021	0.369	50	2.9 (13.2)	38	2.4 (9.2)	26	1.4 (4.4)	11	0.6 (1.3)	11	0.6 (1.4)
19	514	4.93 E-04	0.015	0.254	37	2.4 (9.1)	28	1.9 (6.2)	19	0.9 (2.9)	4	0.4 (0.7)	4	0.4 (0.7)
20	624	7.51 E-04	0.025	0.469	81	2.1 (15.7)	64	1.6 (10.9)	37	0.9 (5.4)	7	0.4 (1.7)	7	0.5 (1.8)
21	648	1.15 E-03	0.026	0.744	118	2.5 (16.4)	96	1.9 (11.4)	53	1.2 (5.6)	17	0.7 (1.8)	18	0.7 (1.9)

8.2.2 Need for adjustment in the calculations identified - calibration

The formula used for calculating the $C_{THC,sed}$ -concentration (in ppm and ppb) uses input values that are different for the four substrate types; with the currently found parameters and using the same bioturbation depth, the sensitivity test with the same bioturbation depth leads to a higher concentration in coarse sand than in mud. Given the knowledge of a larger degree of leaching of hydrocarbons from coarse sands with low TOC than from muds with a higher TOC, it should be clear from this figure that the formula initially proposed used in ERA Acute, which is based on data from the North Sea regardless of substrate (See Stephansen *et al.* 2015), needed adjustment that takes into consideration the differences in TOC of the substrate. Bioturbation leads to mixing of the surface water and interstitial water, leading to a gradual removal of THC that leaches into the IW phase, by flowing water above. The partitioning theory assumes equilibrium, however the process is in the *direction of* equilibrium, not *at* equilibrium. The leaching process needs to be taken into consideration to reflect the effect of TOC on leaching vs. sequestration of THC in soft substrates. This adjustment was suggested as part of the calibration of the model (WP2d), but the suggested approach needed to be tested with respect to sensitivity. Therefore, these tests have been included in the present report.

The standard value of 20 years was proposed based on sites in the North Sea where the substrates in general are finer sands and silts, a longer time frame should be used for mud and a shorter time frame could be used for coarser substrates with lower TOC (for which a lower degree of sequestration would be expected, facilitating washing out the THC from the sediments and thereby faster recovery).

For the sake of implementation, this was proposed to be handled simply in the model, by using a sensitivity factor for correcting this issue. 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. A default value has been proposed in the model to be SF=1, indicating no difference from the general community sensitivity. It is entered into the resource setup-file. This sensitivity factor was originally (Stephansen *et al.* 2015) proposed to be used in case the user has additional information for particularly sensitive *species* where the sensitivity is tied to longer restitution time than would be calculated by the $C_{THC,sed}$ concentrations in the substrate alone. However, the restitution time could also be shorter, and some substrates may have a shorter standard restitution time than the general 20 years that were extrapolated based on summary of the data from the North Sea in the MOD-database by Renaud *et al.* (2008) (see Stephansen et al, 2015, Chapter 11.5.2 for details).

In course of the present sensitivity testing of the soft bottom substrate functions, a change was therefore made to the core calculator as part of the calibration process (WP2d): The SF could be used for species *or substrates* with higher or lower sensitivity due to longer or shorter restitution times than the "standard" of 20 years at assumed maximum contamination from drill cuttings with oil based drilling muds (MOD database).

Using this sensitivity factor for adjusting substrate-based differences was easily implemented in the calculator, and was made available within the time frame of the testing of effects in the model also for substrates with longer or shorter restitution times than 20 years.

The following equation was therefore implemented into the model before finalisation:

Equation 8

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

8.2.3 Tests for calibration of the restitution "sensitivity" factor

8.2.3.1 Knowledge gap

Following the Deep Water Horizon oil spill, assessment of petrogenic hydrocarbons have been carried out under the Gulf of Mexico Research Initiative (GOMRI) programme (http://gulfresearchinitiative.org/study-estimates-carbon-likely-from-deepwater-horizon-spill-in-gulf-sediment/) . In a study published in 2015 it was estimated was that oil-derived carbon equivalent to 3-4.9 percent of total oil reported spilled could be accounted for by carbon found in the sediments. Most of the deposited petrocarbon was located southwest of the spill site where oil plumes were observed in the water column. Sediments on the seafloor may sequester oil long-term, due to reduced oxygen and cold temperatures in deep waters, that slow down the decomposition rate. As assumed above, by the chemical partitioning and *infaunal* bioturbation processes, oil that was originally stored in the sediment could re-enter the water column and re-expose epifauna, but would also by the same mechanisms be transported away, diluted and degraded. However, the authors also point to a knowledge gap regarding how much petroleum-originated carbon that is sequestered in the sediment and the decay rate after an oil spill. There is an important step in gaining a better understanding of potential long term environmental effects, and there is currently no answer to how long the impacts of the DWH oil spill will last in the sediments.

8.2.3.2 Calibration testing

To assist in the calibration of the model, i.e. find, for each substrate, the value of $C_{THC,sed}$ (kg/m^2) at which the calculated value of $C_{THC,sed}$ = ($C_{benchmark\text{-}max,sed}$) (1000 ppm) was found for each of the five main substrate types, using their parameters. The benchmark value is the value at which the contamination is anticipated to be so high that the conditions become anoxic and the degradation slows down.

Table 17 Value of CTHC,sed (kg/m^2) at which CTHC,sed = Cbenchmark-max,sed (1000 ppm) for the five main substrate types.

Substrate	Dry density (kg/m^3)	Water content (%)	TOC (%)	BDepth (m)	Value of $C_{THC,sed}$ (kg/m^2) at which $C_{THC,sed}$ is 1000 ppm ($C_{benchmark\text{-}max,sed}$)	Tres (years at $C_{THC,sed}$) with standard SF=1
Bioclastic coarse sand	2650	25	0.4	0.05	0.1767	19.00
Coarse sand	2750	25	0.4	0.05	0.18334	19.00
Sand	2750	30	1	0.02	0.07858	19.00
Sandy mud	2100	50	1.2	0.01	0.042	19.00
Mud	2100	65	2.4	0.005	0.03	19.00

For the 21 simulations of oil drift carried out, only a few of the exposed cells in each simulation resulted in restitution times above zero (Table 16). As mentioned, the first calculation of concentration of THC in ppm from THC amount in kg/m^2 is decided by substrate-specific parameters. Cells with $C_{THC,sed}$ (ppm) above 50 ppm will result in a restitution time tres>0 years. Most cells have a lower exposure and therefore give no restitution time. Due to the parameters of the initial calculation, the concentrations in the bioturbated layer are highest in mud, as can be expected. The restitution times calculated are therefore significantly longer in mud and muddy sand, than in the coarse sand types.

To adjust for the expected longer restitution times caused by sequestering of THC by substrates with higher TOC content than sand, the following argument was investigated:

The leaching of THC from TOC-bound to water phase is assumed to be the same whether it is leached to interstitial water or the water phase above, although the transport away (dilution) in the water column will remove the THC faster than in interstitial water, which would influence the concentrations, however the exchange between water in the sediment and above will remove THC from both water compartments together. Using a $LogK_{OW}$ of 5.95 and TOC = 2.4% $C_{THC,sed}$ is 16970.6 times higher than the $C_{THC,IW}$ for mud. For sandy mud (TOC= 1.2 %) the ratio $C_{THC,sed}/C_{THC,IW}$ = 8485.3 and for sand (TOC=1%) $C_{THC,sed}/C_{THC,IW}$ = 7071. Directly proportional to the TOC-content in the substrate, the degradation due to leaching can be accounted for by using the SF calculated as follows:

In the current implementation, the "standard" of 20 years at benchmark contamination was used, based on data assumed mostly to be sandy bottom (North Sea).

- TOC of sand is 1 % in these tests, TOC for mud is 2.4 %, ratio TOC_{mud}/TOC_{sand}=2.4
- Relative to sand, it is postulated that the SF for mud should be 2.4, and for sandy mud 1.2
- For coarse sands, with very low ability to sequester THC, is seems reasonable that the THC is washed out reasonably fast and the SF is set to 0.4.

Please note that the above "rule" of the factor seemingly being the same as the TOC-value in % is only valid because the TOC of the "standard is 1%. The SF is calculated as follows:

Equation 9

$$SF_{substr} = TOC_{substr}/TOC_{std.substr.}$$

8.3 Test 5B. Test of the sensitivity factor in different substrates

Values from the 21 simulations given in Table 16 were multiplied with the proposed "sensitivity" factor (SF in the setup and formula) representing the enhanced or slowed degradation due to leaching. The results are shown in Table 18. Using the sensitivity factor = $TOC_{substr}/TOC_{std.substr}$ leads to single cells in mud and sandy mud having very long restitution times. The cell with the longest restitution time using a SF of 2.4 (30080 in simID17) has 0.135 kg/m^2 in the cell, which has an area of 10000 ×10000 m^2, resulting in 1350 tonnes of oil in the cell sediments.

Whether this is overly conservative in the case of whole simulation results and averages for simulations is difficult to assess, given that the results of restitution times from a similar spill, the Deepwater Horizon incident are yet unavailable. In the Braer oil spill, the contamination of the sea floor was evident in the 10 year ban of catching of the burrowing species Norway lobster (*Nephrops norvegicus*) due to exposure in the sediment. In contrast, the epifaunal European lobster was not affected to the same degree.

Coarser sand types and gravels are mainly present in areas where the currents are higher, so that the finer, lighter carbon-rich organic sediment particles and silts do not accumulate as easily. Reducing the time of restitution in the coarse sands additionally will also contribute towards adjusting the restitution model for washing way the actual particles to which the THC is bound.

Table 18. For all cells with $C_{THC,sed} > 0$ kg/m^2, average and maximum restitution times with and without correction for reduced or increased leaching of THC into water phase (relative to sand) (SF). for all substrates.

	Mud				Sandy mud				Sand				Coarse sand				Bioclastic coarse sand			
SimID	Ave NoSF	Ave SF=2.4	Max NoSF	Max SF=2.4	Ave NoSF	Ave SF=1.2	Max NoSF	Max SF=1.2	Ave NoSF	Ave SF=1	Max NoSF	Max SF=1	Ave NoSF	Ave SF=0.4	Max NoSF	Max SF=0.4	Ave NoSF	Ave SF=0.4	Max NoSF	Max SF=0.4
1	2.8	6.72	29.2	70.08	2.5	3	20.6	24.72	1.6	1.6	10.5	10.5	1.1	0.44	3.9	1.56	1	0.4	4.1	1.64
2	2.8	6.72	24	57.6	2.3	2.76	16.9	20.28	1.7	1.7	8.5	8.5	0.7	0.28	3.1	1.24	0.8	0.32	3.2	1.28
3	2.8	6.72	28.3	67.92	2.4	2.88	19.9	23.88	1.5	1.5	10.2	10.2	0.9	0.36	3.8	1.52	1	0.4	4	1.6
4	3.3	7.92	42.5	102	2.7	3.24	30.1	36.12	1.7	1.7	15.6	15.6	0.8	0.32	6.1	2.44	0.9	0.36	6.4	2.56
5	3.5	8.4	62.2	149.28	3	3.6	44.2	53.04	2.4	2.4	23.2	23.2	1.3	0.52	9.4	3.76	1.3	0.52	9.7	3.88
6	4	9.6	53.4	128.16	3	3.6	37.9	45.48	2.2	2.2	19.8	19.8	1.4	0.56	7.9	3.16	1.5	0.6	8.2	3.28
7	4.1	9.84	57.9	138.96	3.2	3.84	41.1	49.32	2.1	2.1	21.5	21.5	1.6	0.64	8.6	3.44	1.6	0.64	9	3.6
8	3.2	7.68	39.7	95.28	2.7	3.24	28.1	33.72	1.7	1.7	14.6	14.6	1.2	0.48	5.7	2.28	1.1	0.44	5.9	2.36
9	2.5	6	28.5	68.4	2.1	2.52	20.1	24.12	1.9	1.9	10.3	10.3	1.2	0.48	3.8	1.52	1.1	0.44	4	1.6
10	3.1	7.44	44.5	106.8	2.7	3.24	31.5	37.8	2.1	2.1	16.4	16.4	1.4	0.56	6.5	2.6	1.4	0.56	6.7	2.68
11	3.9	9.36	57.5	138	3.2	3.84	40.8	48.96	2.3	2.3	21.3	21.3	1.4	0.56	8.6	3.44	1.4	0.56	8.9	3.56
12	3.3	7.92	23.1	55.44	2.8	3.36	16.2	19.44	1.8	1.8	8.2	8.2	1.1	0.44	2.9	1.16	1.1	0.44	3.1	1.24
13	3.4	8.16	23.8	57.12	2.5	3	16.7	20.04	1.7	1.7	8.5	8.5	1.1	0.44	3.1	1.24	1.1	0.44	3.2	1.28
14	2.8	6.72	20.7	49.68	2.5	3	14.5	17.4	1.4	1.4	7.3	7.3	0.8	0.32	2.6	1.04	0.8	0.32	2.7	1.08
15	2	4.8	11.9	28.56	1.7	2.04	8.2	9.84	1.2	1.2	3.9	3.9	0.4	0.16	1.1	0.44	0.5	0.2	1.2	0.48
16	4.2	10.08	59.3	142.32	3.6	4.32	42.1	50.52	2.3	2.3	22	22	1.5	0.6	8.9	3.56	1.5	0.6	9.2	3.68
17	5.2	**12.48**	88.7	**212.88**	4.7	5.64	63.1	75.72	2.8	2.8	33.3	33.3	1.6	0.64	13.7	5.48	1.7	0.68	14.2	5.68
18	2.9	6.96	13.2	31.68	2.4	2.88	9.2	11.04	1.4	1.4	4.4	4.4	0.6	0.24	1.3	0.52	0.6	0.24	1.4	0.56
19	2.4	5.76	9.1	21.84	1.9	2.28	6.2	7.44	0.9	0.9	2.9	2.9	0.4	0.16	0.7	0.28	0.4	0.16	0.7	0.28
20	2.1	5.04	15.7	37.68	1.6	1.92	10.9	13.08	0.9	0.9	5.4	5.4	0.4	0.16	1.7	0.68	0.5	0.2	1.8	0.72
21	2.5	6	16.4	39.36	1.9	2.28	11.4	13.68	1.2	1.2	5.6	5.6	0.7	0.28	1.8	0.72	0.7	0.28	1.9	0.76

8.4 Test 5 C. Test of the restitution thresholds 50 ppm and 25 ppm (soft substrates)

Using the VEC same data sets as in test 4C (individual VECs for each (dominant) FM and soft substrate, as well as some individual sensitive species, the analyses of endpoints were carried out using the same parameters for all VECs, with the exception of the threshold for restitution. In test 4A it was 50 ppm as per recommended default. In test 5 C it was 25 ppm and the results were compared with results with 50 ppm. This does not affect hard bottom restitution times.

The general background level that was proposed on a general basis (Stephansen et al. 2015) as a threshold for restitution was 50 ppm (mg/kg). In the MAREANO project, background levels of oleogenic hydrocarbons are low in Norwegian Sea at Mørebankene and off Lofoten and Vesterålen, observed levels are even lower at Tromsøflaket. PAH is used as an indicator substance of hydrocarbons, and total PAH levels in the upper sediment layer are less than 500µg/kg on the shelf and up to 2500µg/kg on the slope down towards 2000m depth, while THC levels are less than 25mg/kg (25 ppm) (Jensen *et al.* 2016 – Chapter 10 in Buhl-Mortensen *et al.* (eds.), 2016).

To test the significance of the threshold value, two runs of the ERA Acute calculations were carried out, using 50 ppm and 25 ppm as thresholds. The 21 oil drift simulations of from the blowout case (section 2.2) were first run through the ERA Acute Tool version (1.0.1.2 using calculator v.0.59) using "dummy" VEC data with full coverage of all VECs and all feeding modes as individual VEC data sets. Parameter values were used as per the final recommendation obtained from the testing in the current work package (given in Table 15), based on MAREANO data (Buhl-Mortensen *et al.* (eds.), 2016). This is done to test what the maximum impact would be given the exposure from the oil drift simulations only. The *impact* is equal in the two runs and is presented in section 7.3.4.

8.4.1 Restitution times for soft substrates using threshold 50 ppm

Restitution is dependent to the substrate type and is independent of feeding mode, and the results are therefore presented for only one FM for each substrate. FM 5 (exposure through interstitial water) is used as the most relevant. All FMs on the same soft substrates have the same restitution time.

The ERA Acute project is carried out by a consortium of industry partners (Statoil, Total, Norwegian Oil and Gas Association) and experts in environmental risk analysis (Acona, Akvaplan-niva (Project Manager), DNV-GL and SINTEF), supported also by the Research Council of Norway.

ERA Acute is developed to provide a globally applicable, transparent method for quantitative environmental risk assessment of oil spills in four compartments: Sea surface, shoreline, water column and sea floor.

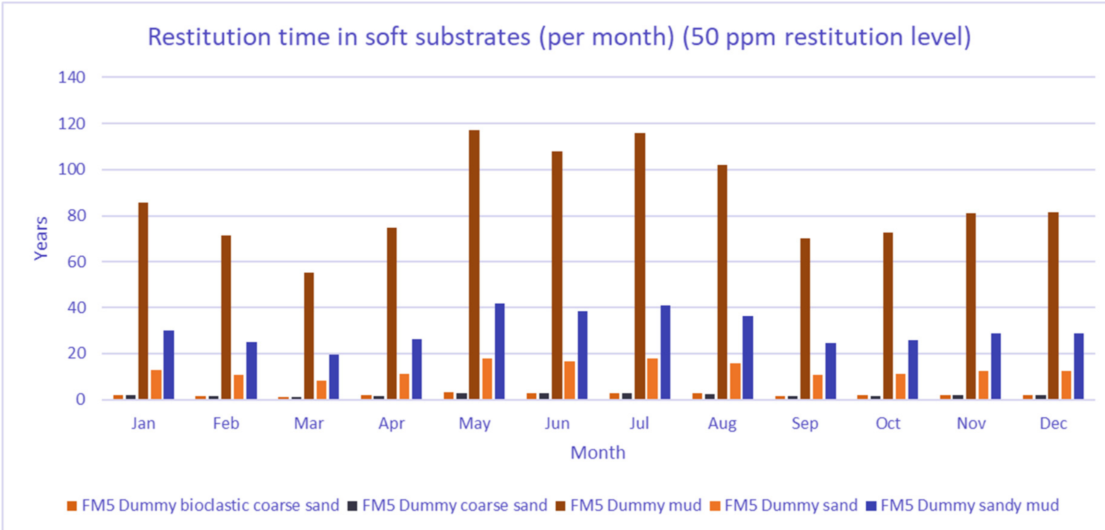


Figure 62. Average restitution times for the simulations in months for 5 soft substrates, using 50 ppm restitution threshold. (Surface blowout, 9000 Sm^3 Oseberg East crude oil per day for 65 days.

The ERA Acute software tool presents monthly impact, restitution times and RDF-values for each chosen VECs. For mud, which has a high TOC-content, the restitution times with the current calculation function are long, using a SF of 2.4 for correction of low leaching of oil from mud. In the simulation with maximum exposure, the THC_{sed}-concentration is 0.1346 kg/m^2 and the t_{res} of cell No.30080 is 213 years. The simulation values are valid for May-August as the 85-day simulation 17 has start date 13.05.2006. The exposure in the sediment in some cells is very high, and there are only 1-2 simulations starting each month, so the monthly average values are calculated using a small statistical sample.

For reference, the maximum and mean impacts are presented in Figure 63, the maximum and mean restitution time in Figure 64 and the maximum and mean RDF values in Figure 65. The results are in line with the EqP theory and the factors used, with respect to the distribution of impact and restitution times between the substrate types.

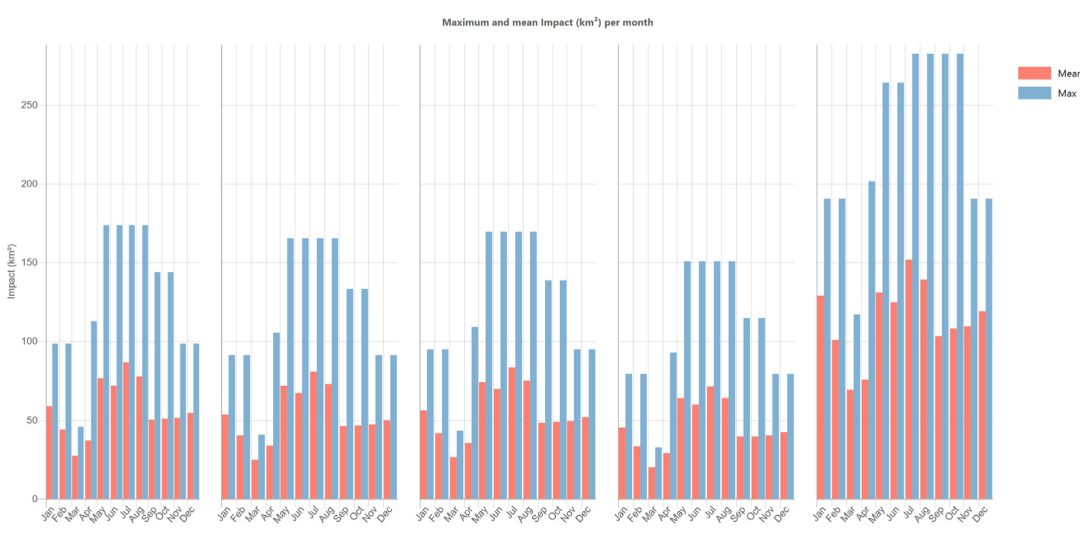


Figure 63. Mean and maximum impact areas (km²) per month for FM5 on 5 soft substrates after a surface blowout with rate 9000 Sm³/day duration 65 days (Oseberg East crude).

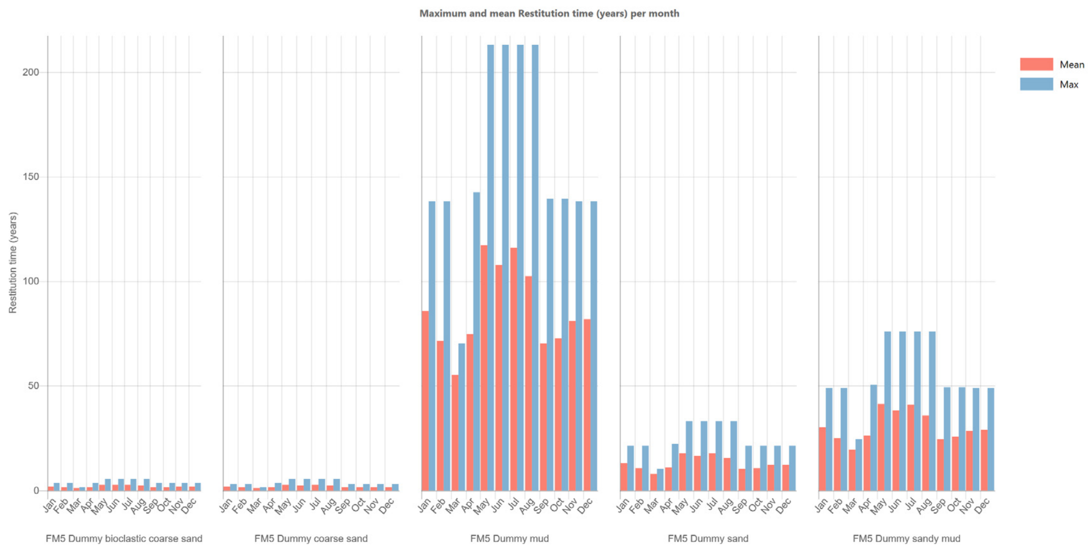


Figure 64. Mean and maximum restitution times (years) per month for soft substrates after a surface blowout with rate 9000 Sm³/day duration 65 days (Oseberg East crude).

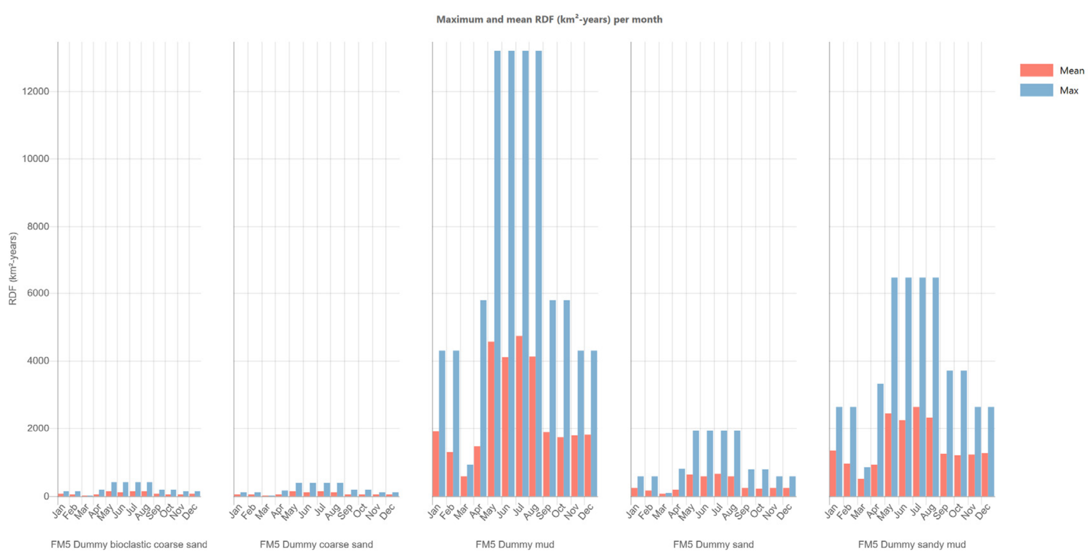


Figure 65. Mean and maximum RDF values (km²years) per month for soft substrates after a surface blowout with rate 9000 Sm³/day duration 65 days (Oseberg East crude).

The reader is also reminded that maximum restitution times in a simulation are **defined by the single cell with the highest restitution value**. Using the oil drift simulation results, the 50 highest C_{THC} values in any cell and any simulation were used to calculate the restitution times for the five soft substrate types (Figure 66). The results show that there are only a few cells that have extremely long restitution times. For mud, the maximum restitution time in most cells are shorter.

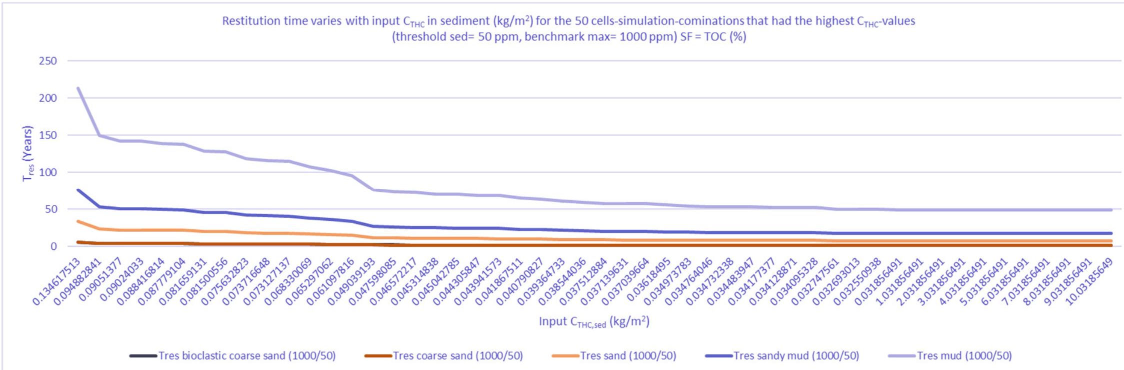


Figure 66. Restitution time varies with input of the oil amounts in sediment in the 50 highest values (irrespective of cells and simulations).

In the simulation with maximum exposure, the THC_{sed}-concentration is 0.1346 kg/m^2 and the t_{res} of cell No.30080 is 213 years, so for this simulation, we reason that there will be a remaining impact in the environment in a steadily decreasing area for 213 years. The maximum area of impact from a simulation in May-August 175 km^2, i.e. corresponding to a total area equivalent to 1.75 cell.

Let us look closer at the simulation 17, which is the worst case simulation with respect to impact in a single cell. For this simulation, the C_{THC}-values in the 574 10x10 km cells that were exposed to a C_{THC}-value above 0 were ranked, and t_{res}-values calculated. Of these, cells were ranked and the 100 highest values selected. Of these, 103 cells had t_{res}-values above 0.

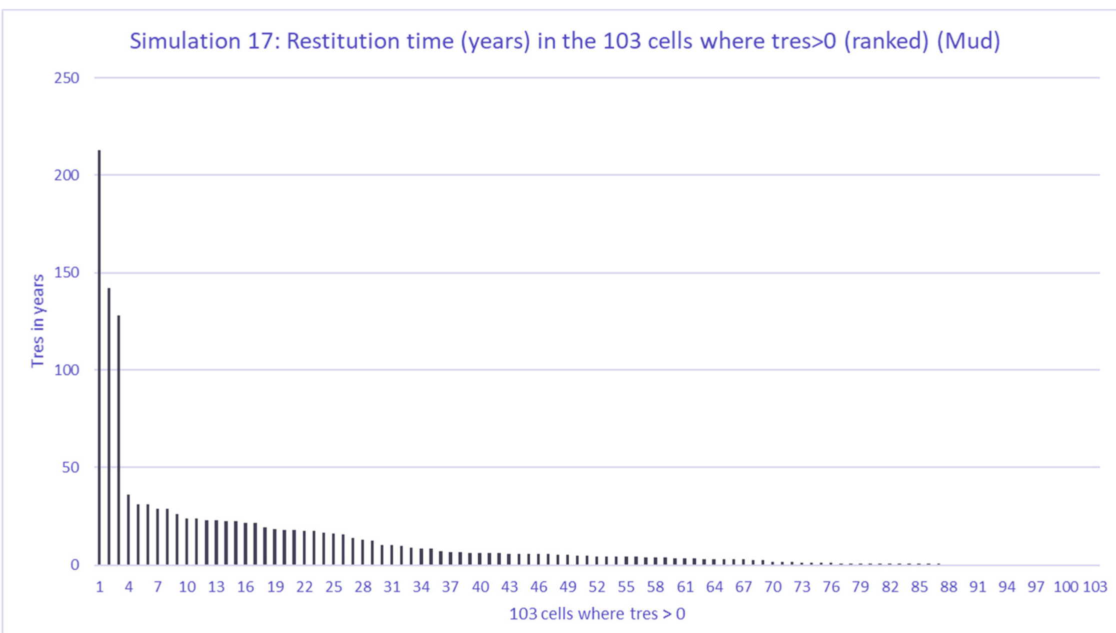


Figure 67. Restitution time in the 103 cells in simulation 17 that had the highest values of C_{THC} in sediment and t_{res} > 0 (mud).

Irrespective of simulation number, 2124 cell values (some in the same cells in several simulations) with tres above 0 years, approximately 40 had restitution times exceeding 50 years (mud) (Figure 68).

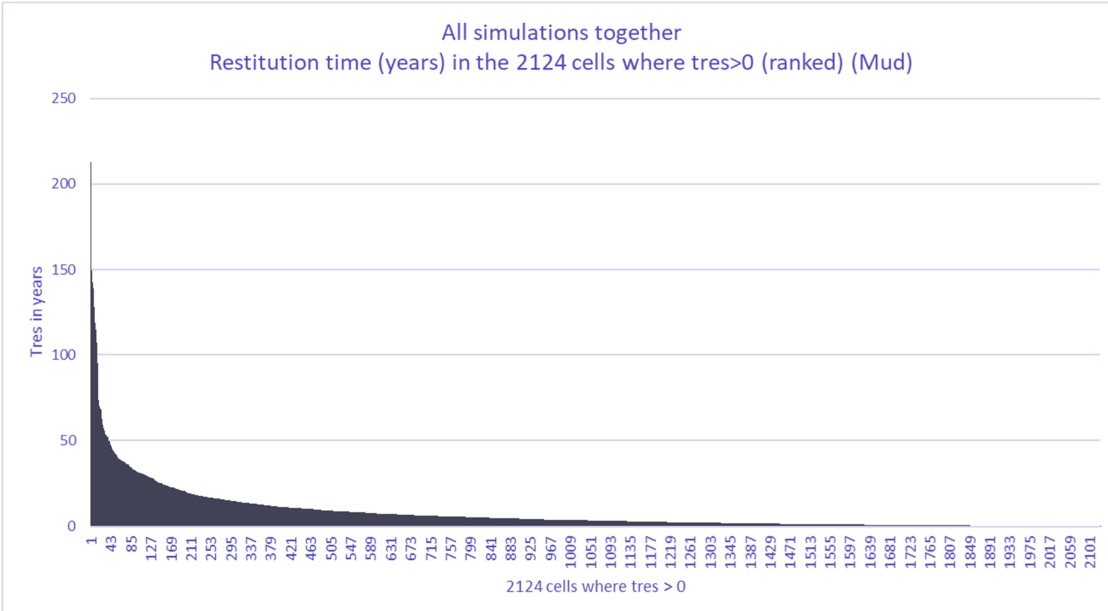


Figure 68. Restitution time in the 2124 cells in all simulations that had the highest values of C_{THC} in sediment and t_{res} > 0 (mud).

8.4.2 Restitution times for soft substrates using threshold 25 ppm

Using a halved threshold concentration for restitution does not impact the restitution time by more than 0.2 years for the coarse sands and 1.2 years for mud (Figure 69). The direct difference in years is mathematically a relationship with the TOC-based factor used to adjust the restitution time equalling half the TOC-value (in percent). The difference means more to substrate types with a low TOC (10 %, see Figure 70) than to substrates with a higher TOC.

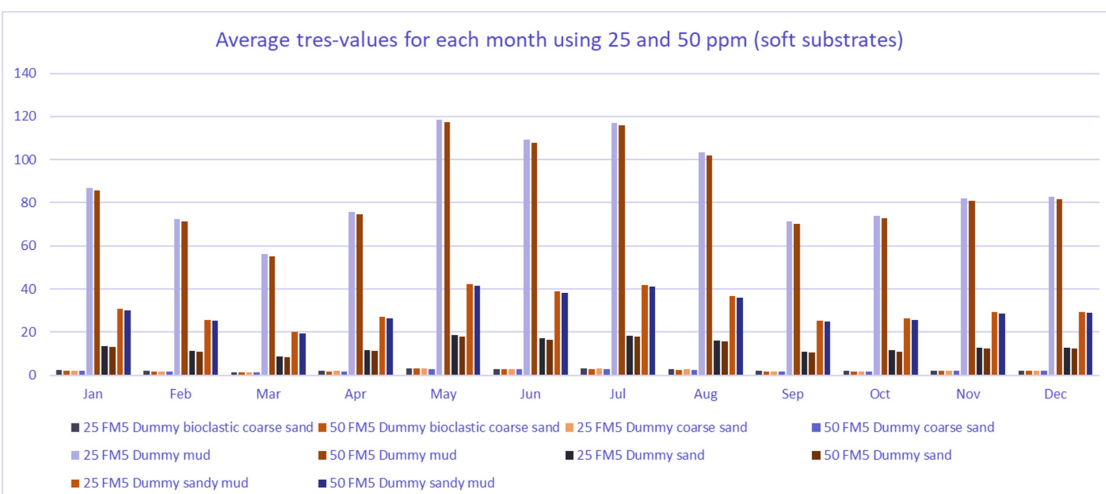


Figure 69. Average restitution times for the simulations in months for 5 soft substrates, using 25 ppm restitution threshold and 50 ppm compared. (Surface blowout, 9000 Sm³ Oseberg East crude oil per day for 65 days.

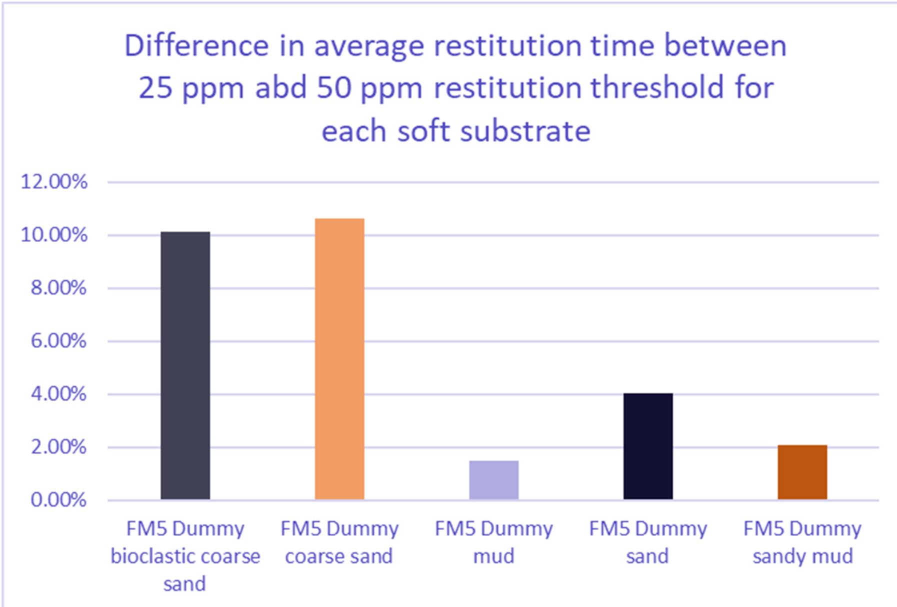


Figure 70. Percent-wise difference in restitution times for the simulations in months for 5 soft substrates, using 25 ppm restitution threshold and 50 ppm compared. (Surface blowout, 9000 Sm^3 Oseberg East crude oil per day for 65 days.

8.5 Discussion and conclusions for calibration of ERA Acute calculator

From the above tests, it would seem that the extreme values found in the cells with the highest C_{THC} in sediment for some simulations may be very long. However, even for mud, the method only gives a t-res > 0 years for input values from the oil drift simulations above 0.0015 kg/m^2, for the restitution time to more than 1 year, more than 0.002 kg/m^2 are needed. Further testing with more simulations would be recommended for a stronger test of the sensitivity. Selecting a percentile value (e.g. 95 percentile value of restitution times) , e.g. based on the total statistics for all simulations could be a reasonable solution, and possibly also weighting the cells' contributions by their probability of being hit by oil. This would need separate testing of options (e.g. weighted or unweighted) as well as using more simulations.

However, the findings of the restitution testing confirm the significance of introducing the sensitivity factor that adjusts the restitution time by a factor corresponding to the TOC-value in percent for the substrate. This in turn means that finding data on accurate values of TOC would further improve the accuracy of the model.

9 Datasets for the Norwegian Sea Test Case

To test ERA Acute for the sediment in the Norwegian Sea, the goal was to obtain data for and adapt a suite of data sets that could be used to demonstrate how ERA Acute can be used and datasets created from available data. Data source is the MAREANO Program which has data for Substrate types, and the data set produced contains data under Norwegian license for public data (NLOD) made available by the Geological Survey of Norway (NGU). Within the scope of testing the ERA Acute model, it was not possible to prepare a full coverage of data for the whole area, nor find more accurate values of bioturbation depths/biogenic mixing depths. Within the results of the MAREANO project, such a data set is expected to be possible to compile by merging datasets for full coverage.

9.1 Substrate-based datasets

Areas with sedimented fine-grained material (mud and sandy mud) are mainly found in the deeper areas. I shallower areas there can be local erosion of fine-grained material on ridges, whereas sand is usually deposited on the lee side of local ridges where the bathymetric currents are reduced in speed. Sedimentation strongly reflects the bottom currents. Erosion due to currents dominate in the shallowest areas, but fine particles may be deposited in in local depressions. In areas where the finer particles have been washed out. Coarser sediments indicate stronger currents. The direction of the deposited finer material is indicative of the predominant direction of the currents. In areas defined as biological material (bioclastic sediments) the sediments are formed by coral biogenic production, with smaller fractions of clay, silt and sand that are transported with currents and caught by the skeletal structure of the corals. (http://www.mareano.no/tema/sedimentasjonsmiljo)

A regional data set of distribution of grain sizes was downloaded from MAREANO, covering the central part of the Norwegian Sea, but not the whole influence area. The data were transferred to the 10x10 km grid for ERA Acute. As given in Table 5, the various sediment types used in MAREANO, were divided into datasets as given in the column "VEC name", providing the data sets of communities based on grain size-defined substrate type. Full data coverage for the area would require merging several MAREANO data sets, as downloading larger areas does not seem to give continuous data sets, this goal was therefore abandoned within the scope of the test. The data set contains polygons of sediment types defined as in: http://www.mareano.no/tema/bunnsedimenter

(see also http://www.mareano.no/tema/dannelse_av_bunnesedimenter)

These substrate types and their parameters are discussed above in the sensitivity testing.

9.1.1 Data availability and feeding mode distributions

The intended implementation of the use of feeding modes is to assign a percentage of the community that has each of the FM, as a property of the data set. This allows for the creation of substrate based community data sets, where the total lethal probability to the community is the sum of the contributions from each FM.

The MAREANO program has collected many samples of baseline documentation of the bottom fauna composition, and this broadly collected material is expected to be able to give the necessary detail if desired the future, based on species identification (Holte *et al., in* Buhl-Mortensen *et al.,* 2016). 1.6 million animals have been sorted out from the samples and identified, many to the species level. There is a great variation in depths in the Norwegian Sea, which provides a wide range of different habitats, and therefore also a high diversity. The faunal changes are related to depth, a general change is observed at 500-800 meters depth along the continental slope, an area with sub-zero temperatures, due to the boundary layer between Arctic and Atlantic water. In MAREANO, it was found that fauna sampled at depths > 2000 m were dominated by species of bristle worms that feed on food particles at the top of the bottom sediments (surface deposit feeders, FM 7), whereas the bristle worms at shallower depths generally represent a wider range of feeding modes (Holte *et al., in* Buhl-Mortensen *et al.,* 2016). At depths below 2000 m, only 2 % of the worms feed by filtering the water above the sediment (*infaunal* suspension feeders (FM6). Beard worms feed by absorbing nutrients from bacteria, these would be assigned to interstitial water exposure only, i.e FM2, although they would not biologically be called carnivores. The MAREANO report "The Norwegian Sea Floor" (Buhl-Mortensen et al, 2016) does not state the fraction of each of the feeding modes present, although this distribution should be possible to obtain from the material.

Figure 7 in chapter "The bottom fauna from Lofoten to Finnmark" (in "The Norwegian Sea Floor", Buhl-Mortensen *et al.,* 2016) contains depth-dependent changes in biomass with depths in relative abundance between Brachiopoda, Crustacea, Sipuncula, Mollusca, Cnidaria and Annelida-Ga & Ow, but omitting sponges (high biomass dominance – up to 90 % of biomass) and the annelid *Galathowenia fragilis* (38% of total no. of individuals). This figure could not be read accurately from the figure shown, but the data seems to be extractable from the extensive data behind the figure.

Although providing ideal data for sediments on the Norwegian Sea seabed; using feeding mode distributions would require detailed compilation of results from sampling and counting from data bases such as MOD or MAREANO. As these data are not readily available in the public domain and is a task that would require a specific data search and extensive work, it was concluded to be a task too detailed for the scope of this test, and most likely also for practical use of the model in risk assessments. To provide a robust solution with the data available, as mentioned previously (Section 7.3.4.1), the data sets with the substrates were split into separate feeding modes. This increases the number of VEC data sets to handle, but provides a more robust and practical way forward for the user, also with regard to accuracy.

If it should be decided to use community-based data sets with such distributions adding up to 100 %, it will be necessary to adjust all value-based categorizations as the resulting numerical values of endpoints will change.

9.1.2 Data sets for the Norwegian Sea VECs (MAREANO-derived)

For the ERA Acute analysis for the Norwegian Sea using "real VECS", the substrate coarse sand, sand, hard substrate and partly sandy mud have significant overlap with the oil drift simulations. For each substrate, a VEC data set was created for each FM.

- Bioclastic community substrate (a bioclastic coarse sand): (http://www.mareano.no/tema/bioklastiske_sedimenter)
    - Bioclastic, epifaunal carnivores FM1 (WC)
    - Bioclastic, infaunal carnivores FM2 (IW)
    - Bioclastic, epifaunal suspension feeders FM4 (WC)
    - Bioclastic, infaunal suspension feeders FM5 (IW)
- Coarse sand community
    - Coarse sand, epifaunal carnivores FM1 (WC)
    - Coarse sand, infaunal carnivores FM2 (IW)
    - Coarse sand, epifaunal suspension feeders FM4 (WC)
    - Coarse sand, infaunal suspension feeders FM5 (IW)
- Sand community
    - Sand, epifaunal carnivores FM1 (WC)
    - Sand, infaunal carnivores FM2 (IW)
    - Sand, epifaunal suspension feeders FM4 (WC)
    - Sand, infaunal suspension feeders FM5 (IW)
- Sandy mud community
    - Sandy mud, epifaunal carnivores FM1 (WC)
    - Sandy mud, infaunal carnivores FM2 (IW)
    - Sandy mud, epifaunal suspension feeders FM4 (WC)

    - Sandy mud, infaunal suspension feeders FM5 (IW)
    - Sandy mud, epifaunal surface deposit feeders FM6
    - Sandy mud, infaunal surface deposit feeders FM7
- Mud community
    - Mud, epifaunal carnivores FM1 (WC)
    - Mud, infaunal carnivores FM2 (IW)
    - Mud, epifaunal suspension feeders FM4 (WC)
    - Mud, infaunal suspension feeders FM5 (IW)
    - Mud, epifaunal surface deposit feeders FM6
    - Mud, infaunal surface deposit feeders FM7
- Hard bottom community
    - Hard bottom, epifaunal carnivores FM1 (WC)
    - (Hard bottom, epifaunal herbivores FM3 (WC) (not included in deep-water data sets)
    - Hard bottom, epifaunal suspension feeders FM4 (WC)

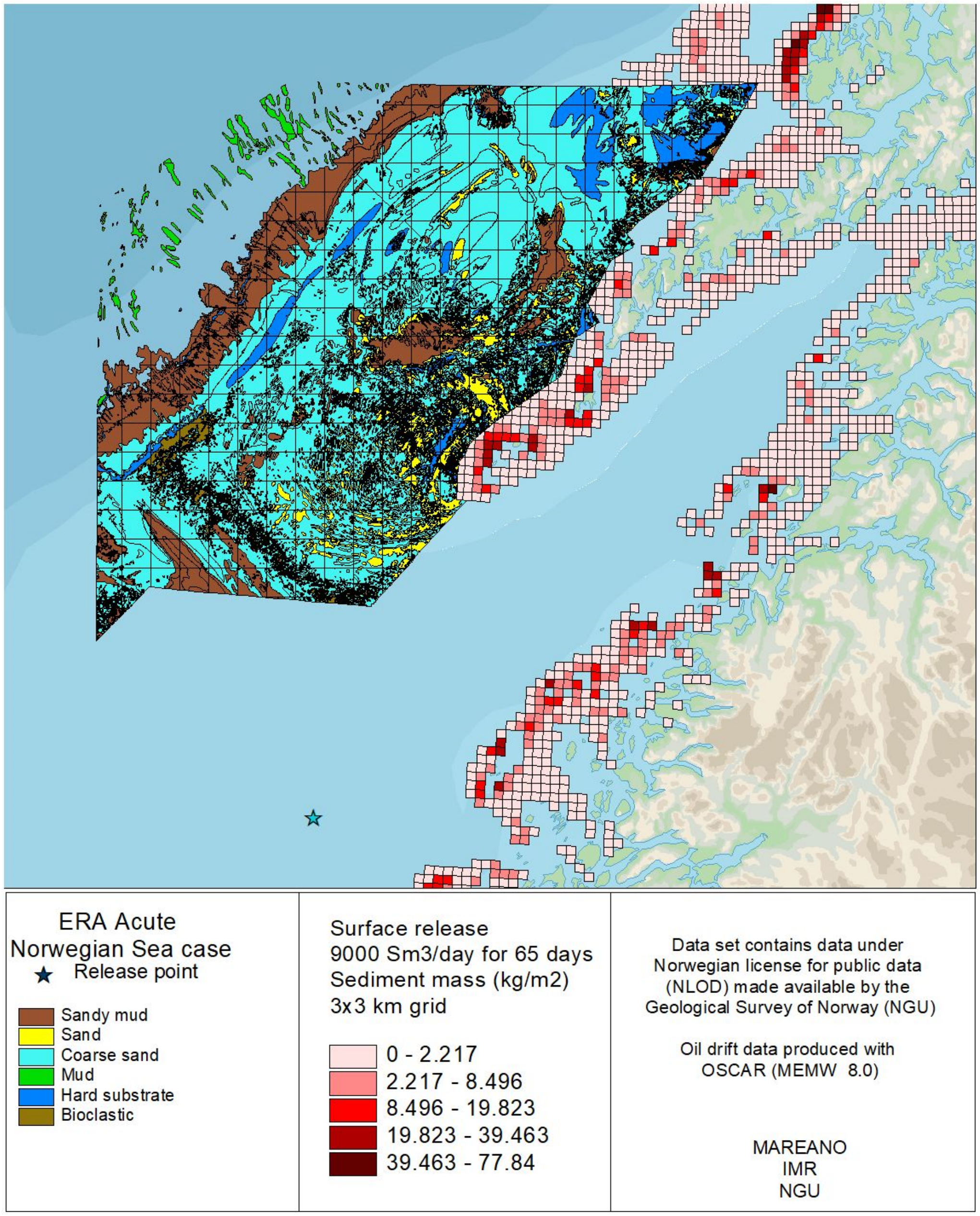


Figure 71. Map of the substrate data (MAREANO/IMR) covering parts of the Norwegian Sea. The map is zoomed in to show more detail, the oil drift simulation is shown zoomed out in Figure 72. As can be seen from the overlap between oil from one single simulation and data set, some impact may be expected for several of the substrate types.

9.2 Specific sensitive species/phyla

MAREANO/IMR have also compiled a dataset covering other parts of the Norwegian Sea/Tromsøflaket with specific sensitive communities of the following species/phyla of vulnerable habitats in deep water, typically sponges, corals and sea pens, which in addition to being sensitive to mechanical injury are sensitive to increased particles in the water, e.g. from drilling http://www.mareano.no/tema/naturtyper/naturtyper/sarbare_naturtyper).

Although the current ERA Acute functions do not include impact from oil spills through covering with contaminated marine snow and sedimented particles containing oil, this is thought to be the primary impact mechanism behind the damages to coral reefs found after the Deep Water Horizon incident (see summary of research up to 2014 in methodology report, Stephansen *et al.* 2015). Several of the suspension feeding species in soft substrates for which there are community data sets, are exposed both in the water column (FM4) and through interstitial water (FM5) as they have parts of their body above sediment and parts in the sediment (sea pens and soft substrate corals). This double exposure is handled by assigning them both exposure routes so that the total exposure is the additive effect, calculated by the sum of both FM4 and FM5.

Raw data are available at: http://www.mareano.no/datanedlasting/kartkatalog/havforskningsinstituttet The raw data were converted to UTM 33 and gridded for ERA Acute on 10x10 km resolution.

These data are shown in Figure 72, which also shows the results of sedimentation of oil from one of the simulations of a surface spill of 9000 Sm^3/day for 65 days, representing one possible outcome. From this single simulation one would not expect impact on other datasets than the *Demospongia*, however since the other single simulations may impact other areas (Figure 2 and Figure 3). The core calculator uses the NETCDF files directly from OSCAR and converts to the chosen ERA Acute grid- The shapefile used for illustration of which area that was impacted was therefore not transferred to the 10x10 km grid, but used in the very first data mining work to indicate an extent (pre-finalisation of the CC-solution).

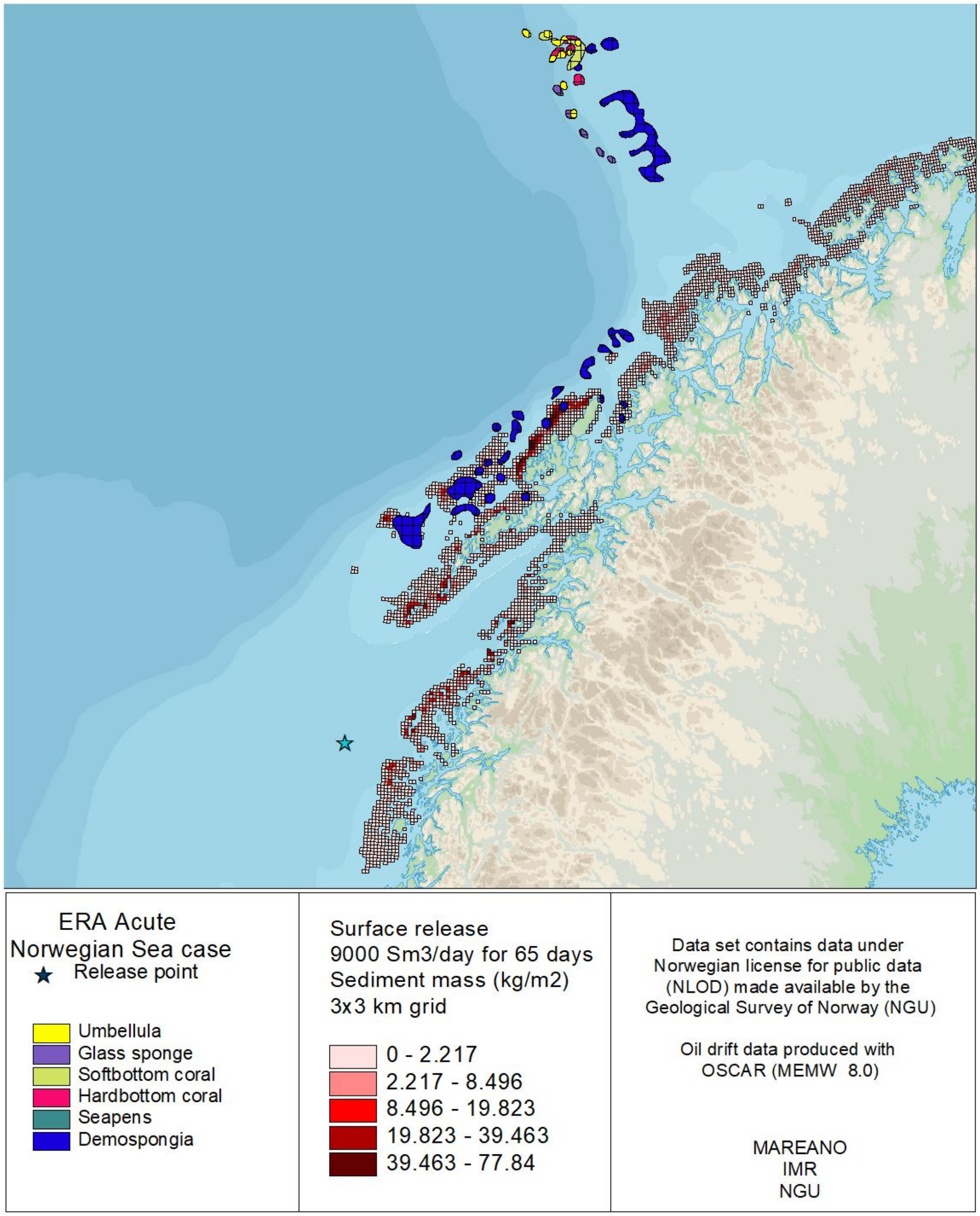


Figure 72. Map of sedimented oil (kg/m2) on the sea floor following a release of 9000 Sm^3/day for 65 days in the Norwegian Sea. (Oil drift results are shown on a 3x3 km grid) (Single simulation). Data from MAREANO/IMR show that there is a potential for impact on *Demospongia from this simulation*.

9.2.1 Demospongia

Demosponges (*Demospongia*) are the most diverse class of sponges). From the images on the webpage http://www.mareano.no/tema/naturtyper/naturtyper/sarbare_naturtyper) there are two types of sponge garden types that both seem from the images to be present on soft substrates (gravelly substrate). Two types of habitat are described in MAREANO, but the data sets do not distinguish between them. Sponges with siliceaous spicules ("svampspikelbunn", are a species complex of large sponges (Species observed in Mareano: *Geodia baretti, G. atlantica, Aplysilla sulfurea, Stryphnus ponderosus* and *Steletta sp.).* For Tromsøflaket and Eggakanten it has been shown that these sponges form a substrate of mud mixed with siliceaous spicules, i.e a soft, coarse, muddy and bioclastic substrate. The second group, ("svampskog") is a complex of medium sized sponges (*Phakellia*, *Axinella* and *Antho*). That are described as being hard substrate species (primarily exposed in the water column). The impact mechanism is the same for both hard bottom and soft bottom suspension feeders/filter feeders exposed in water column (FM4) but the restitution modelling differs. For the test, the data set has been assigned to hard substrate, using the restitution table for deep-sea coral/sponge, as it is not known whether the data are the soft substrate group or the hard substrate group.

9.2.2 Glass Sponges

Glass sponges (*Hexactinellidae*) are found in relatively high colony densities in deep waters. *Caulophacus arcticus* is commonly found on hard bottom substrates in deep waters in northern areas of the Norwegian Sea (lower part of the continental shelf. Although no specific information on the longevity of the Norwegian Sea sponge species were found, some of the sponges in this class are very long-lived and therefore restitution times may be very long. Specific information to quantify the sensitivity factor has not been found, other than information that individual sponges may be more than 15000 years old. However, recolonisation will occur from larvae from nearby sponges, although one old coral colony cannot be replaced within realistic timelines. Most glass sponges are epifaunal filter (suspension) feeders, filtering food particles from the ambient water. The impact mechanism is the same for FM 4 (suspension feeders/filter feeders) and for hard bottom species, the restitution modelling differs. The data set has been assigned to hard substrate as for *Demospongia*.

9.2.3 Sea pens and burrowing megafauna

In the OSPAR list this habitat type is called "sea pens and burrowing megafauna". Most of these communities are on mud or muddy sand/sandy mud substrates, shallower than the *Umbellula* habitat. The species found are mainly the sea pens *Funiculina quadrangularis, Virgularia mirabilis, Pennatula phosforea* and *Kophobelemnon stelliferum.* and Norway lobster (*Nephrops norvegicus*), rugose squat lobster (*Munida sarsi*) and red sea cucumber (*Stichopus tremulus*).

The sea pens are suspension feeders feeding in the water above the sediment, but with parts of their body in the sediment, and therefore also exposed in sediment. (FM 4 + FM5 is therefore used for sea pens to cover exposure both in WC and IW (additive effect)). Lobsters and squat lobsters are burrowing and feed on detritus, crustaceans and worms, FM7 is chosen for these species, as well as for the deposit feeding sea cucumbers.

The distribution of abundance is probably available from more detailed access to MAREANO data, for the testing the data sets for sea pens exposed through both epifaunal and infaunal suspension feeding exposure through 100% FM4 and 100% FM5 are used together, accounting for the additive effect of the exposure routes.

9.2.3.1 Test of conservativity – choice of base substrate for sea pens in shallower waters

MAREANO state that the seapen and burrowing fauna habitat can either be on mud or sandy mud. The factors related to partitioning to interstitial water (FM5) are different between these substrates (following the previous sensitivity testing). The lower TOC of sandy mud leads to higher IW exposure, whereas the smaller bioturbation depth of mud (0.5 cm vs. 1 cm for sandy mud) doubles the starting-point THC concentration in the substrate for mud. A calculation was therefore carried out, and the most conservative alternative was found to be sandy mud with respect to *plet*, and mud with respect to restitution time and RDF (Table 19). The relationship will be the same for FM7 for the burrowing fauna.

The user should make a decision based on choice of conservativity. In the test-analysis for the Norwegian Sea Case, it was chosen to use parameters for sandy mud, as for *Umbellula*.

Table 19 Using 0.1 kg/m^2 as input sediment mass, the difference in *plet$_{IW}$* (FM5) and restitution time and RDF using-recommended values for a given cell with mud or sandy mud parameters.

Substrate	Bdepth (m)	WatC	DryDens	TOC	Cthc,sed,cell (ppb)	THCiw ppb	Plet (%)	Tres (years)	Tres (years) with SF	RDF (with SF)
Mud	0.005	0.65	2100	0.024	3333333	196.4	51.0	65.7	157.6	40.4
Sandy mud	0.01	0.50	2100	0.012	2380952	280.6	69.6	46.6	55.9	19.8

9.2.4 Umbellula stands and associated burrowing fauna

The deepwater sea pen *Umbellula encrinus* is a deep sea species that lives on soft substrate from the middle continental shelf and downwards, the density of the individuals is relatively high. This habitat is stated by MAREANO to be the “deep sea version” of the “seapen and burrowing”, and high densities of hollow-building amphipods are frequently found in areas with *Umbellula*. The substrate where the sea pens live consists of sandy mud, and these seapens are “anchored” with a kind of "foot" that reaches down to about 15 cm into the sediment, the above-sediment part of the animal may rise like a palm tree 1.5-2 meters above the seabed. The *Umbellula* are suspension feeders, feeding on passing particles and zooplankton in the water above the sediment, but with parts of their body in the sediment, and therefore also exposed in sediment as for other sea pens. FM4 + FM5 is chosen as for other sea pens, with 100 % exposure probability for both, reflecting the additive effect of the exposure routes. Although the sub-surface part of the colony sticks 15 cm into the substrate, the Mixing depth is not set to 15 cm. For this habitat, the associated smaller amphipods have more influence on bioturbation depth. The mixing depth for the habitat (both VEC-data sets) are set to 1 cm.

For the Amphipods (burrowing) in sediment, some of these are detritus-feeding and FM 7 (IW + Ing) is chosen 100 % exposure probability (in feeding mode 7 the additive effect is already implemented in the functions). Substrate-related parameters are chosen for sandy mud. (http://www.imr.no/nyhetsarkiv/2015/september/tett_i_tett_med_dyphavssjofjer/en)

9.2.5 Soft-bottom coral garden

Soft bottom coral gardens consist of two main species in Norwegian waters. (*Radicipes gracilis* and *Isidella lofotensis*). They can form dense populations on sandy mud soft substrates. As corals they are suspension feeders, primarily exposed through water column, but with anchorage in soft substrates in sediment, the same exposure modes as for sea pens are deemed most appropriate; including exposure in both IW and WC (with coverage of sedimentation being a significant pathway of exposure). Sediment factors are assigned as for sandy mud, and both the feeding modes FM4 and FM 5 are used, representing the additive effect of double exposure. A video of *R.gracilis* can be seen at http://www.mareano.no/tema/koraller/korallskog , showing a fine sediment type.

9.2.6 Hard bottom coral garden

Hard bottom coral gardens are found in areas with high currents. These gorgonean corals form habitats for fish, brittle stars and small crustaceans. The most common in the hardbottom coral gardens are *Paragorgia arborea*, *Primnoa resedaeformis*, *Paramuricea placomus* and *Swiftia* spp. The latter has not been confirmed in the MAREANO projects as present in Norwegian Sea waters, but is more common in relatively shallow waters in Rogaland. Biodiversity is lower for hard-bottom coral gardens than for coral reefs, however the number of individuals as well as number of species specific for the coral host species make it a rich faunal nature type. Hard bottom coral garden. Assigned to hard bottom algorithms for restitution, and using FM4 for the epifaunic suspension feeders.

9.3 Other sensitive habitats

9.3.1 Coral reefs

The stony corals *Lophelia pertusa* form the basis of deepsea cold water coral reefs in Norwegian waters. In addition to the reef-building corals, *Madrepora oculata, Paragorgia arborea* and *Primnoa resedaeformis* also contribute to the high diversity and complexicity. Several species only live on these coral reefs, for which there are several designated Marine Protected Areas (MPAs) Data sets from IMR exist for these MPAs. However, as several other data sets were included in the test, using the same algorithms, the coral reefs were omitted from the adaptation as there was no significant overlap with the test case oil drift. Hard bottom algorithms should be assigned when adapting data sets for *Lophelia* reefs.

9.4 Summary of recommended standard values for substrates and species VECs

A summary of the recommended values for substrate-based VECs and specific sensitive VECs assigned to a substrate is given in Table 20.

Table 20. Summary of recommended standard values for substrates, and VECs assigned to substrates, based on sensitivity testing of ERA Acute functions.

Substrate	Dry density (kg/m³)	Water content (%)	TOC (%)	BDepth (m)	Sensitivity factor for restitution	Feeding modes	Restitution algorithm
Bioclastic coarse sand	2650	25	0.4	0.05	0.4	FM1,2,4,5 (data sets for each)	SOFT
Coarse sand	2750	25	0.4	0.05	0.4	FM1,2,4,5 (data sets for each)	SOFT
Sand	2750	30	1	0.02	1	FM1,2,4,5 (data sets for each)	SOFT
Sandy mud	2100	50	1.2	0.01	1.2	FM1,2,4,5,6,7 (data sets for each)	SOFT
Mud	2100	65	2.4	0.005	2.4	FM1,2,4,5,6,7 (data sets for each)	SOFT
Hard substrate	NA	NA	NA	NA	NA	FM1,4 (data sets for each)	HARD
Umbellula	2100	50	1.2	0.01	1.2	FM4+FM5	SOFT
Burrowing (with Umbellula	2100	50	1.2	0.01	1.2	FM7	SOFT
Seapens	2100	50	1.2	0.01	1.2	FM4+FM5	SOFT
Burrowing (with Seapens)	2100	50	1.2	0.01	1.2	FM7	SOFT
Demospongia						FM4	HARD
Glass sponges						FM4	HARD
Soft bottom coral garden	2100	50	1.2	0.01	1.2	FM4 + FM5	SOFT
Hard bottom coral garden						FM4	HARD

10 Discussion and conclusions

10.1 Number of simulations used in the Norwegian Sea oil drift modelling

Currently, the seafloor compartment (oiling of sediments) is not included in the stochastic module of the oil drift model used, and the simulations are therefore run manually using the same start-dates as the stochastic runs. Due to the simulation time per run of the ODS for the sediment, a limited number (21) of simulations have been used. This limits the statistical strength of the results somewhat when it comes to drawing general conclusions about risk levels and probabilities for the categories of results. However, the results do show that the amounts of oil in sediment that have been used as "high contamination" levels for testing the parameter values, are possible.

The results of the different deterministic tests are in line with the theory and equations used, and the model results are transparent, which makes the different outcomes of ERA Acute possible to interpret with respect to the data behind results.

10.2 Exposure and impact modelling of FM1 and FM4 – lower water column THC

Currently, the lower water column is not included in the stochastic oil drift model results that have been used for modelling exposure to the water column (FM1, FM4 and FM6). In the best practice guidelines for running oil drift simulations for environmental risk assessments (currently developed for MIRA) the recommendation is to use the upper 50 meters to calculate the average THC-concentration. The is due to the fact that if the whole water column is used, the average concentration is lowered, as the oil in the water column naturally dispersed from a surface oil spill is mostly present in the upper water column layers. The upper 50 meters have been used in the ODS for the Norwegian sea test case. This may artificially resemble an underwater plume of higher oil concentrations, although the geographical placement of cell values are different. It is therefore important to **not** read the results of this test case as a risk assessment of potential impacts from a real spill case of e.g. an underwater plume such as the one that occurred during the DWH incident. Further testing should include investigations of how to best include oil drift simulations in the water column, adapted to use for the lower water column. For the water column compartment VECs (fish eggs and larvae), the upper water layers are the most relevant to report, whereas for FM1, FM4 and FM6 VECs in the sea floor compartment, the lower layers are the most relevant. “Best practice” evaluations of oil drift modelling should take this into consideration. It is assumed, that for surface oil spills, although using the upper water column as a proxy for the lower water column layers may be conservative with respect to the oil amount, the results may as mentioned be offset geographically, ie. high concentrations in the upper water column are most likely not in the same cells as high concentrations in the lower water column.

10.3 Marine snow is currently not included

For organisms assigned to feeding mode 4 – water column exposure of suspension feeders, such as corals and sponges, the algorithm currently uses water column-only exposure. Currently this exposure only uses THC-concentration calculated by the ODS for water column compartment. Currently, modelling of marine snow is not available, this is the mechanism most thought to affect epifaunal species that are primarily exposed through water column, i.e. FMs 1, 4, 6. In the DWH incident, sedimentation of oiled particles in the form of marine snow, was found to be an important mechanism of impact to corals, (see references in Sediment report, Stephansen *et al.,* 2015). The incident coincided with the spring algal bloom, and a MOSSFA (Marine Oil Snow Sedimentation and Flocculent Accumulation) event was the result, bringing contaminated marine snow to the sea floor. This mechanism should therefore be included in addition to the currently used algorithms for sea floor when available, pending improvements to oil drift modelling for sedimentation.

Seapens, *Umbellula* stands and soft bottom corals will also be exposed to falling “marine snow” in the water column.

In December 2017, Eenennaam *et al.* (2018) have published results that further support the conclusion that marine snow should be included for se floor organisms. After the Deepwater Horizon oil spill, a MOSSFA event took place, which they estimated transported 14% of the total released oil to the sediment. This MOSSFA event smothered parts of the benthic ecosystem. In a microcosm study of the effects of oiled artificial marine snow on benthic macroinvertebrates, they found that the amphipod *Corophium volutator* survival was reduced by 80% in oil-contaminated snow. The mudsnail *Hydrobia ulvae* survival was reduced by 40% in oil-contaminated snow, possibly due to consumption of oiled snow. The marine clam *Macoma balthica* was sensitive to marine snow, addition of oil slightly decreased survival. The microcosm study revealed trait-dependent sensitivity to oil with or without marine snow and that the main drivers for organismal response to marine snow and oil were motility, sensitivity to hypoxia and oil toxicity, as well as feeding habits. These very recent studies support that marine snow should be included in ERA Acute modelling for other FMs as well as for the water column-exposed organisms.

10.4 Using two feeding modes for additive effects of two exposure routes

For species such as sea pens, which are both exposed in WC and in sediment (partly *infaunal* suspension feeders), the sum of feeding modes 4 and 5 was chosen to represent the additive exposure. In these tests, FM4 has dominated the impacts, as can be expected from the theory and the influence areas. In FM 5, the leaching of THC into interstitial water is lower than the generally higher water column exposure. However, the current model which includes both, will be able to accommodate future improvements to ODS, if lower water column and sedimentation are reported for the same cell.

10.5 Restitution time sensitivity factors and thresholds, mixing depths

Currently, the proposed calibrated sea floor soft substrate restitution function using a SF which correlates with the TOC of the substrate leads to a longer restitution time in test 5 and 6 than without (preceding tests 4A-C). The calibrated function gives reasonable results, however, the sensitivity tests show that TOC is a parameter for which accurate values are worth finding regionally, along with the mixing depth of the substrate which are the two factors that mean most to the initial calculation of sediment and interstitial water THC concentrations. The threshold value for restitution has less impact on the calculation results.

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