Universitetet
i Stavanger

DET TEKNISK-NATURVITENSKAPELIGE FAKULTET

MASTEROPPGAVE

Studieprogram/spesialisering: Offshore Environmental Engineering	Vår semesteret, 2012 Åpen
Forfatter: Stian Robert Breivik	………………………………………… (signatur forfatter)

Fagansvarlig:
Torleiv Bilstad
Veileder(e):
Harald Torvik

Tittel på masteroppgaven:
Begrensninger av den reviderte DREAM modellen.

Engelsk tittel: Limitations of the revised DREAM model.

Studiepoeng:
30

Emneord: DREAM EIF Bore Avfall Risiko TCC Rotomill	Sidetall: 84 + vedlegg/annet: 8 Stavanger, 15.06.2012 dato/år

Limitations of the Revised DREAM Model

Stian Robert Breivik

6/15/2012

Abstract

DREAM (Dose-related Risk and Exposure Assessment Model) is a risk assessment tool for modeling offshore waste discharge to the marine environment. The drilling waste model was developed through the joint industrial project ERMS (Environmental Risk Management System). The method follows a PEC/PNEC (Predicted Environmental Concentration / Predicted no Effect Concentration) approach as to determine an EIF (Environmental Impact Factor) for the sediment and water column.

The scope of this study was to identify the models limitations for a scenario where drilling waste (cuttings & mud) treated by a TCC (Thermeochemical Cutting Cleaner) unit was discharged to the marine environment. The TCC unit pulverizes oil contaminated cuttings, creating enough heat to vaporize the drilling fluids. The effluent is assumed to contain approximately 0.1 % oil (w/w). Consequently, the main impact from the discharge will be from the drilled cuttings and weighing materials such as barite.

The model was assessed through a Planckett-Burman DOE (Design of Experiment) as to identify the most significant model parameters. 17 model parameters were evaluated in 50 simulations. The stability (Goodness of Fit) of the model was evaluated through a least square root multiple regression analysis. This combined with a literature review formed the basis for discussion and conclusions.

The revised DREAM model is subjected to several assumptions and simplifications. The model is rather complex with substantial variables that may be difficult to standardize or predict. This has resulted in a tool for comparing environmental risk based on different management options. While the model estimated risk has limited relations with the actual consequence of a discharge, it may however shed some light on impact differences between discharge scenarios.

The effluent from the TCC unit may be modeled comparatively in DREAM if some adjustments are made. It is necessary to obtain a representative particle size distribution of the effluent as to predict the fate. The distribution should also have an associated PNEC value for each size interval as to account for non-toxic interactions from cuttings and weight material such as barite.

Preface

This thesis is prepared to fulfill the requirement in the Master of Science degree in the Faculty of Natural Science and Technology in University of Stavanger. The thesis work was carried out from January 2012 until June 2012.

This study's original scope included a risk assessment of a new technology based on analytical results. However, the external sampling team did not manage to acquire the samples within the time-frame of this study. Substantial amounts of work have therefore been abandoned. All elements performed in this study have been self-taught; hence the discussion and conclusion should be taken as light indications.

I was fortunate to be able to do my thesis for Norway's largest petroleum company, Statoil. The experience, knowledge and network that I have obtained will be of great future value. The thesis itself has provided me with a very good introduction into drilling waste and the challenges affiliated with it. I have also met some very knowledgeable people, including some of the developers of the revised DREAM model.

I would like to thank my supervisor from Statoil, Harald Torvik, for always putting me into contact with the right people. Thanks to my internal supervisor Professor Torleiv Bilstad, from the University of Stavanger for moral support and giving me the opportunity to write my thesis at Statoil. Last but not least, my good friend Huaqin Ng who has been an inspiration throughout this study.

I would also like to thank Emily Lyng from IRIS-Biomiljø, Tone Karin Frost, Mathijs Smit and Lars Petter Myhre from Statoil for their input for the fulfillment of this study.

Content

Abstract......1

Preface......3

Content......4

1. Introduction......11

1.1 Background......11

1.2 Scope......12

2. Determining Risk......13

2.1 Risk Assessment Procedure......13

3. Hazard Assessment......15

3.1 Regulations......15

3.2 Drilling Operation......16

3.3 Hazard Identification......19

3.3.1 Drilling Waste......20

3.3.2 Heavy Metals......25

4. Exposure Assessment......31

4.1 DREAM......31

4.2 ParTrack......34

5. Effect Assessment......42

5.1 PNEC......44

5.2 Methods for Determining PNEC......43

5.2.1 Assessment Factors......43

5.2.2 SSD......45

5.2.3 F-PNEC......47

5.2.4 EqP Method......47

5.3 PNEC for SPM......48

5.4 PNEC for Metals ... 49

5.5 PNEC for Sediment Effects ... 53

6. Risk Assessment ... 56

6.1 EIF & Risk ... 56

7. Methodology ... 58

7.1 Methods ... 58

7.2 Model Setup ... 60

8. Results & Discussion ... 65

8.1 Base Case Scenario ... 65

8.2 Sensitivity Analysis ... 69

8.2.1 Water Column ... 70

8.2.2 Sediment ... 74

8.2.3 Model Stability ... 77

9. Conclusions & Recommendations ... 78

9.1 Conclusions ... 78

9.2 Recommendations ... 78

References ... 80

Appendix A ... 85

Appendix B ... 86

Appendix C ... 89

List of Figures

Figure 2-1: Overview of general risk assessment principles 13

Figure 3-1: Overview of drilling process 17

Figure 3-2: Process sketch over the TCC process 18

Figure 3-3: Fate of discharged drill waste components in the marine environment 20

Figure 3-4: Overview of different natural processes occurring in the sediment. 22

Figure 3-5: An illustration of tortuosity. The addition of smaller particles creates a longer pathway (blue line) for a solute through a porous medium, relative to a direct route (red line). 24

Figure 3-6: Layer classification in sediments regarding oxygen conditions for redox zones. 24

Figure 4-1: Layout of the model structure for calculations of potential impact. 31

Figure 4-2: Illustration on how the PEC for burial is measured in the sediment. 35

Figure 4-3: Illustration on how the PEC for oxygen depletion is estimated for the sediment. 38

Figure 5-1: Sigmoidal Dose response relationship. Showing how LC/EC50, LOEC and NOEC are determined 42

Figure 5-2: Graphical presentation of PAF as a function of log NOEC values (table right side) from several different species. 46

Figure 5-3: Species sensitivity to burial by exotic sediment for 32 species. 53

Figure 5-4: Species sensitivity to grain size change for exotic sediment for 32 species. 54

Figure 5-5: Species sensitivity distribution for oxygen change for exotic sediment and 32 species. 55

Figure 6-1: The relation between the PEC/PNEC ratio and the percentage risk for damage on biota. Note when PEC/PNEC = 1, the probability of damage is 5 %. 56

Figure 7-1: Environmental parameter values for the base case. 60

Figure 7-2: Model parameters used for the base case 61

Figure 7-3: Drilling parameters and discharge characteristics for the base case in DREAM. 62

Figure 7-4: Overview over the salinity and temperature profiles used for the simulations. 63

Figure 7-5: Size distribution for cuttings with default values (left) and reduced size interval (right) used in the simulations. 63

Figure 7-6: Size distribution for barite with default values (left) and reduced size interval (right) used in the simulations. 64

Figure 8-1: Vertical and horizontal risk assessment of the base case for the water column. Note, only the black portion is related to PEC/PNEC ratio exceeding 1. 65

Figure 8-2: Graph showing the maximum risk in the water column based on horizontal distance. 66

Figure 8-3: Horizontal risk assessment of the base case for the sediment. Note, only the black portion is related to PEC/PNEC ratio exceeding 1. 66

Figure 8-4: Graph showing the actual sediment risk based on horizontal distance. 67

Figure 8-5: Overview over the water column and sediment EIF results from 50 simulations. All values have been scaled against the base-case EIF value. 69

Figure 8-6: Contribution from each component present in the modeled discharge. 70

Figure 8-7: Half normal plot identifying the main contributing factors for the EIF in the water column. 72

Figure 8-8: Half normal plot identifying the main contributing factors for the restitution time in the water column. 73

Figure 8-9: Contribution to the risk in the sediment from each component present in the discharge effluent. 74

Figure 8-10: Half normal plot identifying the main contributing factors for the sediment EIF. 76

Figure 8-11: Half normal plot identifying the main contributing factors for the sediment restitution time. 76

List of Tables

Table 3-1: Example of major components in WBM's and NAF's. 16

Table 3-2: Identified relevant components for this study. 19

Table 3-3: Heavy metals included in impact calculations for the marine environment. 26

Table 3-4: Mean concentration of metals from 4 different samples of drilling muds (barite). MI-low and NORBAR are samples from US Gulf of Mexico and Norway, respectively. MI-high (high trace amounts) is shown to reflect mud types used in the early 90's in the US Gulf of Mexico. All values ug/g dry weight 27

Table 3-5: Experimental distribution of $K_{dbarite\text{-}seawater}$ coefficients for metals in barite equilibrated for 1-7 d with seawater. Test conditions were salinity=31, temperature = 20 ^{o}C and pH= 7.3 and 8.3. 28

Table 3-6: Presents log $K_{dbarite\text{-}porewater}$ coefficient for metals from 3 barite samples originating from the same source used in table 3-4 (MI-low). Samples were incubated in 4:1 or 10:1 dilutions at pH 3 (with phthalate buffer) equilibrated with barite for 15 min to 48h. 28

Table 3-7: Presents characteristics of sediment samples extracted from Bjørhodebukta in Oslofjorden. The samples were further exposed with thin layers of water based cuttings with barite and illmenite in a benthic mesocosm, while flushed with seawater from Oslofjorden. The redox potential, diffusion gradient in thin film gel probes and oxygen profiles were tested at day 4, 55 and 92. 29

Table 3-8: Presents log Kd values for metals from sediment samples extracted from Bjørhodebukta in Oslofjorden. The samples were further exposed with thin layers of water based cuttings with barite and illmenite in a benthic mesocosm, while flushed with seawater from Oslofjorden. The redox potential, diffusion gradient in thin film gel probes and oxygen profiles were tested at day 4, 55 and 92 30

Table 4-1: Particles size distribution, density and sinking velocity for barite in drilling mud. 32

Table 4-2: Particles size distribution, density and sinking velocity for drill cuttings. 33

Table 4-3: Symbol description for Eq. 4-6 to 4-11. 39

Table 5-1: Assessment factors defined in the EU-TGD for the marine water column. 44

Table 5-2: Assessment factor for extrapolation from acute to chronic, LC/EC50 to NOEC and laboratory to field. 45

Table 5-3: Threshold values derived for bentonite, barite and WBM's based on assessment factors. 48

Table 5-4: Threshold values for barite, bentonite and WBM based on SSD. 49

Table 5-5: Threshold values including background concentration derived through the dutch MPC_{water} method. 50

Table 5-6: Threshold values for metals in the sediment derived by assessment factors. 51

Table 5-7: Final Threshold values for metals in sediment and the water column derived through the EqP method. 52

Table 7-1: Presents the factors evaluated, including range and description, used for the DOE. 58

Table 8-1: Presents the results from the base case water column simulation. 67

Table 8-2: Presents the average results from three base case sediment simulation 68

Table 8-3: The goodness of fit (Rsquare) for the model based on the EIF and restitution time results...... 77

Abbreviations

DOE: Design of Experiment

DREAM: Dose Response Environmental Assessment Model.

EIF: Environmental Impact Factor.

EqP: Equlibrium Partitioning.

ERMS: Environmental Risk Management System.

EU-TGD: European Technical Guidance Document.

F-PNEC: Field-Predicted no Effect Concentration

HOCNF: Harmonized Offshore Chemical Notification Format.

K_d: the distribution coefficient of a chemical between a solid and aqueous phase.

MOD: Environmental Monitoring Database.

NCS: Norwegian Continental Shelf.

OBM: Oil Based Mud.

OECD: Organisation for Economic Co-operation and Development.

OSPAR: Oslo-Paris Convention.

PAF: Potentially affected fraction

PEC: Predicted Environmental Concentration.

PLONOR: List that describes chemicals that are considered to “Pose Little or no Risk”, when discharged to the marine environment.

PNEC: Predicted no Effect Concentration.

RDP: Redox Potential Discontinuity.

SPM: Suspended Particulate Matter.

SSD: Species Sensitivity Distribution.

TCC: Thermeomechanical Cutting Cleaner

WBM: Water Based Mud.

1. Introduction

1.1 Background

Discharge of OBM (Oil Based Mud) contaminated cuttings to sea have been banned by the Norwegian government since 1993 (Singsaas et al., 2007). Today these cuttings are either injected back into a formation, or transported to shore for treatment (Klif, 2011). Re-injection is the favorable alternative as it is cost effective and more environmental friendly with respect to the marine environment. Transportation is generally unwanted due to safety exposure from unsafe crane lifts and additional emissions from shipping (Svensen and Taugbol, 2011). OBM consumption has increased over the last decade (Klif, 2011). Few suitable formations for reinjection has led to a substantial increase of transportation to shore (Svensen and Taugbol, 2011).

The Norwegian government have voiced a stronger regulatory practice for reinjection will be employed in the near future (Klif, 2010). This has led to a search for other options regarding treatment of contaminated cuttings. However, safe and efficient alternatives are few (Svensen and Taugbol, 2011). An unexplored technology on the Norwegian Continental Shelf (NCS) is being assessed by the Norwegian petroleum company Statoil as an alternative to onshore transportation and reinjection. The TCC (Thermeomechanical Cutting Cleaner) unit pulverizes contaminated cuttings, creating enough heat through friction to separate drill fluids from the cuttings to well below the regulatory limit (1 % oil w/w) for discharge to sea. The technology allows for a very high recovery of the base-oil (> 99 %) (TWMA, 2010) .The technology is used frequently for treatment of oil contaminated cutting on offshore installations on the British shelf, but has yet to be tested on the NCS (Oljedirektoratet, 2011).

As part of the “zero harm discharge” principles initiated by the Norwegian government in 1997, several petroleum companies came together with the goal to develop a tool to evaluate the risk of discharging oily waste into the marine environment. The first product was called DREAM (Dose-response Risk and Effects Assessment Model), which is a model designed to evaluate fate and risk of produced water discharges to the marine environment. The second, more recent product is called ParTrack which extends the fate and risk assessment to the sediment and suspended particle effects in the water column to produce an EIF_{DD} (Environmental Impact Factor for Drilling Discharge) (Singsaas et al., 2007). The EIF_{DD} is a measure of the overall probability of adverse effects caused by different stressors on an ecological environment. The method is a quantitative measure of the risks involved when effluents are discharged to the marine environment, and forms a basis for reduction of impacts in a systematic and a quantitative manner (Rye et al., 2006a). Similar to the EIF for produced water, the goal is to integrate EIF_{DD} as a reliable tool for environmental management of drilling discharge (Smit et al., 2006b).

The work behind the ParTrack model was performed through a project called ERMS (Environmental Risk Management System) and was done according to the guidelines of the EU-TGD (European Technical Guidance Document) with some modifications. The project was financed by ConocoPhillips, Eni, ExxonMobil, Hydro, Petrobras, Shell, Statoil, and Total. The companies also provided scientific input. Contractors in the program have been Akvaplan-niva (Norway), Battelle (USA), MUST (Norway), RF-Akvamiljø (Norway), SINTEF (Norway), TNO (The Netherlands), and University of Oslo (Norway) (Singsaas et al., 2007).

1.2 Scope

The TCC unit provides different effluent characteristics than traditional cutting treatment options. Therefore, the objective of this study is to investigate the feasibility of using the revised DREAM model to assess the risk from discharging effluent from a TCC unit to sea.

This will be done through, (1) obtaining sufficient knowledge around the impact from discharging drilling waste to the marine environment, (2) reviewing the work done in the ERMS project as to identify assumptions and simplifications used for the development of the revised DREAM model, (3) identifying the major contributing model factors as to understand which factors are important to consider thoroughly, and (4) assessing the model stability (Goodness of Fit).

2. Determining Risk

2.1 Risk Assessment Procedure

Internationally agreed principles for risk assessment are found in the EU-TGD (European Union Technical Guidance Document), which has also been used as foundation for developing the methodology for estimating the impact of drilling waste. General risk assessment principles are covered in Figure 2-1 (Smit et al., 2006b).

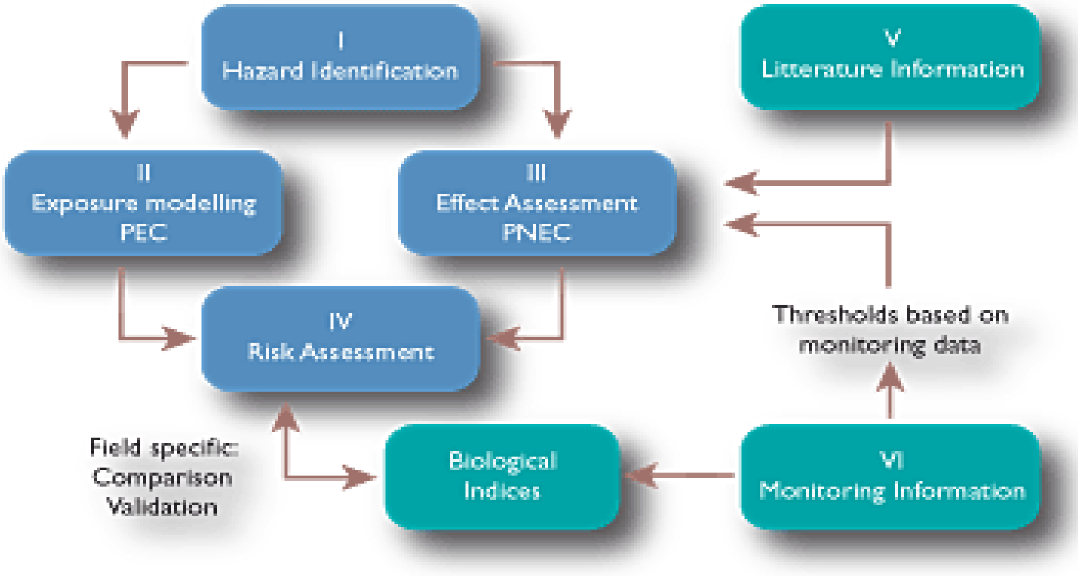


Figure 2-1: Overview of general risk assessment principles

Hazard identification constitutes the first part of a risk assessment. This step includes problem formulation and identifying potential stressors for the assessment. A comprehensive literature study for each component's property is required.

Exposure assessment constitutes the second part of a risk assessment. This includes predicting the magnitude of the stressor in the recipient, e.g. the PEC (Predicted Environmental Concentration) of the component under evaluation.

Effect assessment constitutes the third part of a risk assessment. This is used to predict the PNEC (Predicted no Effect Concentration), through a dose-response relationships of the stressor in relation to selected biological effects.

Risk Assessment includes the fourth part of the assessment. The concentration for each compound discharged to the marine environment is compared to a concentration threshold for that compound. The derived number is called the EIF (Environmental Impact Factor). An unacceptable value is encountered when the EIF is larger than 1.

3. Hazard Assessment

3.1 Regulations

The petroleum industry has to abide rules and regulations set by the Norwegian government when operating on the NCS. The regulations are described through the "The Activities Regulations" (Frost et al., 2006). The most important regulations regarding drilling waste discharge is presented below (§60 & §68).

§60 Discharge of oily water

"Oily water shall be cleaned prior to discharge to sea. This does not apply to displacement water.

A treatment plant shall be operated with environmentally optimal effect regardless of whether the discharge limitations, cf. the third subsection, can also be met with reduced treatment effect. When evaluating what is the environmentally optimal effect, the degree of treatment shall be evaluated in relation to e.g. use of chemicals.

The oil content in water discharged to sea, shall be as low as possible, cf. Chapter II of the Framework Regulations and Sections 7 and 8 of the Management Regulations. The oil content shall not exceed 30 mg oil per litre of water as a weighted average for one calendar month.

The operator shall obtain permission according to Chapter 3 of the Pollution Control Act (in Norwegian only) for injection of oily water."

§ 68 Discharge of cuttings, sand and solid particles

"Cuttings from drilling and well activities, sand and other solid particles shall not be discharged to sea if the content of formation oil, other oil or base fluid in organic drilling fluid exceeds ten grams per kilo of dry mass.

The operator shall obtain a permit pursuant to Chapter 3 of the Pollution Control Act (in Norwegian only) to inject materials such as cuttings, sand and solid particles."

Norway is a member of OSPAR (Oslo-Paris Commision), which is a mechanism to protect the marine environment through application of strong principles to prevent and eliminate pollution to the North-East Atlantic (OSPAR, 2012). Chemicals used by the OSPAR countries are subjected to the HOCNF (Harmonized Offshore Chemical Notification Format) document. HOCNF includes documentation of eco-toxicological properties of all chemicals used by the petroleum industry on the NCS. The tests are standardized and have to be performed by OSPAR approved laboratories. The following test parameters are required: (1) Biodegradability, (2) Bioaccumulation, and (3) Acute Toxicity. Chemicals that are deemed environmentally safe to discharge are listed in the PLONOR-list (Pose Little or no Risk) (Frost et al., 2006).

3.2 Drilling Operation

The sequences for drilling operations are initiated by driving a metal pipe with a diameter of 30" (conductor pipe) into the seabed to a depth of approximately 50 meters. This pipe maintains the stability of the shallow drilling hole and protects against pollution of seawater. New drilling pipes are added as the well deepens. Each drilling section is concluded by a cementing casing (Singsaas et al., 2007).

During drilling, a mixture of water, clay, weighing material and chemicals (called a drilling fluid or drilling mud) is used (Table 3-1). Drilling fluids are characterized according to type of base fluid. Generally they are defined as WBM (Water Based Mud) and NAF (Non-Aqueous Fluids). NAF is normally referred to as OBM or SBM (Synthetic Based Mud) (ASME, 2004). Drilling muds are the largest-volume waste from the offshore petroleum industry (Singsaas et al., 2007).

Table 3-1: Example of major components in WBM's and NAF's.

WBM	NAF
76 % Seawater	46 % non-aqueous base fluid
15 % Barite	33 % Barite
7 % Bentonite	18 % Brine
2 % Other	2 % Emulsifier
	1% Other

Source: ASME (2004)

The functions of drilling fluids are extensive and critical for an efficient and safe drilling operation. The major functions are to: (1) Move cuttings to the surface, (2) control formation pressure and well-hole stability (3) cool and lubricate the drill bit and (4) control corrosion. The fluids are circulated down the drill string and through the drill-bit, and back to the surface via the annulus (Fig. 3-1). The drill cuttings follow the circulating fluid to the surface (ASME, 2004).

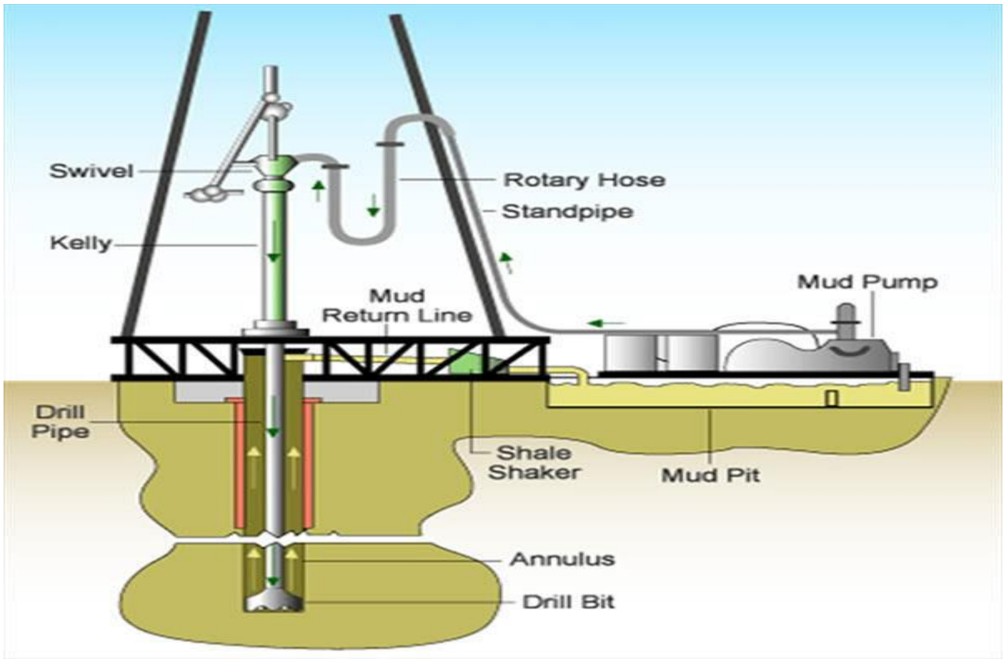


Figure 3-1: Overview of drilling process (ASME, 2004)

Traditionally drilling fluids are separated from cuttings on shale shakers, where the residual oil fraction is relatively large. The recovered fluids are sent back to the mud pit. If the cuttings are contaminated by OBM, they have to be treated onshore, or re-injected to a suitable formation (ASME, 2004). For this study the contaminated cuttings are directly transported from the well hole into the TCC mill (Fig. 3-2). The mill uses kinetic energy to beat solids by a hammer arm. The friction creates sufficient heat (240-300 °C) to flash-evaporate the oil and water from the cuttings (Orszulik, 2008). The vapors are recovered in separate condensers where the oil is normally returned to the active mud system (ASME, 2004). The process leaves an oil content of less than 1 % oil w/w, which is in accordance with the Norwegian regulatory demand for disposal to sea (§ 68). The remaining fraction is trapped due to oil in the rock interstices, and requires more energy to release (Orszulik, 2008).

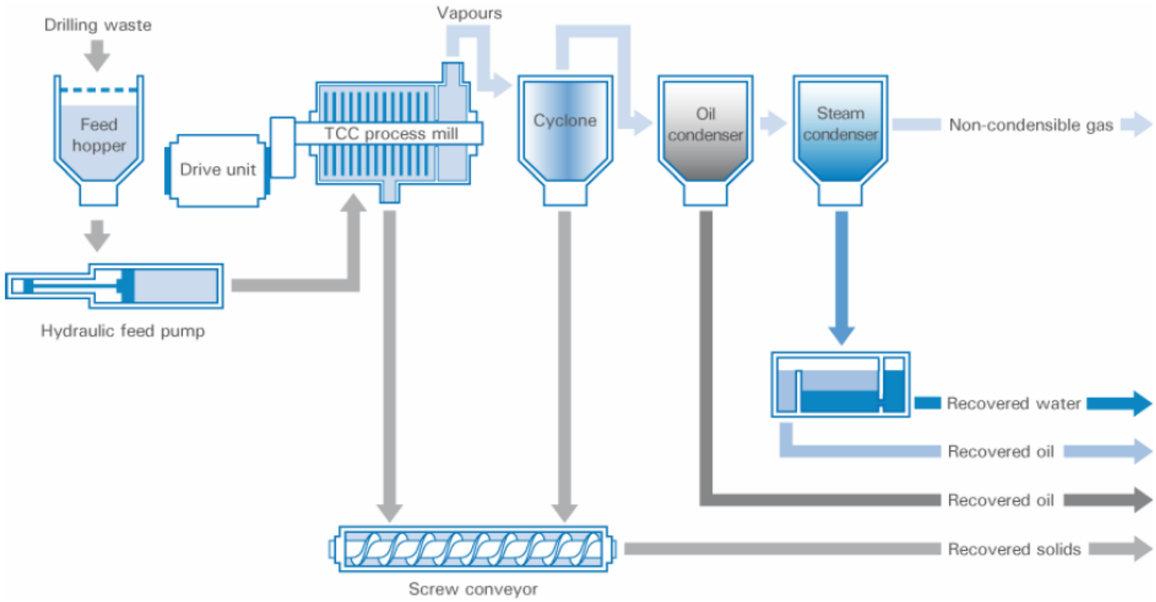


Figure 3-2: Process sketch over the TCC process.[1]

The vapors are passed on to a cyclone unit for further fractionation. The crushed cuttings are sent to a screw conveyor where the cuttings are cooled and transported to a designated discharge point. As can be seen from Figure 3-2, the base oil is recovered and can be reused in the drilling procedure.

The TCC distributor TWMA promotes that the hydrocarbon retained in the recovered solids is less than 0.1 % (w/w). The hydrocarbons in the recovered water are typically less than 20 mg/l with 5-15 mg/l suspended solids, which is less than the regulatory limit for sea disposal (§ 60). The capacity of the unit is normally around 50 000 tons per Annum (TWMA, 2010).

---

[1] http://www.offshore-technology.com/contractors/environmental/thermtec/thermtec1.html

3.3 Hazard Identification

Table A.1 in the Appendix contains a list of possible stressors from drilling waste suggested by the ERMS. The ERMS recommends assessing the following interactions:

- **Water Column**
  - Toxicity of Chemicals
  - Toxicity of heavy metals
  - Effects from suspended particles
- **Sediment**
  - Toxicity of chemicals
  - Toxicity of heavy metals
  - Burial of organisms
  - Change in sediment structure
  - Oxygen depletion

The oil content is presumably much lower than the regulatory demand. Hence, this study has investigated a simplified stressor list (Table 3-2), as these components are assumed to contribute substantially more than the small organic fraction associated with the cuttings.

Table 3-2: Identified relevant components for this study.

Metals	**Comments**
Cadmium, Chromium, Copper, Mercury, Lead and Zinc.	Attached to barite.
Added Chemicals (PLONOR)	Does not require a discharge permit (Green Chemicals)
Barite	Weighting chemical (Barium sulfate). Most abundant solid ingredient in most muds.
Bentonite	Montmorillonite clay. Normally a major solid ingredient in muds.

Source: Adapted from Smith et al., 2006b, p.18.

3.3.1 Drilling Waste

Particles released through drilling waste will undergo a number of physical-chemical processes released into the marine environment. The transport processes involve advection, dispersion, flocculation/aggregation, settling, deposition, consolidation, erosion, re-suspension, re-entrainment, and change in bed evaluation. The fate of discharged drilling waste will depend upon the local oceanographic conditions, quantity and conditions of discharge, amount, property, and sinking velocity of particles from muds and cuttings (Smit et al., 2006a). Figure 3-3 presents some fates of cuttings and mud components in the marine environment.

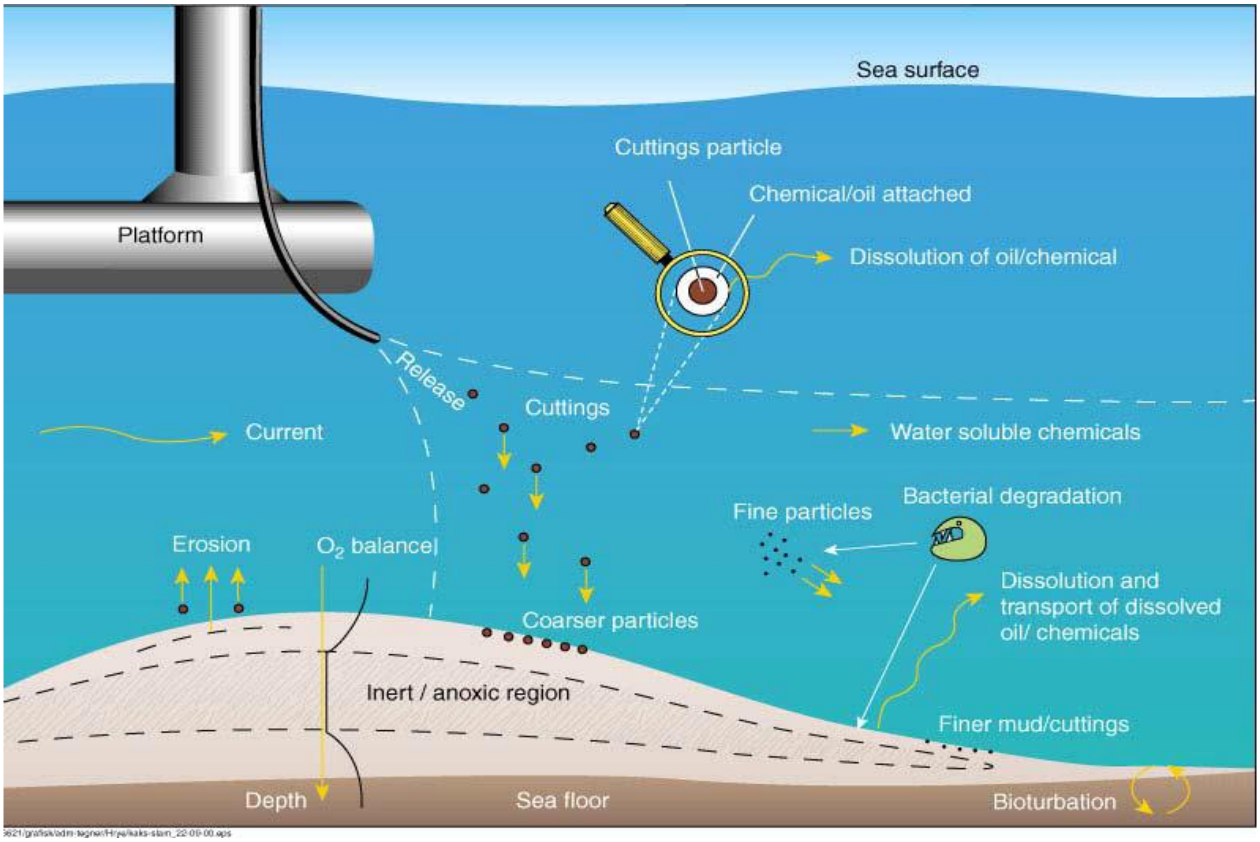


Figure 3-3: Fate of discharged drill waste components in the marine environment (Singsaas et al., 2007)

Fate & Effects in the Water Column

Discharged drilling waste consist mostly of particles from clay minerals, barite and crushed rock, which become dispersed into the marine environment. The solid phase differentiates depending on size and density, where large and heavy particles are rapidly deposited onto the sea-floor. Small particles (< 0.01 mm) can stay suspended in the water column for weeks and months. Consequently, large zones (plumes) of increased turbidity are created around the discharge point such as drilling platforms (Smit et al., 2006a).

Particles that remains suspended over a long period of time may be more prone to metal or chemical dissolution into the water column as it has longer time to reach equilibrium with the water phase. Cuttings associated with OBM have a higher sinking velocity due to the “sticky” property the particles gain through the adherence of OBM. The particles flocculate into larger agglomerations, and gain higher sinking velocities. Cuttings associated with WBM are observed to have limited flocculation properties, where the velocities are observed to be similar to clean particles not contaminated by drilling fluids (Rye, 2005).

The effects from hard and angular (sharp edges) SPM (Suspended Particulate Matter) in the water column may be physical damage through abrasion, clogging of gills or damage to the gastrointestinal tract. SPM concentrations around 200 mg/l have been observed to cause these types of effects. Embryos and larvae have been observed to be more sensitive, where concentrations from 100 mg/l show a significant reduction (Smit et al., 2006a).

High turbidity values in the water column may decrease light penetration, and consequently interfere with the primary production of algae, such as *Skeletonema costatum*. The alteration in production may lead to a bloom period or a change in species diversity. Fish are also sensitive to water turbidity as they depend on water clarity to recognize pray. The increase in turbidity may cause specie migration due to unfavorable hunting condition. Mackerels are observed to avoid waters with a SPM concentration of 10 mg/l (Smit et al., 2006a).

Fate & Effects in the Sediment

The deposited top layer of aquatic sediments is continuously reworked by biological activity such as feeding, moving and defecation. Also physical processes such as erosion, re-suspension, and waves strongly influence the sediment (Fig. 3-4) (Meysman et al., 2007).

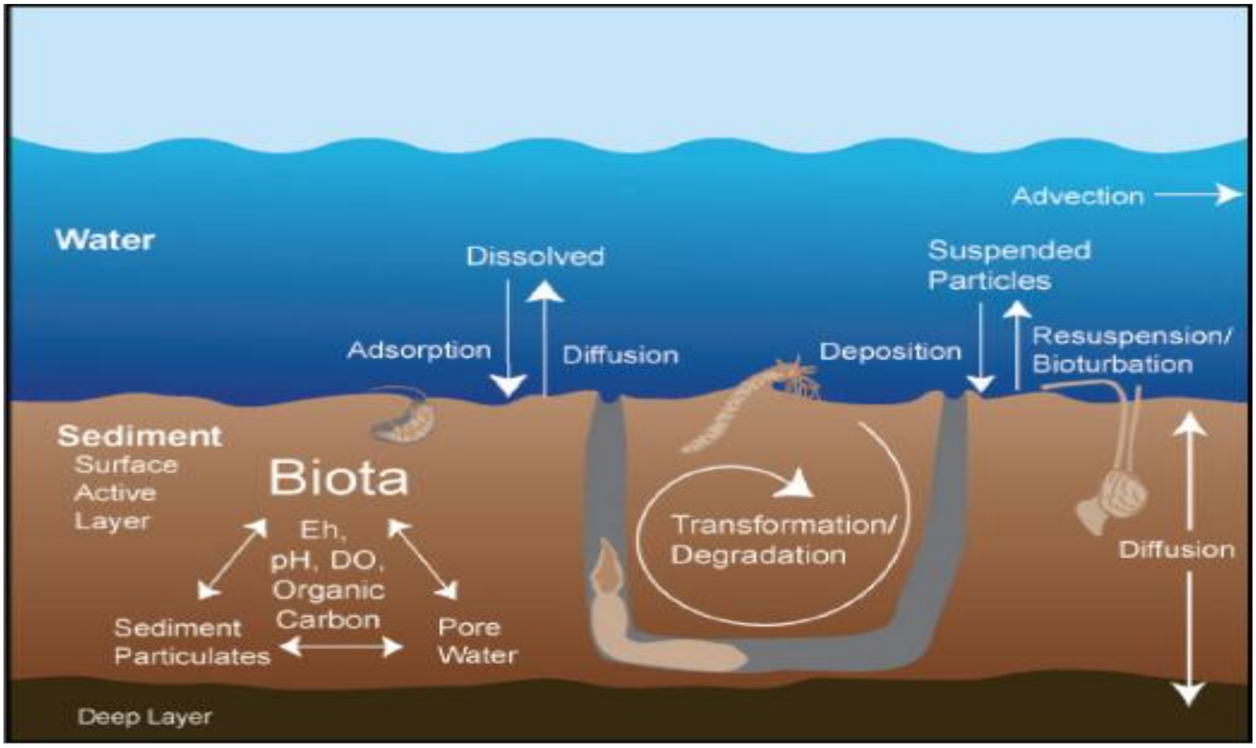


Figure 3-4: Overview of different natural processes occurring in the sediment (Valeur, 2011).

The most affected species from the deposition are benthic filter feeders. Mussels, cockles and shellfish are typical filter feeders. They collect food from suspension. They mostly feed on small organisms such as bacteria, micro-zooplankton and phytoplankton. They differentiate potential food sources by size, which indicates that grain size of SPM may be of importance. SPM grain sizes within the range of the filter feeders food source, may lead to a high SPM filtering effect of particles, causing obstruction and clogging of the filter apparatus (Smit et al., 2006a).

The sediment mixing regime is highly influenced by the process where benthic dwelling organisms turbates down the sediments, which causes the overlying layer to mix (Smit et al., 2006b). This strongly affects the spatial distribution of different types of particles in the sediments. The distribution may include inert particles with attached components (organics, metals, contaminants) (Meysman et al., 2007). Drilling particles often contain attached substrate (organic carbon). Smaller particles have a larger total surface area, and will therefore contain more substrate than larger particles (Schaanning, 2012).

A study performed by Trannum et al. (2009) investigated the effects of sedimentation from WBM cuttings and natural sediment on the benthic macro faunal community and ecosystem processes. Particles from natural sediment and water-based drill cutting were added to benthic communities in layer thicknesses of 3–24 mm in a mesocosm set-up. The result showed that natural sediments had no effect on the community, whereas WBM cuttings showed a substantial reduction on number of taxa, abundance and biomass. It was concluded that the effects were probably caused by addition of substrate, most likely glycol in mud, which consumed most of the available oxygen through biodegradation. It was also noticed when the top layer reached a certain thickness, the effect from sediment activity had no impact on the oxygen levels (Trannum et al., 2009).

Schaanning et al. (2008) studied a glycol-ilmenite based WBM used in the North Sea. 2-5 mm of WBM cuttings was added to a clean sediment samples in a 0.1 m^2 microcosms were the benthic community was monitored for 84 days. Anoxic conditions was observed under, not within, the added layer. It was concluded that bioturbation was stimulated by the initial addition of thin layers of water based cuttings, leading to a rapid influx of substrate and oxygen, causing anoxic conditions. This experiment also indicated that the increased oxygen influx was inhibited by addition of layers exceeding a certain cutoff value (in this experiment it was estimated to be 3.1 mm nominal thickness).

Grain size, shape, and diffusion coefficients are characteristics for porosity (Shen and Chen, 2007). Prediction of mixing coefficients is often performed through assuming constant average porosity. According to Meysman et al. (2007), "*constant average porosity may be adopted without any particular sacrifice of accuracy in the calculation of mixing coefficients.*"

The change in sediment size distribution from mixing natural sediment with drilling particles may cause a change in diffusion rates. Mixing of smaller particles reduces diffusion rates by the effects of tortuosity (Fig 3-5). Molecular diffusion is often linked to porosity by scaling the diffusion coefficient for tortuosity (Shen and Chen, 2007).

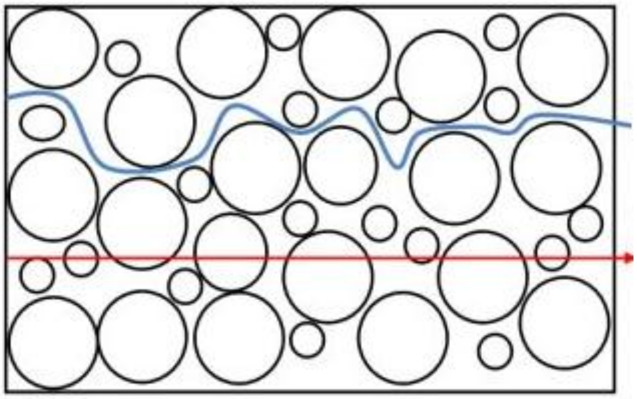


Figure 3-5: An illustration of tortuosity. The addition of smaller particles creates a longer pathway (blue line) for a solute through a porous medium, relative to a direct route (red line).[2]

According to Smit et al. (2006b) oxygen depletion in the sediments may be expressed as an effect from the reduction of the total oxygen in the upper sediment layer, also referred to as redox potential discontinuity (RPD). The sediment can be divided into oxic, suboxic and anoxic layers (Fig. 3-6). Each layer is associated with its respective oxidation reduction potential.

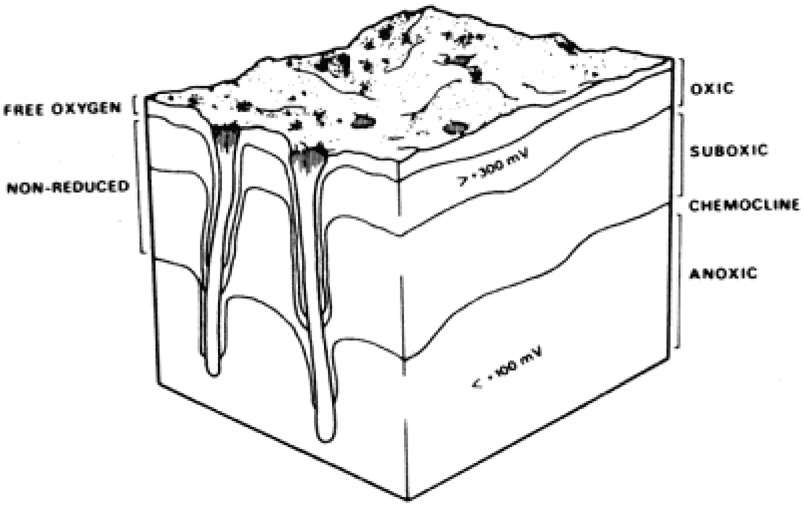


Figure 3-6: Layer classification in sediments regarding oxygen conditions for redox zones.

---

[2] Illustration taken from http://www.groundwatersoftware.com/v9_n10_tortuosity.htm

The macrofaunal diversity is observed to be severely reduced under oxygen depleted overlying bottoms. No single taxa are observed to dominate the macrofauna when oxygen is absent. However, foraminifera’s and some larger metazoans are observed to display abundance close to hypoxic conditions. Presumably these organisms have adapted to the stressful environment. Responses from bacteria, small protists and meiofauna as a consequence of reduced oxygen concentration are poorly known (Smit et al., 2006a).

Supplying the sediments with organics increases the oxygen demand and further promotes the toxicity produced by sulphate-reducing bacteria. However, oxygen concentrations in unaffected control sediments are frequently observed to be low. A single study reported that lowest observable change in oxygen without affecting benthic diversity was 20 % (Smit et al., 2006b).

According to Schaanning (2012), particle size plays an important role when looking at diffusion of pore water components. However, Schaanning (2012) also states that effects from changing the grain size distribution is low compared to the effects from the presence of chemicals, or any other reactive substance.

3.3.2 Heavy Metals

Metals of environmental concern usually exist as trace impurities in barite, bentonite clay or cuttings from the sediments. Barite and bentonite clay are the most frequently used solids in drilling mud, and both are in the PLONOR list. The main purpose of adding these solids is to increase viscosity (bentonite) and serve as a weighing agent (barite) to counteract reservoir pressure. Barite constitutes the major fraction of the two. Thus, barite is the main source for heavy metal contamination (Neff, 2010).

Barite is a soft, dense natural mineral. Seawater contains a relative high concentration of sulfate (0.28 mM), which makes particulate barite quite stable. Barite concentrations are observed to range from 3-34 ug/l, and normally the concentration increases with depth (Neff, 2007).

Heavy Metals in the Water Column

The small bioavailable fraction of metals can be present as free metal ions, hydrated ions, charged metal complexes, uncharged inorganic complexes and organometallic complexes. Cadmium, chromium, copper, mercury, lead and zinc are metals that may exceed 10 times the background concentrations due to drilling operations (Neff, 2007). Frost et al. (2006) performed a review of literature for the selection of heavy metals to include in a risk assessment for drilling waste. Table 3-3 presents the conclusion of the study.

Table 3-3: Heavy metals included in impact calculations for the marine environment.

Metal	Abundant in Cuttings?	Potentially Bioavailable?	Aquatic Toxicity Data Adaquate?	Include in $EIF_{Sediment}$?	Include in EIF_{water}?
Arsenic	No	No	Yes	No	No
Barium	Yes	No	Non-Toxic	No	No
Cadmium	Sometimes	Yes	Yes	Yes	Yes
Chromium	Yes	Yes	Yes	Yes	No
Copper	Sometimes	Doubtful	Yes	Yes	Yes
Lead	Yes	Yes	Yes	Yes	Yes
Mercury	Sometimes	Doubtful	Yes	Yes	Yes
Nickel	No	Doubtful	Yes	No	Yes
Zinc	Yes	Yes	Yes	Yes	Yes

Source: (Frost et al., 2006)

These metals are present in barite as insoluble mineralized sulfide salts (sphalerite and pyrite). The insoluble fraction is non-toxic with low mobility (Neff, 2007). Table 3.4 serves as reference point for metal concentrations in barite from drilling mud in comparison to natural background concentrations in the marine environment. Mud types consist of high (MI-high) and low (MI-low & NORBAR) trace amounts of metals.

Table 3-4: Mean concentration of metals from 4 different samples of drilling muds (barite). MI-low and NORBAR are samples from US Gulf of Mexico and Norway, respectively. MI-high (high trace amounts) is shown to reflect mud types used in the early 90's in the US Gulf of Mexico. All values ug/g dry weight

Metal	MI-low	MI-high	NORBAR	Marine sediments
Barium	538000	524000	NA	1-2000
Cadmium	0.35	0.77	0.05	0.1-0.6
Chromium	15	6.5	40	36-110
Copper	98	88	86	7-33
Iron	6600	9270	25300	20000-60000
Mercury	0.44	5.9	0.05	0.03-0.14
Lead	318	243	18	10-33
Zinc	35	167	1211	27-88

Source: (Crecelius et al., 2007)

Metals tend to associate with sulfides. The oxidized layer of the seawater and pore water has a high concentration of reducible sulfates. Thus, metal dissolution is directly depending on the redox potential. Sulfides can arise under hypoxic conditions, or it may diffuse from sub-oxic sediments. Solubility product values are often hard to estimate, and literature values may vary with several order of magnitudes (Neff, 2007).

The metal in the solution will most likely not reach equilibrium with the solid metal sulfides before the solids settle, as the reaction rate for the dissolution is slow. Thus, an empirical approach is necessary to obtain a representative prediction of the bioavailable metals in the water column. The approach suggested is measuring the solid barite-seawater distribution coefficient ($K_{dbarite\text{-}seawater}$) for heavy metals under different conditions with the end-point to reflect its most toxic state. The coefficient itself reflects the ratio between the metal concentration in barite and the metal concentration in the solution (C_{barite}/C_{water}) (Crecelius et al., 2007). Table 3-5 lists experimental derived partition coefficients for metals in seawater under normal conditions.

Table 3-5: Experimental distribution of $K_{dbarite\text{-}seawater}$ coefficients for metals in barite equilibrated for 1-7 d with seawater. Test conditions were salinity=31, temperature = 20 °C and pH= 7.3 and 8.3.

Metal	**Barium**	**Cadmium**	**Chromium**	**Copper**	**Mercury**	**Lead**	**Zinc**
Log $K_{dbarite\text{-}seawater}$	7.17 - 7.40	2.60 - 3.78	4.11 - 4.34	4.3 - 4.90	5.48 - 6.11	4.30 - 4.48	3.30- 4.30

Source: (Crecelius et al., 2007)

Heavy Metals in the Sediments

In contrast to the water column, deposited particles eventually reach equilibrium with the pore-water. Sulfate concentrations in the pore water of the sediments control the solubility of barite. If anoxic conditions occur in the sediment, sulfate-reducing bacteria may use sulfate as an electron source and generate sulfides (Neff, 2007).

The narrow pH range in the sediments has little effect on the solubility of barite, but the low pH in the gut fluids of benthic invertebrates may cause dissolution of the metals adsorbed to sediment barite (Neff, 2007). A study performed by Crecelius et al. (2007) indicated that the metal dissolution was substantially larger under low pH conditions. Neff (2007) recommends using pH values to resemble these conditions (pH = 2.3 - 6) when establishing partitioning coefficients for barite and pore-water. Table 3.6 presents $K_{dbarite\text{-}porewater}$ coefficient values metals in low pH conditions.

Table 3-6: Presents log $K_{dbarite\text{-}porewater}$ coefficient for metals from 3 barite samples originating from the same source used in table 3-4 (MI-low). Samples were incubated in 4:1 or 10:1 dilutions at pH 3 (with phthalate buffer) equilibrated with barite for 15 min to 48h.

Metals	**Barium**	**Cadmium**	**Chromium**	**Copper**	**Mercury**	**Lead**	**Zinc**
Log Kdbarite-porewater (MI-low)	4.62	0.94	3.12	1.79	6.94	1.88	1.80

Source: (Crecelius et al., 2007)

Several grades of barite were also tested in anoxic and oxic environments. The barite sample that was used originated from a high blend mud that had high trace amounts of metals (not used on the NCS today). In an oxic environment the trace metals were observed to be quite low, and posed no danger to biota. Under anoxic conditions only small amounts of barium and zinc were observed to increase in the porewater after months of incubation. The mud types used today has much lower trace metal concentrations, and is assumed to have little or no dissolution into the porewater (Neff, 2007).

The work from Scaanning et al. (2011) argues that the traditional equilibrium method for solid-water is a poor approach for the determination of a metal partition coefficient, as any well-mixed sample would fail to mimic the interface between the sea-bed deposit and the overlying water. The highest abundance of organisms is within the first few centimeters of the deposit, and they are subjected to steep gradients with regards to redox potentials, dissolved oxygen and ion concentration available for metal complexation and precipitation. In addition, the study argues that the pH may vary by 0.5-1 units, and may pose a significant effect due to large variations compared to the range of pH in seawater habitats. The same study provided different K_d values derived through an empirical study performed in a mecosome. Characteristics of the samples are found in Table 3-7, and the new partition coefficient in Table 3-8.

Table 3-7: Presents characteristics of sediment samples extracted from Bjørhodebukta in Oslofjorden. The samples were further exposed with thin layers of water based cuttings with barite and illmenite in a benthic mesocosm, while flushed with seawater from Oslofjorden. The redox potential, diffusion gradient in thin film gel probes and oxygen profiles were tested at day 4, 55 and 92.

	% of Dry Weight		**mg/g D. Weight**						
	<63 um	TOC	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Control Sediment	78	3.18	0.182	8	43	0.380	41	70	150
Barite Cuttings	35	2.90	0.828	79	67	0.037	61	36	97
Illmenite Cuttings	58	2.02	0.253	155	54	0.033	70	10	160

Source: (Schaanning et al., 2011)

Table 3-8: Presents log Kd values for metals from sediment samples extracted from Bjørhodebukta in Oslofjorden. The samples were further exposed with thin layers of water based cuttings with barite and illmenite in a benthic mesocosm, while flushed with seawater from Oslofjorden. The redox potential, diffusion gradient in thin film gel probes and oxygen profiles were tested at day 4, 55 and 92

Metal	**Pb**	**Ni**	**Zn**	**Cd**	**Hg**	**Cr**	**Cu**
Log Kd	3.8 - 4.8	3.8 – 4.2	3.2 – 4.2	3.3 – 4.0	3.3 – 5.1	3.9 – 5.7	3.7 – 4.0

Source: (Schaanning et al., 2011)

4. Exposure Assessment

4.1 DREAM

The PEC is a three-dimensional measure for the concentration over time in an environmental compartment. All compounds in the discharge that are assumed to represent a potential for harmful impact on biota are included. DREAM evaluates particles from a specific discharge point (Lagrangian approach). The model predicts the fate of each compound in the recipient based on the influence of environmental factors such as currents, turbulence, density, mass, sinking velocities, biodegradability, evaporation, adsorption to particles and background concentrations (Smit et al., 2006b). The ParTrack model builds on the DREAM model to extend the risk assessment to the sediments and suspended particle effects in the water column (Reed et al., 2011). Figure 4-1 presents a general layout of the model.

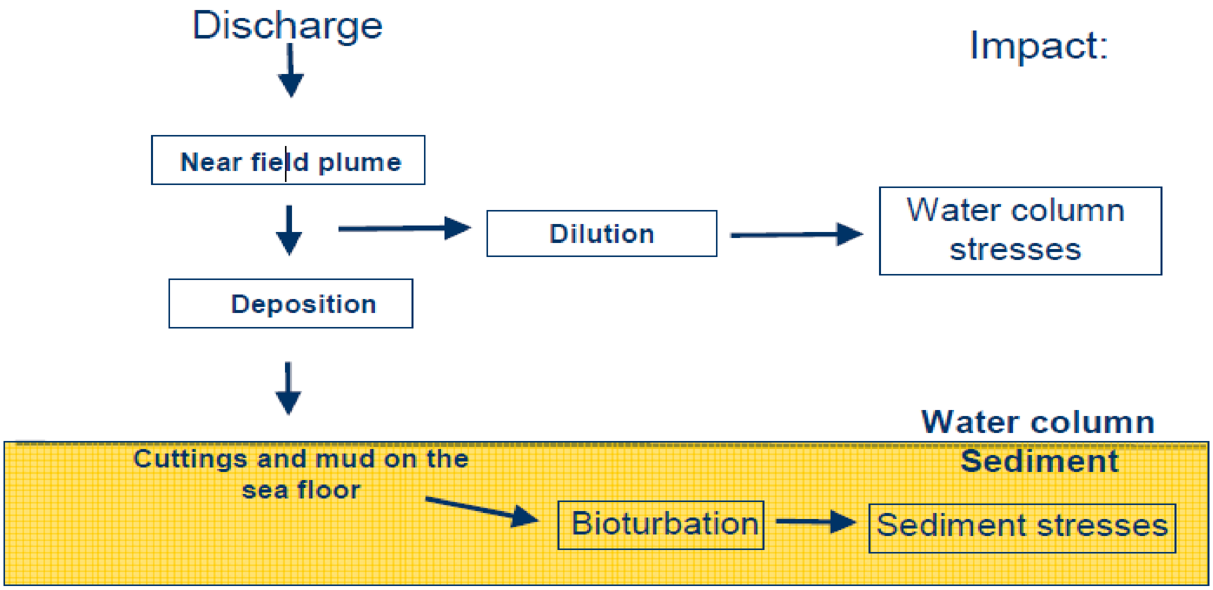


Figure 4-1: Layout of the model structure for calculations of potential impact (Rye et al., 2006a).

Near field plume

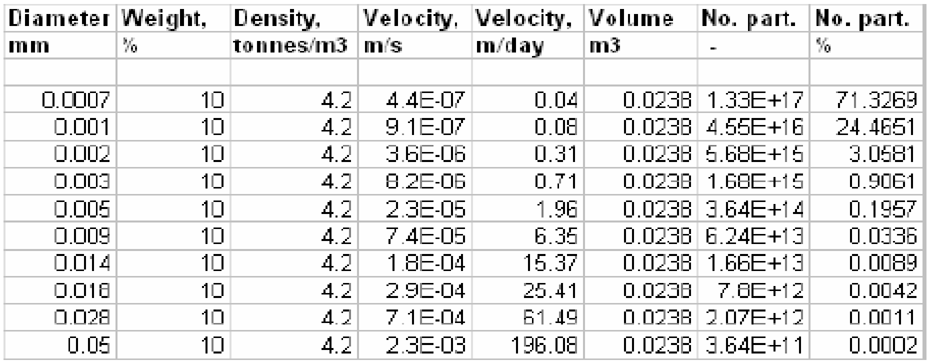
The near field plume accounts for the descent of drill cuttings and mud. The plume is subjected to the oceanic conditions such as currents and vertical variation with respect to the ambient salinity and temperature (stratification). After a certain depth the plume will level out, or sink directly to the bottom. The model allows users to input wind and current profiles, as well as building a representative stratification profile. (Rye et al., 2006a).

Deposition

The "DEPOSITION" factor accounts for the spreading of the effluent based on stratification, currents, sinking and deposition of the particles (including chemicals) on the sea floor. Particle velocities depend on their size and density. The model also accounts for the possibility that particles may agglomerate. Biodegradation are excluded in the sinking phase, due to the limited time the particles stay suspended (Rye et al., 2006a).

The particle size distribution for cuttings and barite used in DREAM was determined from an exploration in the Barents Sea performed by Saga in 1994 (Table 4-1 & 4-2) (Cited in Rye, 2005).

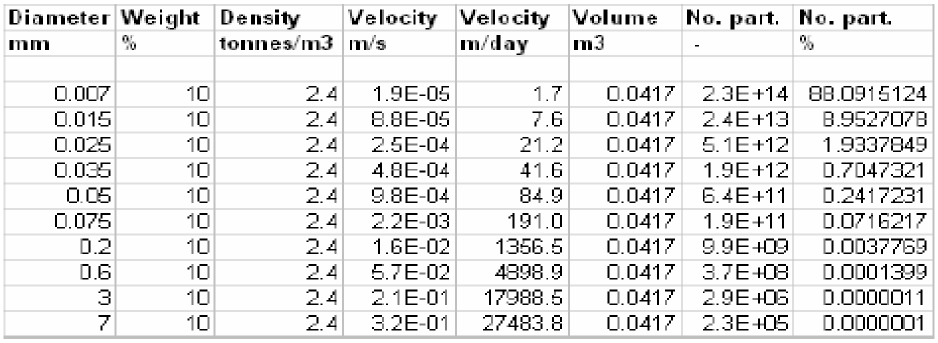
Table 4-1: Particles size distribution, density and sinking velocity for barite in drilling mud.



Diameter mm	Weight, %	Density, tonnes/m3	Velocity, m/s	Velocity, m/day	Volume m3	No. part. -	No. part. %
0.0007	10	4.2	4.4E-07	0.04	0.0238	1.33E+17	71.3269
0.001	10	4.2	9.1E-07	0.08	0.0238	4.55E+16	24.4651
0.002	10	4.2	3.6E-06	0.31	0.0238	5.68E+15	3.0581
0.003	10	4.2	8.2E-06	0.71	0.0238	1.68E+15	0.9061
0.005	10	4.2	2.3E-05	1.96	0.0238	3.64E+14	0.1957
0.009	10	4.2	7.4E-05	6.35	0.0238	6.24E+13	0.0336
0.014	10	4.2	1.8E-04	15.37	0.0238	1.66E+13	0.0089
0.018	10	4.2	2.9E-04	25.41	0.0238	7.8E+12	0.0042
0.028	10	4.2	7.1E-04	61.49	0.0238	2.07E+12	0.0011
0.05	10	4.2	2.3E-03	196.08	0.0238	3.64E+11	0.0002

Source: Saga, 1994 cited in Rye, 2005 p.4

Table 4-2: Particles size distribution, density and sinking velocity for drill cuttings.



Diameter	Weight	Density	Velocity	Velocity	Volume	No. part.	No. part.
mm	%	tonnes/m3	m/s	m/day	m3	-	%
0.007	10	2.4	1.9E-05	1.7	0.0417	2.3E+14	88.0915124
0.015	10	2.4	8.8E-05	7.6	0.0417	2.4E+13	8.9527078
0.025	10	2.4	2.5E-04	21.2	0.0417	5.1E+12	1.9337849
0.035	10	2.4	4.8E-04	41.6	0.0417	1.9E+12	0.7047321
0.05	10	2.4	9.8E-04	84.9	0.0417	6.4E+11	0.2417231
0.075	10	2.4	2.2E-03	191.0	0.0417	1.9E+11	0.0716217
0.2	10	2.4	1.6E-02	1356.5	0.0417	9.9E+09	0.0037769
0.6	10	2.4	5.7E-02	4898.9	0.0417	3.7E+08	0.0001399
3	10	2.4	2.1E-01	17988.5	0.0417	2.9E+06	0.0000011
7	10	2.4	3.2E-01	27483.8	0.0417	2.3E+05	0.0000001

Source: Saga, 1994 cited in Rye, 2005 p.4

4.2 ParTrack

Four sediment effects are modulated in the revised DREAM model.

- **Burial.** Represented by the thickness of the added layer originating from the discharge.
- **Toxicity.** The toxicity is estimated by calculating the concentration of chemicals in the added sediment.
- **Free oxygen depletion.** The reduction of oxygen in the pore water is determined by calculating the difference between the concentration before and after the discharge.
- **Change in grain size.** The new grain size profile is estimated by allowing the new formed layer to mix with the natural sediment.

Burial

The burial parameter is represented by the thickness of the deposition of cuttings and weight material. The thickness of the added layer over time is estimated by Equation 4-1. The value will be used to estimate PEC for burial risk. Figure 4-2 presents a graphical illustration on how the PEC for thickness is estimated.

$$Burial = \frac{1}{1-\varphi}\sum_i \frac{M_i}{\rho_i} \qquad \text{(Eq. 4-1)}$$

M_i = mass of particle (i) deposited pr. m^2 of the sediment area

ρ_i = density of particle (i)

φ = porosity

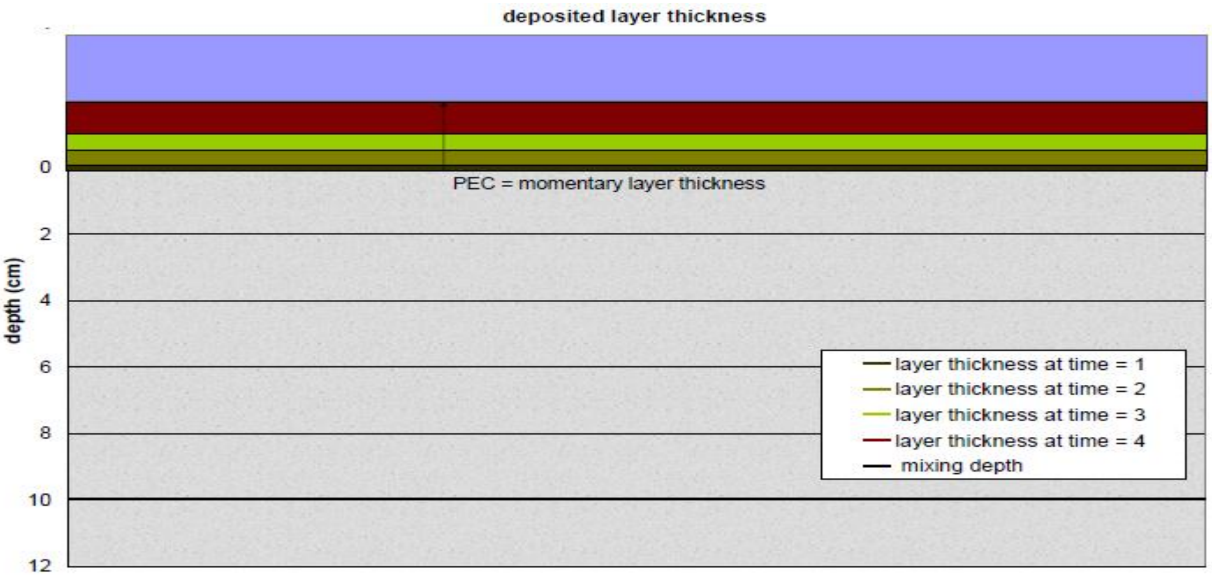


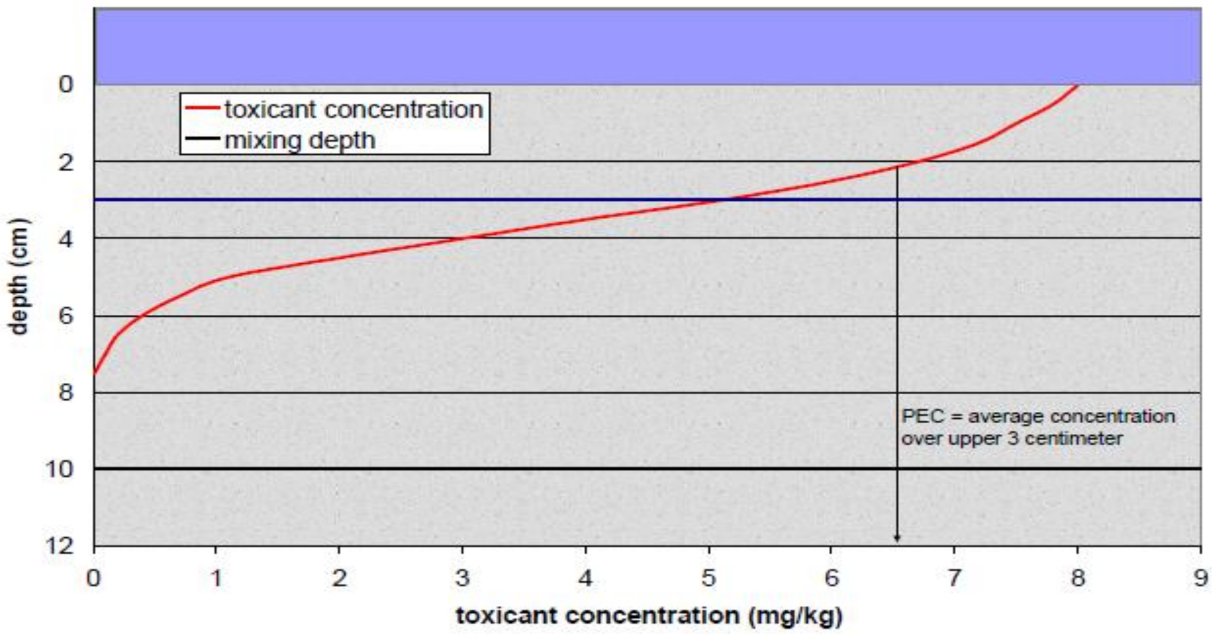
Figure 4-2: Illustration on how the PEC for burial is measured in the sediment (Smit et al., 2006b).

Toxicity from Chemicals

The effect of bioturbation will cause the added layer to mix with the original sediments. The average chemical concentration from the top 3 cm is derived by Equation 4-2. Figure 4-3 shows a graphical illustration of how the toxicant PEC is estimated (Smit et al., 2006b).

$$\text{Sediment chemical concentration} = \frac{1}{3\ \text{cm}} = \int_0^{3\ \text{cm}} \mathrm{C(z)dz} \qquad \text{(Eq. 4-2)}$$

$\mathrm{C(z)}$ = concentration of the chemical deposited on the seafloor with the cuttings.



PEC = average concentration over upper 3 centimeter

Figure 4-3: PEC gradient for chemicals based on sediment depth (Smit et al., 2006b).

Grain Size

The effect of bioturbation will also produce a new gradient with respect to the original median grain size in the sediments. The average median grain size change in the upper 3 cm is estimated by Equation 4-3. Figure 4-4 presents a graphical illustration on how the PEC gradient for change in median grain size is estimated (Smit et al., 2006b).

$$Grain\ size\ change = \frac{1}{3\ cm} = \int_0^{3\ cm} D(z)dz - D_{original} \qquad \text{(Eq. 4-3)}$$

$D(z)$ = median grain size after discharge (diameter)

$D_{original}$ = median grain size before discharge

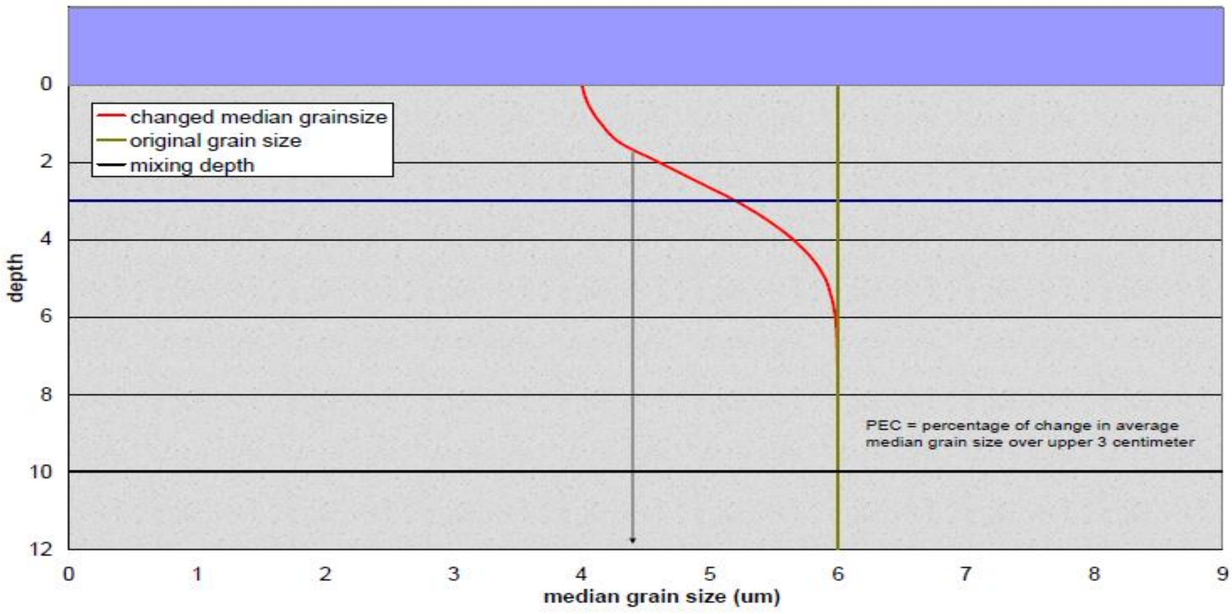


Figure 4-4: Illustration on how the PEC gradient for median grain size is estimated with respect to the sediment depth (Smit et al., 2006b).

Oxygen Depletion

The DREAM model expresses the thickness of the oxygenated sediment layer as the integrated oxygen concentration over depth, or the total amount of oxygen in the RDP-layer. The oxygen depletion is defined as "*the reduction of the oxygen content (%) in the sediment layer due to the discharge, integrated over the layer where bioturbation is taking place*". The oxygen profile is estimated by calculating the natural oxygen concentration before and after deposition. The difference in the concentration is due to the release of chemicals to the sediment. Equation 4-4 expresses how the depletion is estimated. Figure 4-5 presents a graphical illustration of the gradient (Smit et al., 2006b).

$$O_2\ depletion\ (\%) = 100\frac{\int_0^L \varphi O_2(z)dz\ (after\ discharge)}{\int_0^L \varphi O_2(z)dz\ (before\ discharge)} \qquad \text{(Eq. 4-4)}$$

$O_2(z)$ = oxygen concentration in the pore water.

φ = porosity.

L = sediment depth.

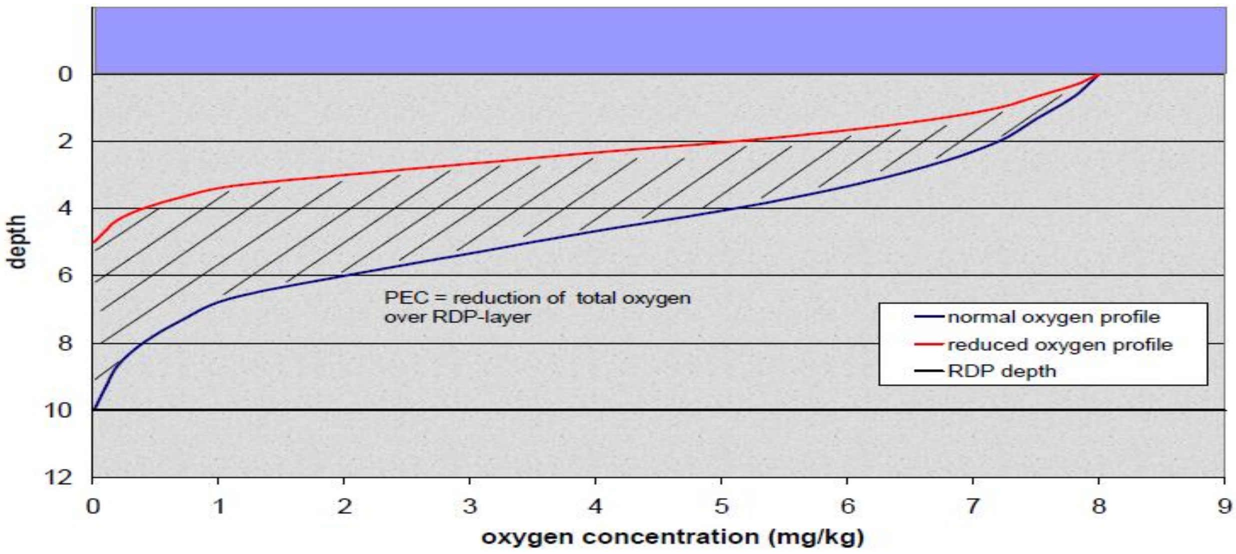


Figure 4-5: Illustration on how the PEC gradient for oxygen depletion is estimated for the sediment. (Smit et al., 2006b)

The Numerical Model

The processes are modulated through differential equations (digenetic equations). The sea bottom is assumed to have a homogenous deposited layer where the top layer is fully aerated. Two differential equations (Eq. 4-6 & 4-7) are used to describe the natural occurring degradation and oxygen concentration in the pore water before deposition (initial concentration). Boundary conditions include the sediment surface and at the bottom of modeled sediment layer (10 cm). New equations and extensions are used to evaluate the impact or change in the sediments (Eq. 4-8 to 4-12) (Rye et al., 2006b).

Processes Occurring Before Discharge

- The free oxygen concentration in the pore water

$$\frac{\partial O_2}{\partial t} = \frac{D_0 \partial^2 O_2}{\theta^2 \partial z^2} - \frac{1-\varphi}{\varphi}[\gamma_1 k_1 C_1]\frac{O_2}{K_{O2}+O_2} \qquad \text{(Eq. 4-6)}$$

- The natural organic matter in the sediment

$$\frac{\partial C_1}{\partial t} = \frac{\partial}{\partial z}\left(D_B \frac{\partial C_1}{\partial z} - wC_1\right) - [k_1 C_1]\frac{O_2}{K_{O2}+O_2} \qquad \text{(Eq. 4-7)}$$

Processes Occurring After Discharge

- The free oxygen concentration in the pore water

$$\frac{\partial O_2}{\partial t} = \frac{D_0 \partial^2 O_2}{\theta^2 \partial z^2} - \frac{1-\varphi}{\varphi}[\gamma_1 k_1 C_1 + \gamma_2 k_2 C_2]\frac{O_2}{K_{O2}+O_2} \qquad \text{(Eq. 4-8)}$$

- The natural organic matter in the sediment

$$\frac{\partial C_1}{\partial t} = \frac{\partial}{\partial z}\left(D_B \frac{\partial C_1}{\partial z} - wC_1\right) - [k_1 C_1]\frac{O_2}{K_{O2}+O_2} \qquad \text{(Eq. 4-9)}$$

- The added organic matter (chemicals) from the discharge

$$\frac{\partial C_2}{\partial t} = \frac{\partial}{\partial z}\left(D_B \frac{\partial C_2}{\partial z} - wC_2\right) - [k_2 C_2]\frac{O_2}{K_{O2}+O_2} \qquad \text{(Eq. 4-10)}$$

- The change in grain size in the sediment

$$\frac{\partial R_{ave}}{\partial t} = \frac{\partial}{\partial z}\left(D_B \frac{\partial R_{ave}}{\partial z} - wR_{ave}\right) \qquad \text{(Eq. 4-11)}$$

Table 4-3: Symbol description for Eq. 4-6 to 4-11.

Symbol	Description	Symbol	Description	Symbol	Description
∂	Partial derivative	**C_2 (z)**	Concentration of biodegradable organic matter in the sediment	**w**	Burial velocity from natural sediment deposition (cm/year)
t	Time dimension	**D_0**	Diffusion coefficient for oxygen porewater (cm2/s)	**γ_1**	Redfield number combined with mol weights of C1 and O2
z	Vertical dimension	**θ**	Tortuosity of the sediment	**γ_2**	Redfield number combined with mol weight of C2 and O2
O_2 (z,t)	The free oxygen pore water	**DB (z,t)**	Bioturbation coefficient	**k_1**	Biodegradation rate of natural organic matter
C_1 (z)	Concentration of biodegradable organic matter in the sediment	**φ**	Porosity of the sediment	**k_2**	Biodegradation rate of added chemicals
K_{O2}	Saturation constant (Monod-type)	**μ**	Dynamic viscosity (centipoise)	**T**	Absolute temperature in the pore water

Equations 4-6 to 4-10 are linked and must be solved simultaneously. Equations 4-6 to 4-7 and 4-9 to 4-11 can't be solved analytically as they are non-linear. A finite difference method utilizing an implicit/central differencing is used to discretize the system. The problem domain x = [0,L] is divided into N elements (N+1). The coupled system is solved by an iterative algorithm. The time steps starts from the initial conditions and calculates profiles by substituting the previous iteration values while checking the state variables (O_2, C_1, C_2, R_{ave}) for convergence (Rye et al., 2006b).

Assumptions

The free oxygen diffusion is assumed to be much larger than the combined effects from bioturbation and burial. Therefore, the bioturbation and burial terms were excluded from Eq. 4-6. Change in molecular diffusion due to tortuosity (θ) is accounted for by dividing the diffusion coefficient by the tortuosity squared (θ^2). The tortuosity is assumed to be only related to the porosity (φ). The porosity is assumed to be constant, where a value of 0.6 was deemed appropriate (Rye et al., 2006b).

$$\theta^2 = 1 - \ln \varphi^2 \qquad \text{(Eq. 4-12)}$$

The actual diffusion coefficient for oxygen (D_0) in the pore water and the dynamic viscosity (μ) is assumed to follow the relationship described in Eq. 4-13 and 4-14, respectively.

$$D_0 = \frac{(0.2604+0.006383)\mathrm{T}*10^{-5}}{\mu} \qquad \text{(Eq. 4-13)}$$

$$\mu = 1.7910-0.06144*temp+0.001451*temp^2 \qquad \text{(Eq. 4-14)}$$

Natural burial (w) is assumed to decrease with depth (H), according to the linear relationship:

$w = 3.5/H$ *when* $H > 35$ *m depth*

The bioturbation ($D_B(z)$) is assumed to be dependent on the water and sediment depth. Furthermore, it is assumed that the bioturbation coefficient (D_{Bave}) is largest at the sediment surface and decreases with depth (z). The bioturbated depth (L) is frequently observed to be 10 cm on average. It appears to be invariant with respect to varying water depth and varying natural burial velocities (Rye et al., 2006b) .

$$D_B(z) = 3D_{Bave}(1 - \frac{z}{L})^{2} \qquad \text{(Eq. 4-15)}$$

The bioturbation coefficient (D_{Bave}) is assumed to be related to the burial factor (w), and have the relationship:

$$D_{Bave} = 15.7w^{0.6} \qquad \text{(Eq. 4-16)}$$

Biodegradation or respiration is expressed by Monod kinetics (Eq. 4-17). When evaluating the organic concentration, it follows a linear relationship. The oxygen concentration is hyperbolic (Rye et al., 2006b).

$$\left(\frac{\partial C}{\partial t}\right)_{reaction} = -kC\frac{O_2}{K_{O2}+O_2} \qquad \text{(Eq. 4-17)}$$

The biodegradation rate (k_1) has been observed to be dependent on the burial velocity w. The organic fraction in the top sediments (10-20 cm) is biodegraded in a short time frame. The remaining organic matter fraction in the lower part of the layer is slowly biodegraded. The total organic matter biodegradation rate is calculated by Eq. 4-18 (Rye et al., 2006b) .

$$k_1 = 3.0w^{0.6} + 0.4w^{0.6} \qquad \text{(Eq. 4-18)}$$

To account for the different molecular weights the Redfield number (γ_1) has been implemented. The factor is based on the reaction of oxygen with carbon to form CO_2, and some reactions which involves nitrogen and phosphorous. The value used is approximately 3.47 (Rye et al., 2006b).

5. Effect Assessment

5.1 PNEC

The obtained exposure values of stressors are compared to levels where it might cause an effect. Laboratory experiments are used to assess responses from biota, where the results are used to derive a sensitivity list that describes the dose-response relationship. The dose-response relationships is the determination of the dose or concentration that causes a 50 % effect intensity over a specific test time (normally 48 or 96 hours) in a specific test organism. This implies the dose or concentration which affects 50 % of the tested population. The mortality to the exposed organism is defined as the 50 % lethal dose or concentration (e.g. LD_{50} & LC_{50}). Different sub-lethal effects (e.g. growth inhibition) are expressed as the 50 % effect dose or concentration (e.g. ED_{50} & EC_{50}). Figure 5.1 presents a typical dose-response relationship (Beyer, 2011).

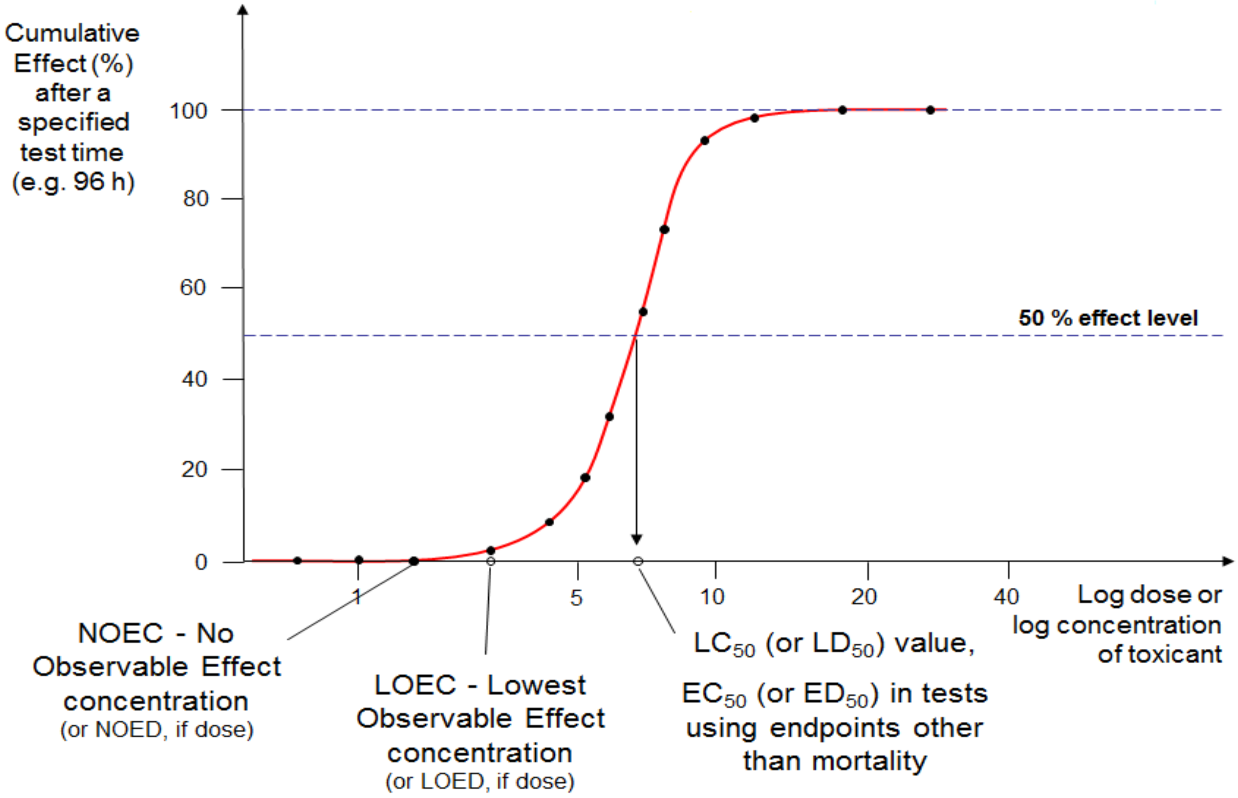


Figure 5-1: Sigmoidal Dose response relationship. Showing how LC/EC_{50}, LOEC and NOEC are determined.

5.2 Methods for Determining PNEC

The PNEC is the lowest estimated limit for effects on the biota in the recipient for a single chemical component or component group. PNEC values for different stressors are determined by rules outlined in the EU-TGD. Usually this includes assessment factors and SSD (Species Sensitivity Distribution). The equilibrium partitioning method may be used when toxicological data for sediment organisms are low. However, it is recommended to perform as many assessments as possible, and choosing the lowest PNEC (Smit et al., 2006b).

5.2.1 Assessment Factors

Assessment factors are the most common method for deriving PNEC values when sound quality data from literature are unavailable. Mostly, data from one single species toxicity test is used. The main assumption for applying this method is that the most sensitive species from the ecosystem is used (Bjørgesæter, 2006).

Preferably, there should be used toxicity data from three taxonomic or trophic levels when determining PNEC values for a given substance. To address lacking toxicity data, assessment factors are used as an extrapolations tool from single species toxicity test to multi-species ecologic effects. PNEC for a specific compound is determined by dividing the LC/EC_{50} or NOEC/NOLC by the assessment factor based on the amount of information that is provided (Smit et al., 2006b).

Assessment factors address uncertainties such as interspecies variation and short-term to long-term toxicity extrapolation. As seen from Table 5-1, short-term studies (acute) yields a high factor, whereas more long-term studies (chronic), with established NOEC values, produces a lower factor (Smit et al., 2006b).

Table 5-1: Assessment factors defined in the EU-TGD for the marine water column.

Data set	Assessment Factor
Lowest short term LC/EC50 from freshwater or saltwater representative of three taxonomic groups (algae, crustaceans and fish) of three trophic levels	10 000
Lowest short term LC/EC50 from freshwater or saltwater representative of three taxonomic groups (algae, crustaceans and fish) of three trophic levels + two additional marine taxonomic groups (e.g. echinoderms, molluscs)	1000
One long term NOEC (from freshwater or saltwater crustaceans reproduction or fish growth studies)	1000
Two long term NOEC (from freshwater or saltwater species representing two trophic levels (algae and/or crustaceans)	500
Lowest long term NOECs from three freshwater or saltwater species (normally algae and/or crustaceans and/or fish) representing three trophic levels	100
Two long term NOECs from freshwater or saltwater species representing two trophic levels (algae and/or crustaceans and/or fish) + one long term NOEC's from an additional marine taxonomic group (e.g. echinoderms, molluscs)	50
Lowest long term NOECs from three freshwater or saltwater species (normally algae and/or crustaceans and/or fish) representing three trophic levels + two long term NOECs from additional marine taxonomic groups (e.g. echinoderms, molluscs)	10

Source: (EC, 2003)

5.2.2 SSD

The SSD approach is an alternative to assessment factors aimed at providing information on the sensitivity of a community exposed to a certain stressor. Inter-species variation is accounted for by evaluating the tested species as a sample from a community distribution, where the empirical mean and standard deviation is used to determine a percentile which is sufficiently low as to not cause harm to the majority of the community. The concentration at this level is defined as "hazardous concentration for p percent of the species", designated HCp (Straalen, 2002).

The method is applied whenever large long-term data sets exists on different taxonomic groups. The main assumption for using SSD is that the selection of species is representative for all species in the community under evaluation. Statistical extrapolation from the variation in species sensitivity is used to establish threshold values (Table 5-2). Normally, sensitivity data are log transformed and fitted against a pre-determined distribution. The minimum number of species required to use SSD is 10 NOECs from at least 8 different taxonomic groups (Smit et al., 2006b, Wheeler et al., 2002).

Table 5-2: Assessment factor for extrapolation from acute to chronic, LC/EC50 to NOEC and laboratory to field.

Convertion	Factor
LC/EC$_{50}$ to NOEC	10
Acute to Chronic	10
Laboratory to Field Data	10

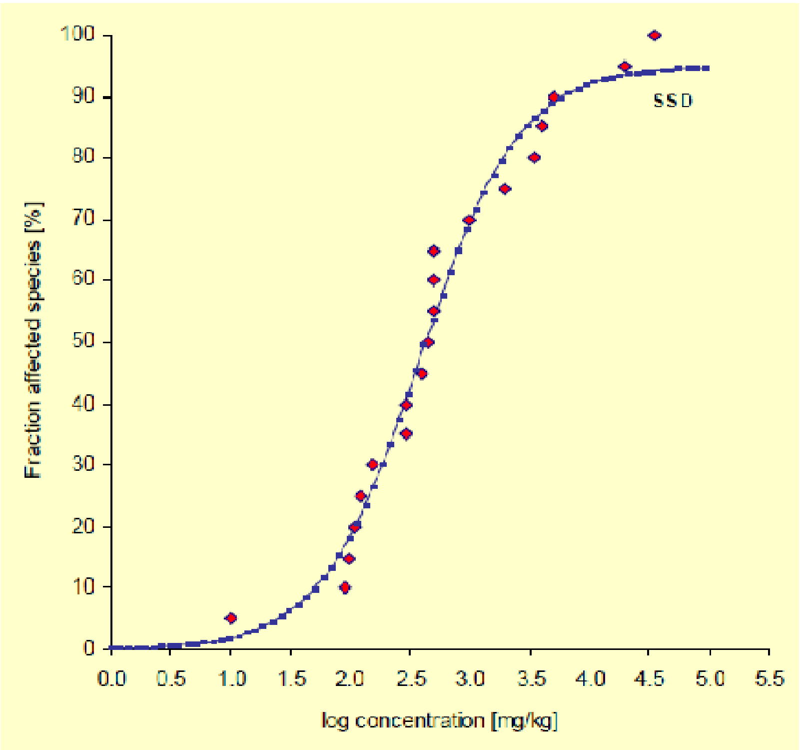
PNECs are determined by choosing a specific percentile from the distribution. The 5th percentile, with a 50 % confidence interval, is often used for pragmatic reasons. This is often referred to as the PAF (Potential Affected Fraction), where 5 % of the species are assumed to be affected. PNEC's are calculated from Eq. 5-1. Assessment factors in this equation are based on uncertainties in the information used (Smit et al., 2006b).

$$\text{PNEC}_{\text{seawater}} = 5\ \%\ \text{SSD}\ (50\ \%\ \text{c.i.})/\text{AF} \qquad \text{(Eq. 5.1)}$$

c.i.= confidence interval

AF = assessment factor

Fig. 5-2 presents a typical SSD plot, where log transformed concentration is plotted against the fraction of affected species. The mean (Xm) represents the position of the distribution on the x-axis, and the slope of the curve is determined by the standard deviation (Sm). In this example the Xm provides an indication of the mean concentration for the effects of suspended mud particles to marine species. The Sm represents the interspecies variation in sensitivity of suspended particles for the different marine species (Smit et al., 2006a).



Species	logNOEC	PAF
Algae 1	1.00	5
Crustacean 1	1.95	10
Crustacean 2	2.00	15
Crustacean 3	2.04	20
Crustacean 4	2.09	25
Mollusc 1	2.19	30
Mollusc 2	2.48	35
Mollusc 3	2.48	40
Mollusc 4	2.60	45
Mollusc 5	2.66	50
Mollusc 6	2.70	55
Mollusc 7	2.70	60
Mollusc 8	2.70	65
Mollusc 9	3.00	70
Sea star1	3.30	75
Sea star 2	3.54	80
Fish 1	3.60	85
Fish 2	3.70	90
Fish 3	4.30	95
Fish 4	4.54	100

Figure 5-2: Graphical presentation of PAF as a function of log NOEC values (table right side) from several different species.

5.2.3 F-PNEC

The F-PNEC (Field-Predicted no Effect Concentration) method was developed as an alternative to laboratory results. The threshold values are derived from field data of benthic macro benthos living in close contact with the substance under evaluation. Single species are plotted as a function of their abundance against the natural contamination concentration. EC_{50} for sensitive species are estimated from a scatter plot based on a linear regression technique. This method requires large data sets with chemical and biotic information from sediment conditions, ranging from unpolluted areas to highly polluted areas.

Data sets regarding chemical and biological information from the NCS can be extracted from the Norwegian Oil Industry Association (OLF). The data sets are called “the MOD-database”. The information was collected in the period of 1990 to 2001, and contains information from 2206 species, where 3 238 371 individuals (macro benthos) were collected from 2428 sediment samples. Design and analytic procedure for the entire MOD followed ISO/IEC/EN 17025 (Bjørgesæter, 2006).

EC50s is determined based on the following two criteria’s:

- “The species must be occurring in more than 30 sediment samples with different concentration levels, i.e. this set the minimum resolution on the x-axis.
- The abundance of the species must be greater than 100 individuals, i.e. this set the minimum resolution on the y-axis.”

5.2.4 EqP Method

A provisional calculation of $PNEC_{sediment}$ by the EqP (Equilibrium Partitioning) method is allowed when eco-toxicological data are unsatisfactory or unavailable for sediment-dwelling organisms. It is further recommended that the lowest derived PNEC value from the EqP method and assessment factors is used when assessing risk (EC, 2003).

The EqP method has a solid established theoretical basis for non-ionic organics and metals. Assumptions for the development of EqP are listed below (Frost et al., 2006).

- The uptake and hence bioavailability, bioaccumulation and toxicity are closely related to the pore water concentration.
- Equilibrium exists between the concentration of the substance sorbed to the solid phase (sediment) and the concentration in solution in pore water/interstitial water; related by a single partition coefficient.
- The sensitivity distribution for a substance to aquatic and benthic organisms is equal."

5.3 PNEC for SPM

No regulatory framework exists for determining impacts from SPM, as standardized testing procedures are lacking. Combined with low availability of test data have resulted in low quality information regarding effects from SPM. Background concentration of SPM in the North-Sea is usually in the range of 10-20 mg/l. Both assessment factors and SSD have been evaluated to develop representative threshold values (Smit et al., 2006b).

Literature values for LC/EC$_{50}$ are mostly determined from acute effects from three taxonomic groups (crustaceans, fish and algae). As only short-term data are available, an assessment factor of 10 000 (marine environment) have been used for the lowest LC/EC$_{50}$. Table 5-3 presents an overview of estimated PNECs for barite, bentonite and WBM based on assessment factors (Smit et al., 2006b).

Table 5-3: Threshold values derived for bentonite, barite and WBM's based on assessment factors.

Type of weighing material	**Barite**	**Bentonite**	**WBMs**
Number of effect data	30	17	82
Number of LC/EC50	15	12	63
Number of taxonomic groups	5	5	4
Lowest effect value (mg/L)	0.5	2	5

Lowest LC/EC50 value (mg/L)	32	9.6	2.6
PNECs using an assessment factor of 10 000	0.0032	0.00096	0.00026

Source: Adapted from Smit et al. (2006a)

A SSD approach was further used to determine PNEC values for barite, bentonite and WBM. The results (Table 5-4) proved to be more realistic with respect to background concentrations on the NCS (Smit et al., 2006a).

Table 5-4: Threshold values for barite, bentonite and WBM based on SSD.

Weighting material	**Barite**	**Bentonite**	**WBMs**
Number of EC_{50} values	20	12	63
Number of species with 1 or more EC_{50} values	15	12	13
Xm	8.01	7.51	8.81
Sm	3.05	3.25	1.05
HC_5	20.0	8.8	79.8
PNEC* (ppm)	0.20	0.088	0.8

**HC5 value transformed from EC50 to chronic no-effect level by an assessment factor of 100.*

Source: Adapted from Smit et al. (2006a)

5.4 PNEC for Metals

Maximum Permissible Concentration (MPC_{water}), produced by the Dutch international Institute of Public Health and the Environment, was evaluated for metal threshold values. MPC_{water} is defined as "*the concentration above which the risk for the ecosystem is considered unacceptable*" (Smit et al., 2006b).

The MPC_{water} is determined by Eq. 5-2. MPA_{water} is defined as "*the acceptable metal addition in a specific environmental compartment originating from anthropogenic sources*". The background concentration (Cb_{water}) consists of both the bioavailable fraction and the inert fraction (not bioavailable) (Frost et al., 2006).

$$\mathrm{MPC_{water}} = \mathrm{MPA_{water}} + \mathrm{Cb_{water}} \qquad \text{(Eq. 5-2)}$$

$\mathrm{MPC_{water}}$ = Maximum Permissible Concentration in the surface water (ug/L)
$\mathrm{MPA_{water}}$ = Maximum Permissible Addition in the surface water (ug/L)
$\mathrm{Cb_{water}}$ = background concentration in the surface water (ug/L)

MPC_{water} values with a 95 % protection level were used to determine a sensitivity distribution by statistical extrapolation. Table 5-5 represents values determined based on conditions in the Netherlands. The MPA_{water} concentrations are based on statistical extrapolation of NOECs from both fresh- and seawater (Frost et al., 2006).

Table 5-5: Threshold values including background concentration derived through the dutch MPC_{water} method.

Metal	**MPA_{water} (ug/L)**	**Cb_{water} (ug/L)**	**MPC_{water} (ug/L)**
Cadmium	0.34	0.025	0.37
Copper	1.1	0.25	1.4
Lead	11	0.02	11
Inorganic mercury	0.23	0.0025	0.23
Methyl-mercury	0.01	0.0025	0.013
Nickel	1.8	NA	NA
Zinc	6.6	0.35	7

Toxicity data from long-term studies in general, and from several major benthic phyla (cnidarian, echinoderms and mollusks) are quite low. It was also reported an imbalance between available guidelines for testing phyla, and representative phyla naturally occurring in the sediments. Consequently, high assessment factors were used to derive PNECs for metals in the sediment. Table 5-6 lists assessment factors used and the calculated $PNEC_{sediment}$. An assessment factor of 1000 is used for most metal as there was reliable lethality data (acute) from 3 different taxonomic groups. Mercury is assigned 10 000, as only one acute test was discovered (Frost et al., 2006).

Table 5-6: Threshold values for metals in the sediment derived by assessment factors.

Metal	Assessment factor	$PNEC_{sediment}$ (mg/kg dw)	NCS-background (mg/kg dw)
Cadmium	1000	0.00126	0.003-0.13
Copper	1000	0.0068	0.3-17.2
Chromium	1000	0.0147	2.58-39.2
Lead	1000	0.029	1.92-46.5
Mercury	10 000	0.00152	0.003-0.10
Zinc	1000	0.0319	0.42-83.7

However, background concentrations found in the Norwegian Continental Shelf (Table 5-7) are often higher than the estimated PNEC values. The Dutch EqP method was therefore deemed more appropriate for calculating sediment metal PNECs. The approach is based on establishing empirical partition coefficients (k_p) between sediment and water together with the water quality criteria (MPA) including background concentrations ($Cb_{sediment}$) of natural occurring metals (Frost et al., 2006).

$$MPCsediment = Kpsediment * MPAwater + Cbsediment \qquad \text{(Eq. 5-3)}$$

$MPC_{sediment}$ = Maximum Permissible Concentration in marine sediment [mg/kg]

$Kp_{sediment}$ = partition coefficient sediment and water [m^3/m^3]

MPC_{water} = Maximum Permissible Concentration in the surface water

$Cb_{sediment}$ = background concentration in the sediment [mg/kg]

The PNEC for heavy metals in the water column is equal to MPA_{water}. PNEC for metals in the sediment is calculated by Eq. 5-4.

$$PNEC_{sediment} = Kp_{sed.barite-seawater} * PNEC_{water} + Cb_{sediment} \quad \text{(Eq. 5-4)}$$

$PNEC_{sediment}$ = Predicted No Effect Concentration in marine sediment [mg/kg]
$Kp_{sed.barite-seawater}$ = partition coefficient barite particles and porewater [m3/m3]
$PNEC_{water}$ = Predicted No Effect Concentration in seawater [mg/L]
$Cb_{sediment}$ = background concentration in the sediment [mg/kg]

Table 5-7 presents the final partitioning coefficients, background concentrations of metals in the sediment and PNEC values included in the DREAM model. The PNEC values are derived through statistical extrapolation of data applied in the Netherlands. Mean background concentrations are based on all reference and regional stations for the Norwegian Continental Shelf (Frost et al., 2006).

Table 5-7: Final Threshold values for metals in sediment and the water column derived through the EqP method.

Metals	**$PNEC_{water}$ (MPA_{water}) (ug/L)**	**Log $K_{D(barite-porewater)sediment}$ (L/kg)**	**$PNEC_{sediment}$ (MPA_{sed}) (mg/kg)**	**Cb_{sed} (mg/kg)**	**$PNEC_{sediment}$ (MPC_{sed})(mg/kg)**
Cadmium	0.34	1.46	0.009792	0.037	0.05
Chromium	8.5	3.24	14.773	14.6	29.37
Copper	1.1	1.64	0.04807	4.1	4.15
Lead	11	1.9	0.8734	10.7	11.57
Mercury (inorganic)	0.24	4.79	14.1818	0.021	14.20
Zinc	6.6	1.84	0.4567	20.7	21.16

5.5 PNEC for Sediment Effects

Burial

Threshold values for burial effects are derived mostly on assumptions. The few empirical studies that exist are based on escape potential probability (EPn), which is the probability for an organism to escape from burial effects at a certain depth. The results are given as EP_{10} values, including both exotic and native sediments. Figure 5-3 presents a SSD for burial by exotic sediment for 32 species. PNEC for burial is suggested to be equal to HC_5 (0.65 cm) (Smit et al., 2006b).

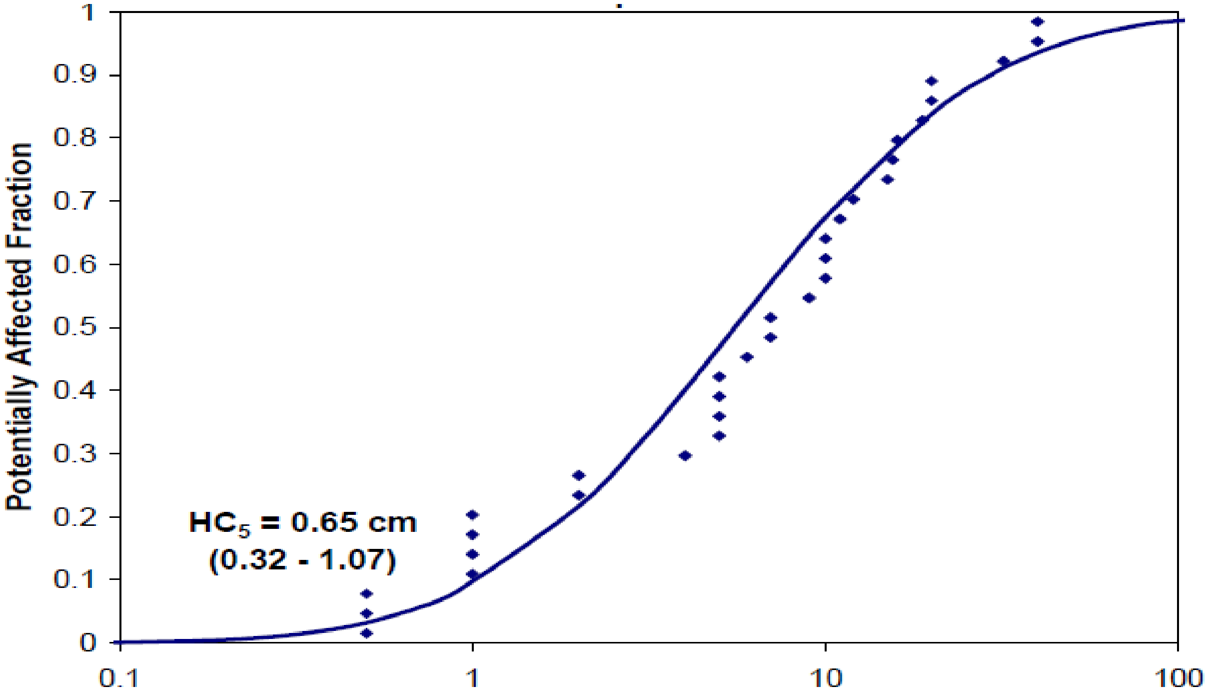


Figure 5-3: Species sensitivity to burial by exotic sediment for 32 species (Smit et al., 2006b).

Grain size change

The effects from grain size changes are derived based on the sensitivity of species towards changes in the median grain size. The medians are defined as the "grain size window of occurrence", where species are designated to grain sizes occurring in their natural environment.

Figure 5-4 presents species sensitivity to changes in grain size. 300 species from a total of 10 locations were used to derive the threshold value. Assessment factor was judged to not be of relevance for grain size change. PNEC for grain size change is therefore equal to the HC_5 value (52.7 micrometer) (Smit et al., 2006b).

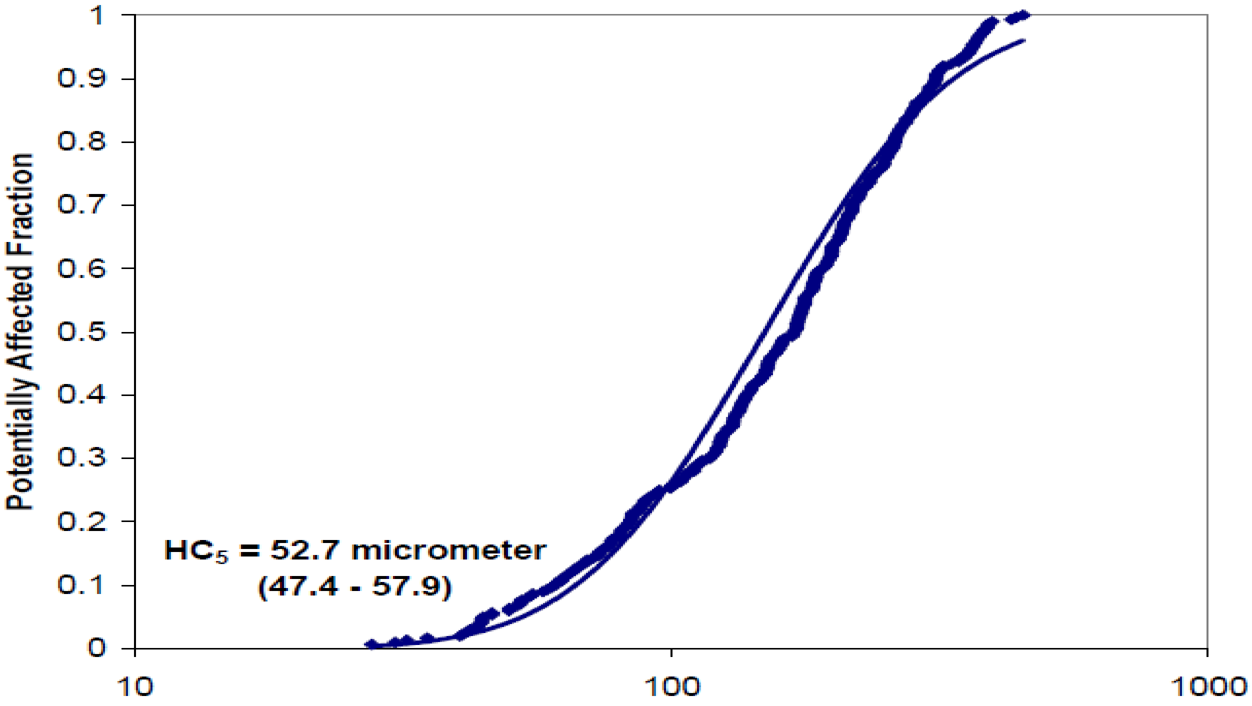


Figure 5-4: Species sensitivity to grain size change for exotic sediment for 32 species (Smit et al., 2006b).

Reduction of the Oxygenated Layer

The HC_5 value for oxygen depletion is based on a theoretical risk curve. It is assumed that the reduction of the oxygenated layer is linear with respect to the risk of oxygen depletion. Figure 5-5 presents the predicted community change as a function of oxygen depletion. The maximum allowable oxygen reduction used as PNEC is set to 20 % (HC_5), when the RDP is assumed to mimic the oxygen profile (Smit et al., 2006b).

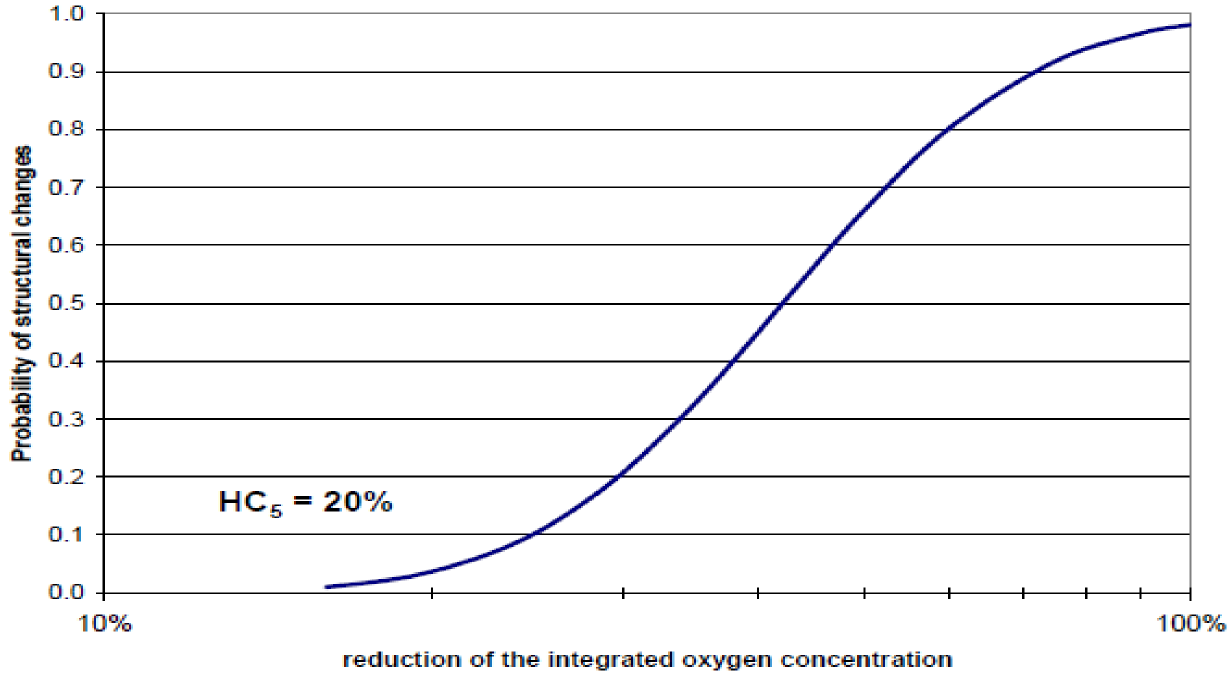


Figure 5-5: Species sensitivity distribution for oxygen change for exotic sediment and 32 species (Smit et al., 2006b).

6. Risk Assessment

6.1 EIF & Risk

The EIF for a substance or group of substance is related to the water volume where the PEC/PNEC ratio exceeds unity. "*An EIF of unity is defined as a water volume 100m x 100m x 10m (10^5 m^3) in which there is a risk of impact to the 5 % most sensitive species*". However, the method does not account for interactions among chemicals. The ratio can't be directly compared as it is only an indicator for different modes of action. PAF and concentrations are therefore calibrated such as the PNEC corresponds to a 5 % PAF level. Figure 6-1 shows an example of the relation between the PEC/PNEC ratio and the probability of damage (risk) (Rye et al., 2006b).

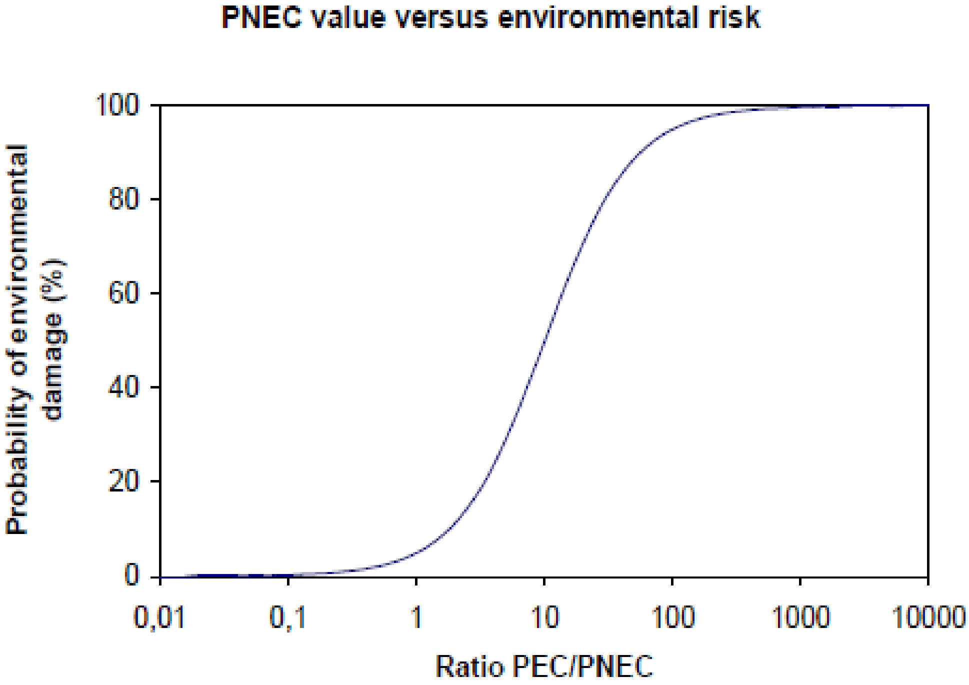


Figure 6-1: The relation between the PEC/PNEC ratio and the percentage risk for damage on biota. Note when PEC/PNEC = 1, the probability of damage is 5 % (Rye et al., 2006b).

The curve is determined from Eq. 6.1, based on the work of Karman and Reerink (1997) cited in Rye (2006a).

$$Risk = \int_{0}^{lnPEC/PNEC} \left\{ \frac{1}{S_m\sqrt{2\pi}} exp^{\frac{-(y-X_m)^2}{2S_m^2}} \right\} dy \qquad \text{(Eq. 6-1)}$$

Risk = probability that species will be affected

X_m = *mean of the logarithmically transformed data* ($X_m = 2.85$)

S_m = *standard deviation of the logarithmically transformed data* ($S_m = 1.74$)

y = variable that describes the normal probability density function from 0 to ln PEC/PNEC.

The risk is calculated as a sum of compounds in the recipient as independent probabilities (Rye et al., 2006b).

7. Methodology

7.1 Methods

The influence of model parameters was assessed through a DOE. A non-geometric Plackett-Burman (P-B) screening design was as all main effects are estimated with the same precision. One does not have to anticipate which factors will be important for the main result. P-B designs are suitable for studying up to k = (N-1) / (L-1) factors (k), where N is the number of trials and L is the number of levels. The method aims to identify the main contributors to the main result (Antony, 2003). For this study the main results consist of:

1. The EIF for the water column and sediment.
2. Restitution Time for the water column and sediment.

The advantage with screening designs is that it allows one to assess several factors with a limited number of trial runs. The disadvantage is that interactions between factors are not assessed (Antony, 2003). Table 7-1 presents the setup for the DOE.

Table 7-1: Presents the range and description for the factors used for the DOE.

Factor	Description	Type	Base	Min	Max
Particles	Number of particles the model uses to evaluate fate of all compounds.	Continuous	4000	2000	6000
Output Interval	How often the result is written (min). (Water Column)	Continuous	6	12	18
Time Step	Time step for the iteration procedure (min). (Water Column)	Continuous	5	2	8
Outlet Diameter	Outlet of the discharge pipe (m).	Continuous	0.75	0.5	1.0
Discharge Depth	The release depth of the effluent (m).	Continuous	25	0	50
Sediment Grain Size	The natural occurring grain size (mm).	Continuous	0.15	0.1	0.2
Sediment Porosity	The natural occurring porosity.	Continuous	0.6	0.4	0.8

PNEC Barite	The predicted no effect concentration of barite.	Continuous	200	100	300
Metal Fraction in Barite	Total metal fraction for all metals in barite.	Continuous	0	-50%	50%
Effluent Temperature	The effluent temperature before discharge.	Continuous	15	10	20
O_2 concentration at the seafloor	The natural occurring oxygen concentration.	Discrete	9	5	9
Ambient Data	Salinity and temperature gradient.	Discrete	Yes	No	Yes
Wind Profile	Wind file is used by the model.	Discrete	Gullfaks	Ekofisk	Gullfaks
Size Distribution Barite	The size distribution of barite in the effluent.	Discrete	Default	Reduced	Default
Size Distribution Cuttings	The size distribution of cuttings in the effluent.	Discrete	Default	Reduced	Default
Concentration Grid Dimension	The concentration grid dimensions used by the model.	Discrete	100x100x10	200x200x20	100x100x10
Habitat Grid Dimension	Size of the habitat.	Discrete	50x50	50x50	100x100

Continuous factors were scaled by dividing the standard deviation with the base case value as shown in Eq. 8.1.

$$Scaled\ Factor = \frac{FactorValue - BaseCaseValue}{BaseCaseValue} \qquad \text{(Eq. 8.1)}$$

Discrete factors are given the value 0 or 1, where the base case is 0 and the adjusted factors are set equal to 1. Five center-point simulations and one replicate for all simulations are included in the case matrix (Table C.1 in Appendix C). Centerpoints allows for a better measure of process stability and curvature check. Replicate simulations may provide information regarding simulation noises (differences between two identical simulations) (NIST/SEMATECH, 2003).

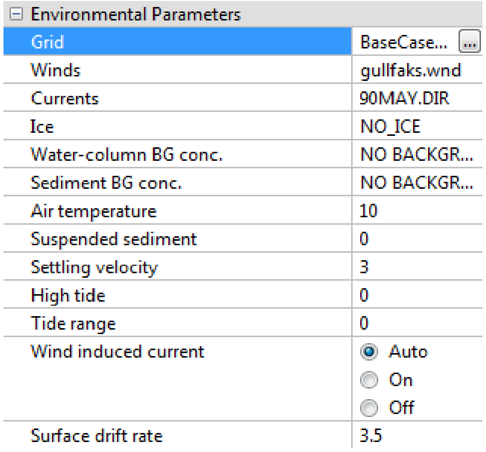
The complete scaled sensitivity matrix can be found in Appendix C, Table C-1. Model stability was evaluated through the statistical software JMP v.10.1, using a least square root multiple regression analysis. R^2 provides some information about the “goodness of fit” of a model. *“In* *regression, the* R^2 *coefficient of determination is a statistical measure of how well, the regression line approximates the real data points. An* R^2 *of 1.0 indicates that the regression line perfectly fits the data” (*Nagelkerke, 1991).

7.2 Model Setup

The choice of model input values for the base case have been to a large degree been based on the DREAM user manual. The chosen values used in the base case might not be representative for a real discharge scenario.

Environmental Parameters

Figure 7-1 presents the environmental parameters in DREAM. The simulation is performed for a 30 days period based on two different wind profiles and one current profile derived from May 1990. These are standard wind and current inputs in DREAM. The sediment simulation is for 10 years.



⊟ Environmental Parameters

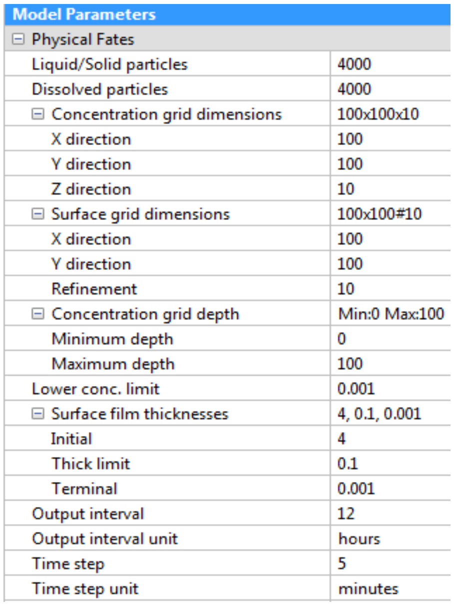
Grid	BaseCase...
Winds	gullfaks.wnd
Currents	90MAY.DIR
Ice	NO_ICE
Water-column BG conc.	NO BACKGR...
Sediment BG conc.	NO BACKGR...
Air temperature	10
Suspended sediment	0
Settling velocity	3
High tide	0
Tide range	0
Wind induced current	● Auto ○ On ○ Off
Surface drift rate	3.5

Figure 7-1: Environmental parameter values for the base case.

Model Parameters

Figure 7-2 presents the model parameters used for the base case. Surface grids and film thickness are assumed not applicable for this scenario, as this is most likely an option used for oil spills, or when evaporation from the sea surface is important.

- Liquid/solid and dissolved particles is number of particles the model uses to estimate the fate of the drilling discharge. More particles yield a higher resolution, but also increase the modeling time.
- The concentration grid dimension is the volume for each cell where the EIF is calculated.
- The concentration grid depth is simply how deep the model should calculate the EIF for.
- The lower concentration limit is the lowest concentration the model uses to calculate EIF for.
- Output interval is the time until the model writes the output results. To high output interval might lead to by-passing critical results.
- Time step is related to the how often the numerical iteration procedure occurs. A high time step might lead to by-passing critical results.



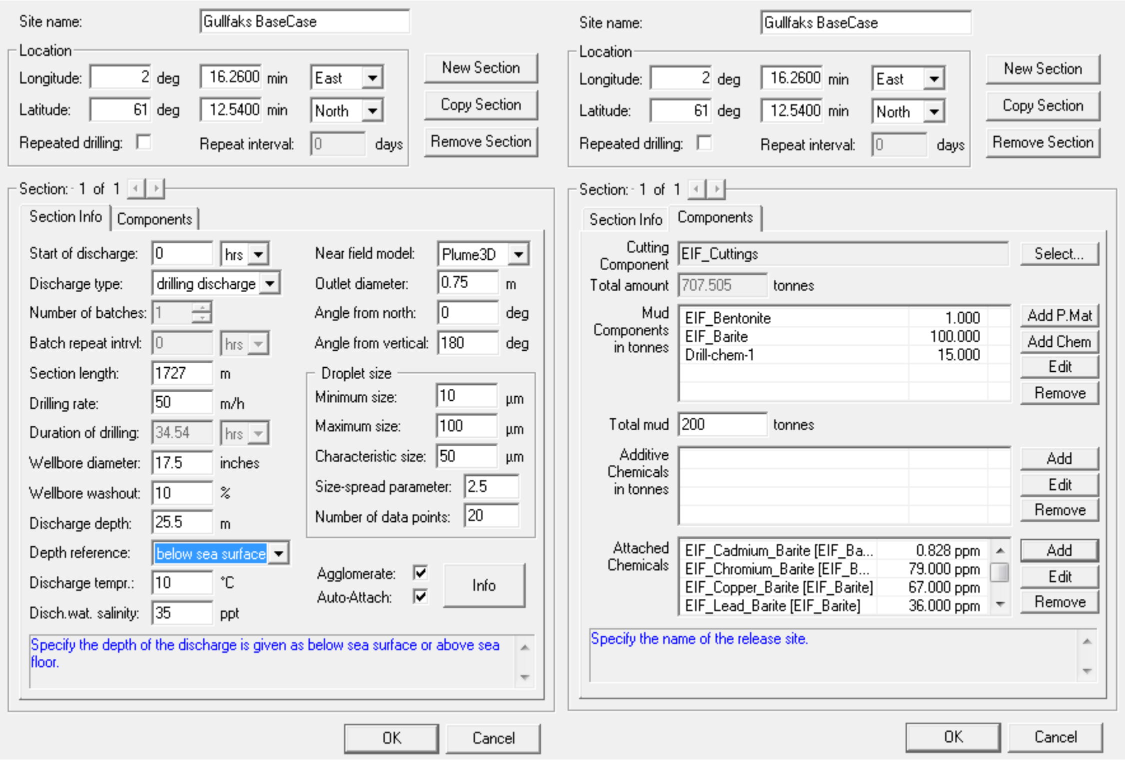
Model Parameters	
⊟ Physical Fates	
Liquid/Solid particles	4000
Dissolved particles	4000
⊟ Concentration grid dimensions	100x100x10
X direction	100
Y direction	100
Z direction	10
⊟ Surface grid dimensions	100x100#10
X direction	100
Y direction	100
Refinement	10
⊟ Concentration grid depth	Min:0 Max:100
Minimum depth	0
Maximum depth	100
Lower conc. limit	0.001
⊟ Surface film thicknesses	4, 0.1, 0.001
Initial	4
Thick limit	0.1
Terminal	0.001
Output interval	12
Output interval unit	hours
Time step	5
Time step unit	minutes

Figure 7-2: Model parameters used for the base case

Drilling Scenario

A generic well was introduced as to reflect a relatively simple drilling procedure. The TCC will only be used on well size 17.5” or smaller, as this is when OBM is normally used. The well section length is set to 1727 meters, with a rate of penetration (ROP) at 50 meters/hour. Washout factor is set to recommended value provided in DREAM (10 %). Discharge depth is set to 25 meters below sea surface facing downwards (180) with an effluent temperature of 15 ^{o}C. The rest is default values.

The components used as the effluent consist of cuttings, bentonite, barite, a drilling chemicals package and seawater. Heavy metals are assumed attached to barite only, as the contribution from bentonite is assumed far less due to the low volume compared to barite. The metal fractions are taken from Schaanning et al. (2008) (Table 3-7). The drilling chemical package is a mix of chemicals normally found in most common WBM used on the NCS today. This is a standard package found in the DREAM software.


Site name: Gullfaks BaseCase
Location
Longitude: 2 deg 16.2600 min East
Latitude: 61 deg 12.5400 min North
Repeated drilling: ☐ Repeat interval: 0 days
Section: 1 of 1
Section Info | Components
Start of discharge: 0 hrs
Discharge type: drilling discharge
Number of batches: 1
Batch repeat intrvl: 0 hrs
Section length: 1727 m
Drilling rate: 50 m/h
Duration of drilling: 34.54 hrs
Wellbore diameter: 17.5 inches
Wellbore washout: 10 %
Discharge depth: 25.5 m
Depth reference: below sea surface
Discharge tempr.: 10 °C
Disch.wat. salinity: 35 ppt
Near field model: Plume3D
Outlet diameter: 0.75 m
Angle from north: 0 deg
Angle from vertical: 180 deg
Droplet size
Minimum size: 10 µm
Maximum size: 100 µm
Characteristic size: 50 µm
Size-spread parameter: 2.5
Number of data points: 20
Agglomerate: ☑
Auto-Attach: ☑
Specify the depth of the discharge is given as below sea surface or above sea floor.

Site name: Gullfaks BaseCase
Location
Longitude: 2 deg 16.2600 min East
Latitude: 61 deg 12.5400 min North
Repeated drilling: ☐ Repeat interval: 0 days
Section: 1 of 1
Section Info | Components
Cutting Component: EIF_Cuttings
Total amount: 707.505 tonnes

Mud Components in tonnes

EIF_Bentonite	1.000
EIF_Barite	100.000
Drill-chem-1	15.000

Total mud: 200 tonnes
Additive Chemicals in tonnes

Attached Chemicals

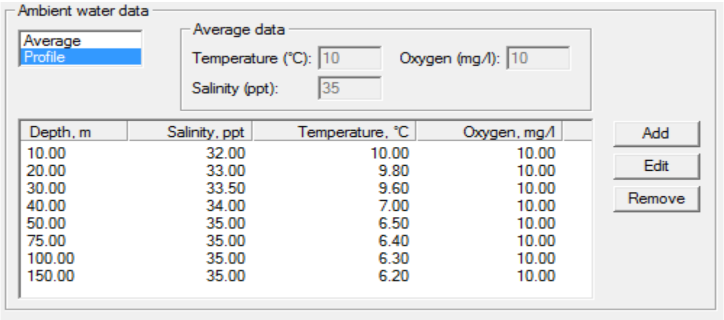
EIF_Cadmium_Barite [EIF_Ba...	0.828 ppm
EIF_Chromium_Barite [EIF_B...	79.000 ppm
EIF_Copper_Barite [EIF_Barite]	67.000 ppm
EIF_Lead_Barite [EIF_Barite]	36.000 ppm

Specify the name of the release site.

Figure 7-3: Drilling parameters and discharge characteristics for the base case in DREAM.

Stratification

Ambient water input was used as a discrete factor as to evaluate the effects from introducing a thermocline and pynocline (Fig. 7-4). The factor consists of two levels, either as average or user specified (profile). When the data is turned on average, the model assumes a constant stratification of both salinity (35 ppt) and temperature (10 ^{0}C). The ambient data utilized was found in OSPAR (2000).



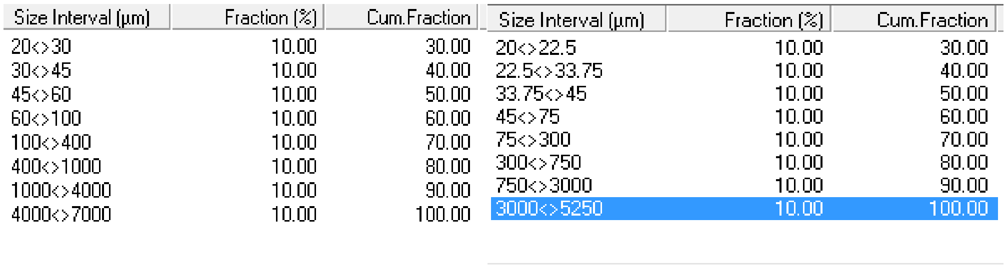
Temperature (°C): 10
Oxygen (mg/l): 10
Salinity (ppt): 35

Depth, m	Salinity, ppt	Temperature, °C	Oxygen, mg/l
10.00	32.00	10.00	10.00
20.00	33.00	9.80	10.00
30.00	33.50	9.60	10.00
40.00	34.00	7.00	10.00
50.00	35.00	6.50	10.00
75.00	35.00	6.40	10.00
100.00	35.00	6.30	10.00
150.00	35.00	6.20	10.00

Figure 7-4: Overview over the salinity and temperature profiles used for the simulations.

Particle Distribution

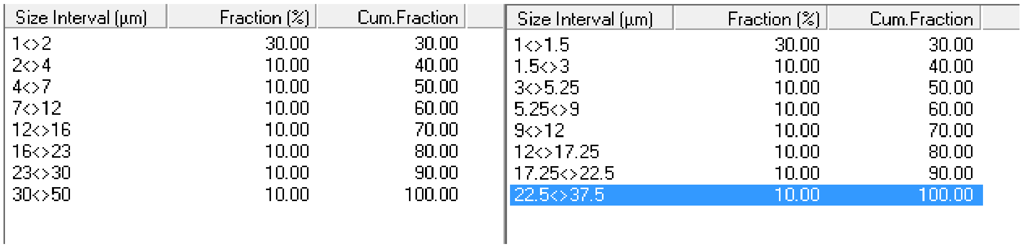
The main particle fractions are from cuttings and barite. The two factors will be modeled as discrete factors with 2 levels, one for the default DREAM value and one with a reduced size interval (Fig. 7-5 and 7-6).



Size Interval (µm)	Fraction (%)	Cum.Fraction
20<>30	10.00	30.00
30<>45	10.00	40.00
45<>60	10.00	50.00
60<>100	10.00	60.00
100<>400	10.00	70.00
400<>1000	10.00	80.00
1000<>4000	10.00	90.00
4000<>7000	10.00	100.00

Size Interval (µm)	Fraction (%)	Cum.Fraction
20<>22.5	10.00	30.00
22.5<>33.75	10.00	40.00
33.75<>45	10.00	50.00
45<>75	10.00	60.00
75<>300	10.00	70.00
300<>750	10.00	80.00
750<>3000	10.00	90.00
3000<>5250	10.00	100.00

Figure 7-5: Size distribution for cuttings with default values (left) and reduced size interval (right) used in the simulations.



Size Interval (µm)	Fraction (%)	Cum.Fraction
1<>2	30.00	30.00
2<>4	10.00	40.00
4<>7	10.00	50.00
7<>12	10.00	60.00
12<>16	10.00	70.00
16<>23	10.00	80.00
23<>30	10.00	90.00
30<>50	10.00	100.00

Size Interval (µm)	Fraction (%)	Cum.Fraction
1<>1.5	30.00	30.00
1.5<>3	10.00	40.00
3<>5.25	10.00	50.00
5.25<>9	10.00	60.00
9<>12	10.00	70.00
12<>17.25	10.00	80.00
17.25<>22.5	10.00	90.00
22.5<>37.5	10.00	100.00

Figure 7-6: Size distribution for barite with default values (left) and reduced size interval (right) used in the simulations.

8. Results & Discussion

8.1 Base Case Scenario

The base case simulation was performed with the set-up described in Section 7.2. All risk and EIF results are based on instantaneous values from the time where the risk is at its maximum. The restitution time is the time taken until the risk is below 5 % (Reed et al. 2011). Figure 8-1 and 8-3 presents the graphical output from the water column and sediment simulation, respectively. Figure 8-2 and 8-4 show the numerical risk values based on the distance from the release source.

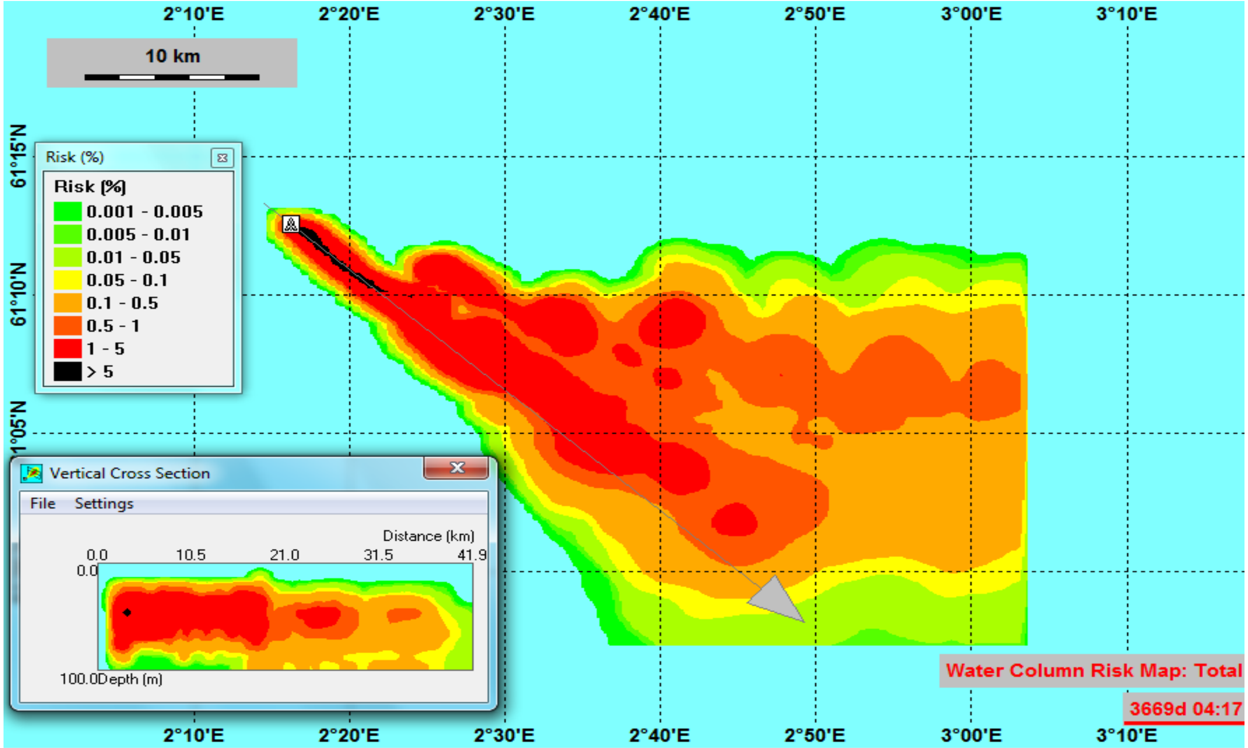


Figure 8-1: Vertical and horizontal risk assessment of the base case for the water column. Note, only the black portion is related to PEC/PNEC ratio exceeding 1.

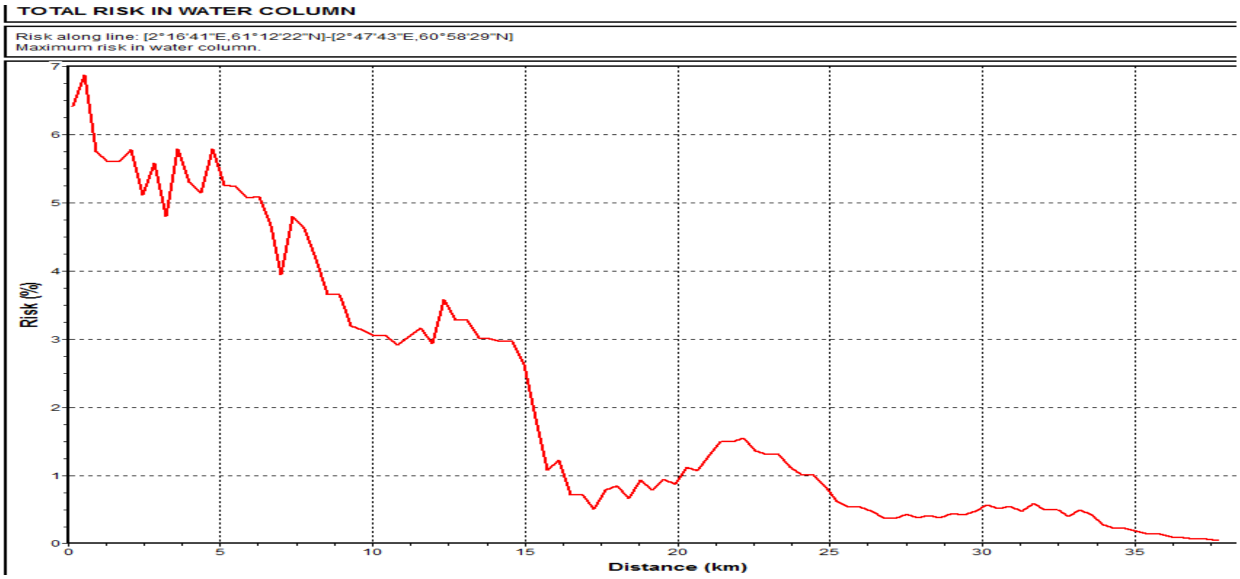


Figure 8-2: Graph showing the maximum risk in the water column based on horizontal distance.

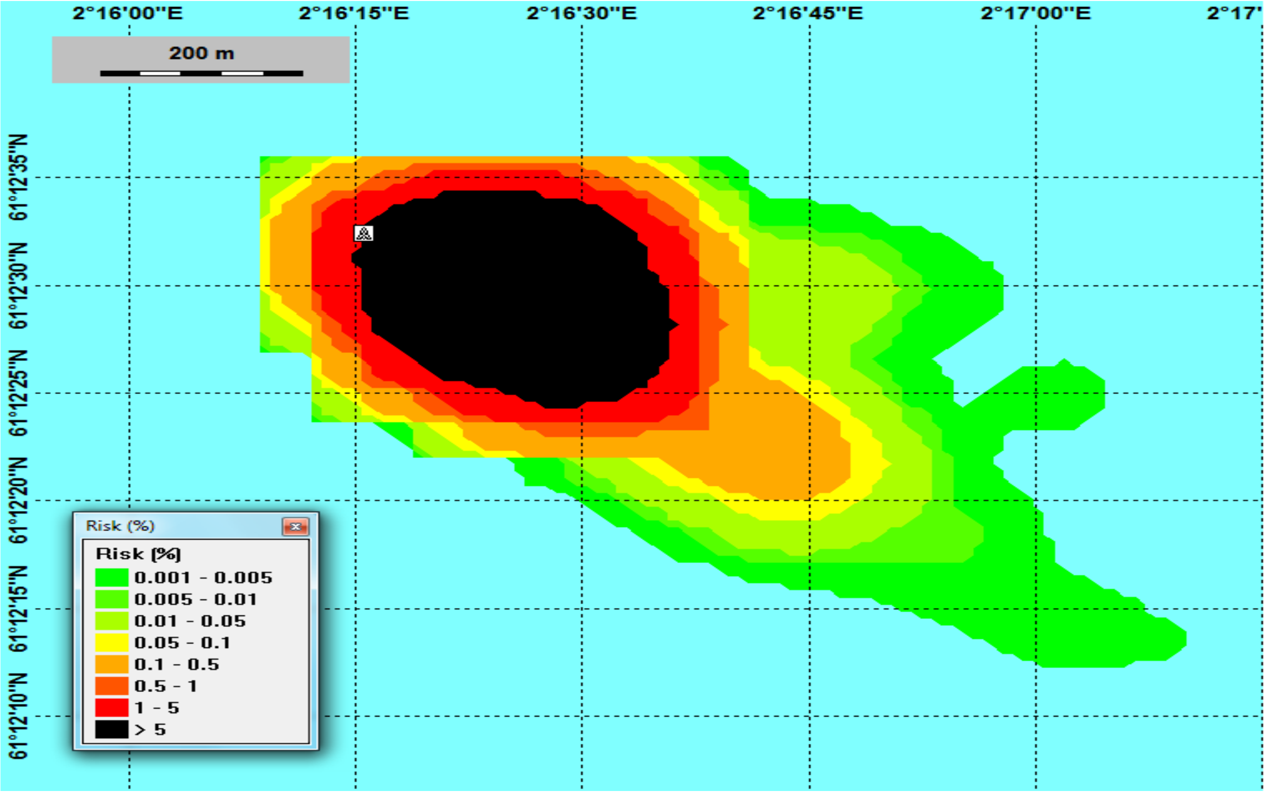


Figure 8-3: Horizontal risk assessment of the base case for the sediment. Note, only the black portion is related to PEC/PNEC ratio exceeding 1.

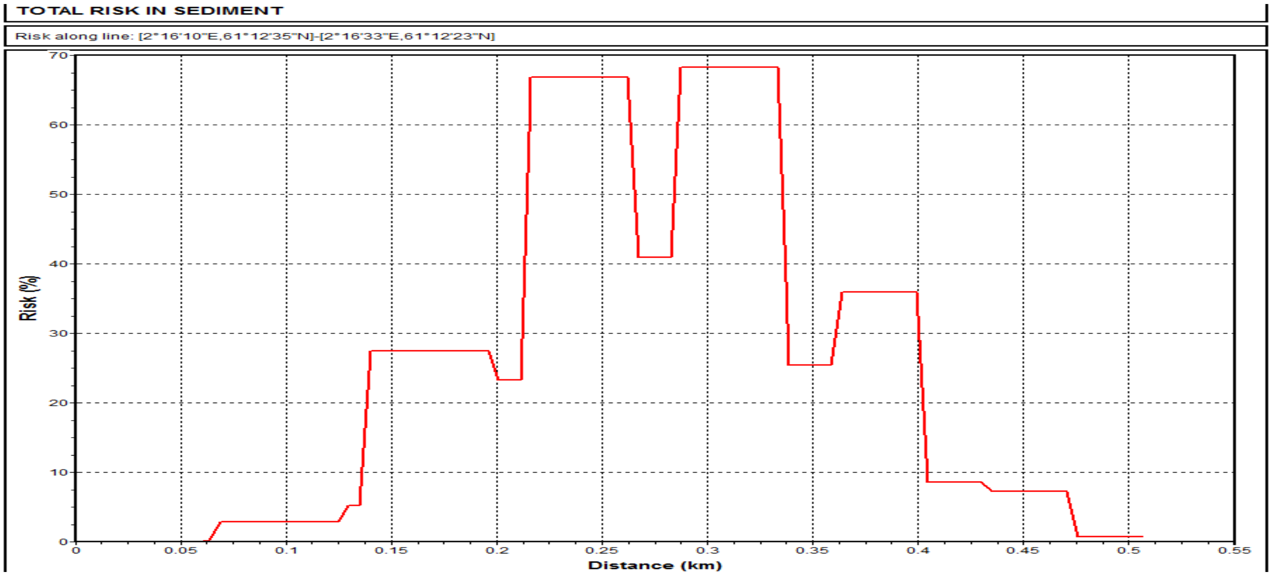


Figure 8-4: Graph showing the actual sediment risk based on horizontal distance.

The EIF, restitution time and the contributing factors to the EIF are presented in Tables 8-1 and 8-2.

Table 8-1: Presents the results from the base case water column simulation.

Factor	Value
EIFWaterColum	552
Restitution Time in the Water Column (d)	2,5
Metal Contribution to EIF in the Water Column (%)	0
Barite Contribution to EIF in the Water Column (%)	94
Drill Chemical Contribution to EIF in the Water Column (%)	3
Cuttings Contribution to EIF in the Water Column (%)	0
Bentonite Contribution to EIF in the Water Column (%)	2

Table 8-2: Presents the average results from three base case sediment simulation

Factor	***Value***
EIFSediment	3,75
Restitution Time in the Sediment (d)	1689
Metal Contribution to EIF in the Sediment (%)	0
Contribution of Oxygen Depletion to the Sediment EIF (%)	0
Contribution of Drill Chemicals to Sediment EIF (%)	0
Contribution of Thickness to Sediment EIF (%)	2,58
Contribution of Change in Grain Size to Sediment EIF (%)	97,42

8.2 Sensitivity Analysis

The sensitivity analysis consisted of 50 simulations excluding the base case. The matrix test regime can be found in Table C-1 in Appendix C. The EIF results from each simulation were scaled against the EIF from the base-case (Eq.8.2) to reflect the magnitude of variation. The results are presented in Figure 8-5. The numerical results are located in Table C-2 in Appendix C.

$$EIF(Scaled) = \frac{EIF(Simulation) - EIF(Base\ Case)}{EIF(Base\ Case)} \qquad \text{(Eq.8.2)}$$

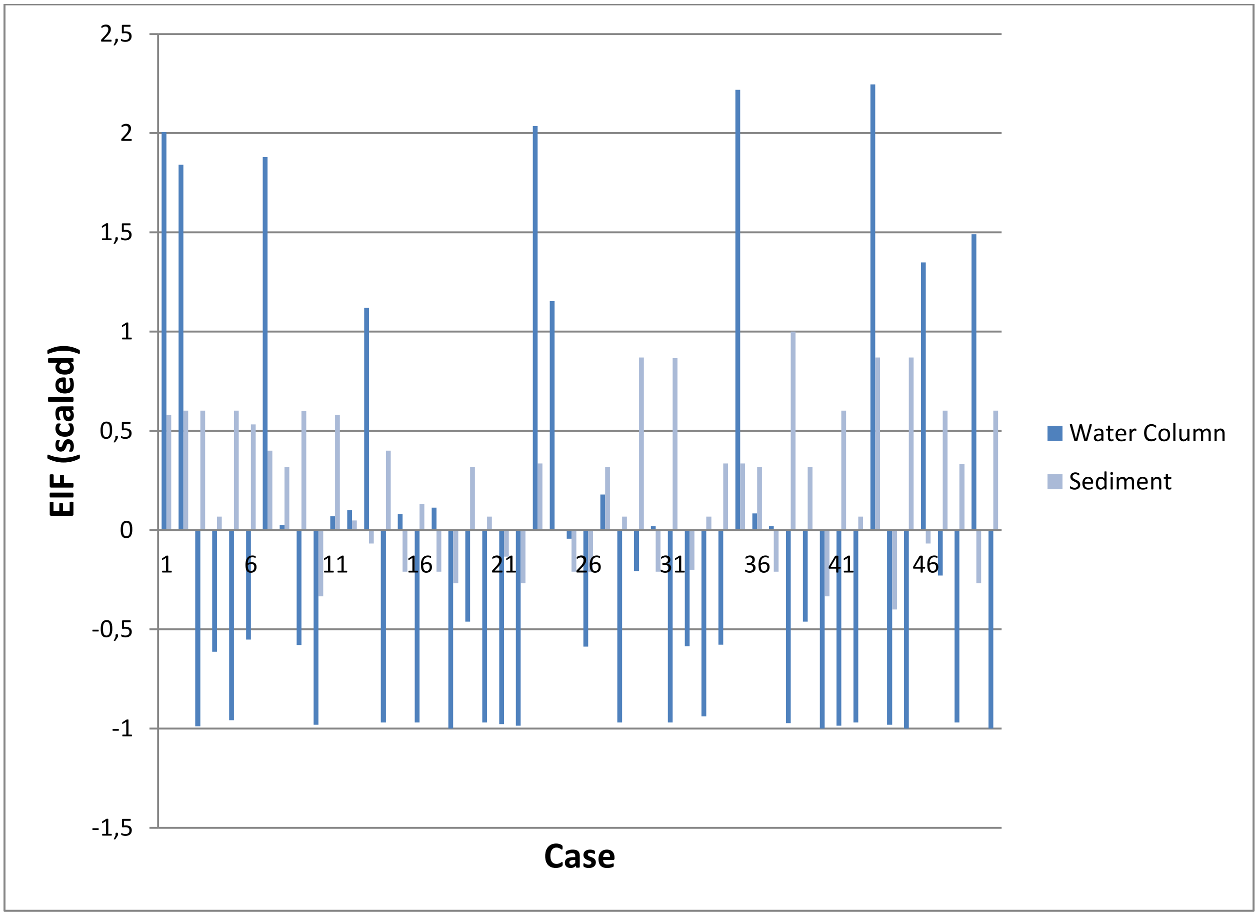


Figure 8-5: Overview over the water column and sediment EIF results from 50 simulations. All values have been scaled against the base-case EIF value.

As can be observed from Fig. 8-5 the variations are relatively large. A few simulations produced over twice the scaled EIF from the base case for the water column. The sediment EIF shows a good variation as well, where several results range from 0.5-1 times larger than the base case. This reflects that some of the chosen factors contribute substantially and others much less.

8.2.1 Water Column

Figure 8-6 presents the contributing components for each simulation to the EIF for the water column. The numerical results are located in Table C-4 in Appendix C. Notice that some simulations does not stop at 100 %. It is unclear as to why this has happened. It may be due to simulation “noise”.

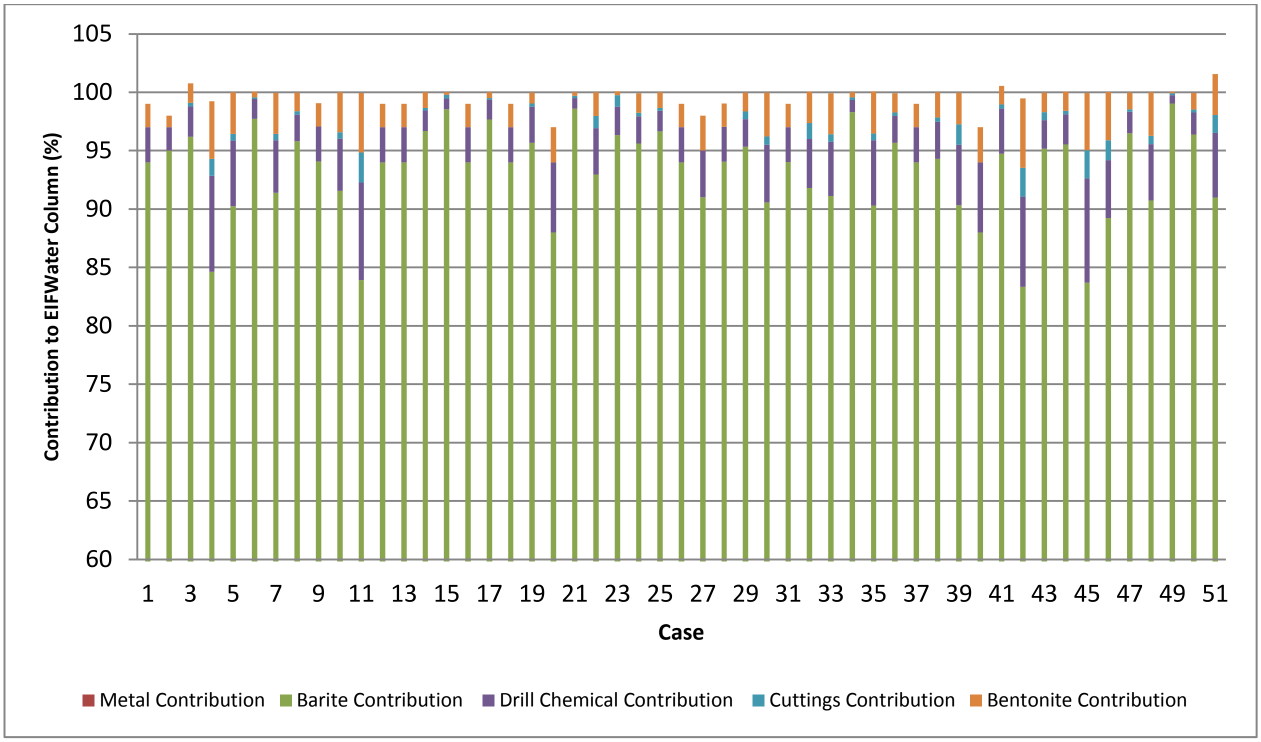


Figure 8-6: Contribution from each component present in the modeled discharge.

Barite is by far the major EIF contributing component in the water column. Barite is however present on the PLONOR list, and is deemed safe to discharge into the marine environment by OSPAR. This study might argue that (1) barite shouldn’t be on the PLONOR list, (2) the results are biased due to non-representative input values, or (3) the PNEC for barite is underestimated. It is in the authors opinion that it a mix of the two foremost points, especially the last. The volume of “drill chemical” and bentonite used in the simulations might be rather low compared to barite.

Barite would therefore naturally be the dominating component. However, the EIF values range between 0 to 1700 (see Table C-4 in Appendix C), where the major cause is still barite. Barite threshold values are derived through a SSD approach based on relatively few experimental results. Hence, the results are extrapolated by a factor of 100 to obtain the appropriate PNEC value. The large extrapolation technique might have caused the threshold value to be underestimated.

The cuttings fraction shows a very limited influence on the EIF. No correlation between change in EIF and size reduction could be found. This indicates that threshold values for substances with size distributions are constant for all sizes. It can be discussed whether this is representative for the TCC technology, where the cuttings are pulverized to smaller particles, possibly with sharp edges. A possibility would be to derive PNEC values based on size interval.

In these simulation heavy metals are attached to barite only. The short exposure time of barite to the water column should substantially limit dissolution of heavy metals. The results in Fig. 8-6 confirm this. The EIF for the water column is not influenced by heavy metals at all.

Figure 8-7 presents a half normal plot showing the main contributing factors to the EIF for the water column.

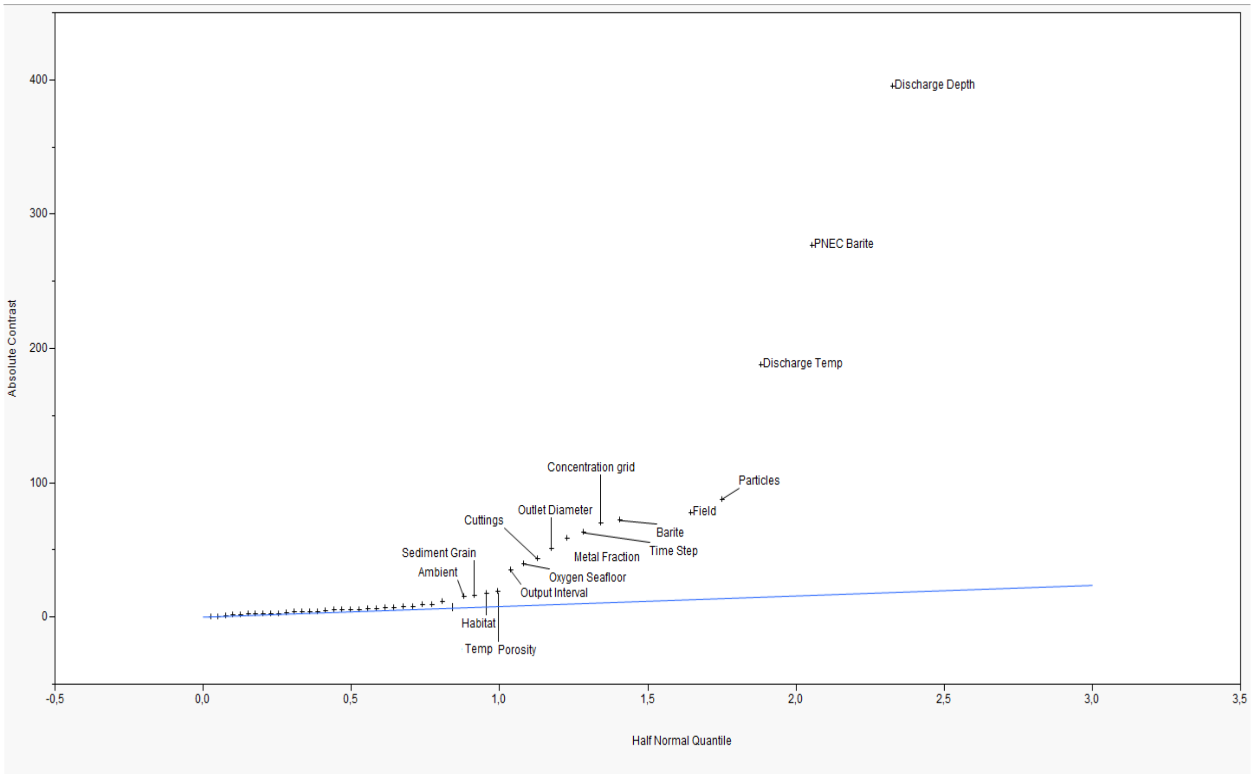


Figure 8-7: Half normal plot identifying the main contributing factors for the EIF in the water column.

Not surprisingly the discharge depth influences the most. Increasing the discharge depth will naturally yield a much lower contaminated sea volume before the waste reaches the seafloor. The second highest factor is the PNEC value for Barite. As already discussed, barite is the major contributing component in the water column. Altering the PNEC value would therefore influence the EIF result in similar manner. The discharge temperature also shows a significant contribution. It is however unclear why this factor influences the EIF in this magnitude.

Model parameters as number of particles, concentration grid and time step influence the results in the same degree as the wind profile and the size distribution of barite. It might be of future value to standardize these parameters as to avoid the same influence as environmental factors, which should form the basis for the assessment.

The main contributing factors for the restitution time are presented in Figure 8-8. Note that the contrast (Y-axis) is low compared to the previous EIF plot. This is because the restitution time in the water column is very low (2.5-3.5 s) compared to the EIF (0-1700).

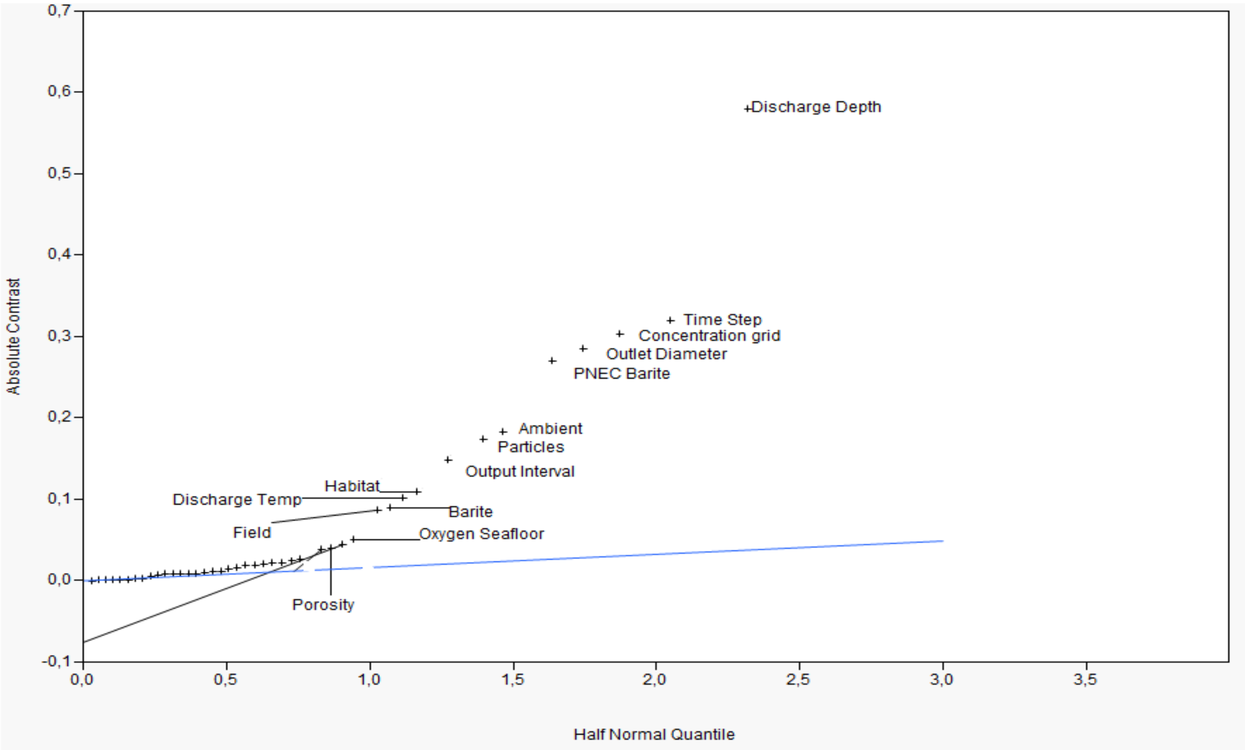


Figure 8-8: Half normal plot identifying the main contributing factors for the restitution time in the water column.

The discharge depth is the major controlling factor. Waste released closer to the sediment will naturally cause the deposition to take less time due to less vertical distance. The next bulk of factors include model specific parameters (time step and concentration grid), the discharge outlet diameter and PNEC for barite. Based on the already discussed influence of PNEC for barite, it is reasonable to assume that it is of similar importance to use correct input values for the other factors when regarding the water column restitution time. A too high time step might lead to missing results as the iteration procedure “jumps” over critical simulation areas.

The size distribution of cuttings and barite did not have a significant impact on the result. Reducing the distribution should cause the particles to remain suspended longer, and consequently increase the restitution time. This would change the particle fate all together. The reason for this might be that the size distribution factors were used as discrete factors, whereas they should have been continuous. Discrete factors are only a set of options (in this case 0 & 1). Continuous factors follow a linear relationship, which is more appropriate.

8.2.2 Sediment

The contribution to the risk in the sediment is presented in Figure 8-9. The numerical values are located in Table C-3 in Appendix C.

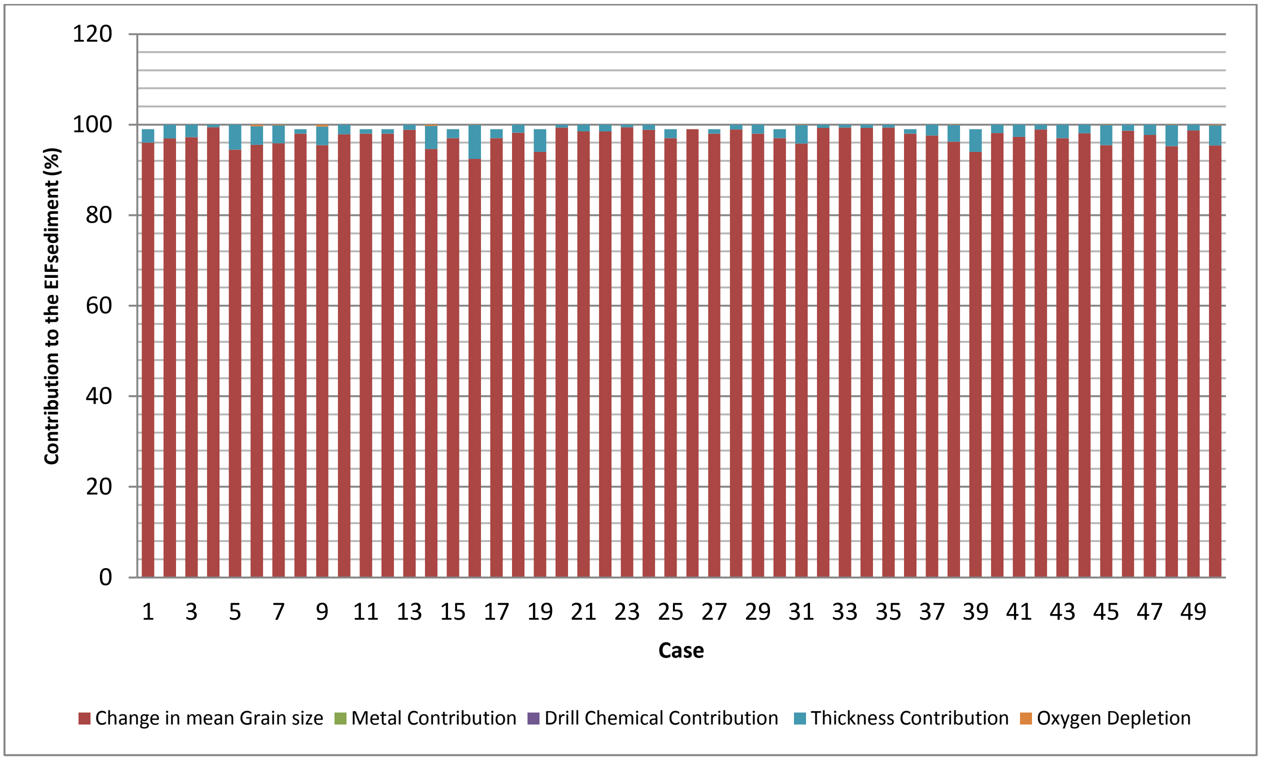


Figure 8-9: Contribution to the risk in the sediment from each component present in the discharge effluent.

The major effect is from the change in the sediment mean grain size due to the deposition of particles from the discharge. There is almost no contribution from oxygen depletion, toxicity from chemicals or heavy metals. This might indicate that the input data for chemicals might be too low compared to the large volume of cuttings and barite used for the simulation.

The amount of barite used in the simulations rise some concern as to why the representations from heavy metals are so low. The amount of heavy metals attached to barite used in this study was taken from Schaanning et al. (2011). This provides some justification for the validness of the values used. The method for determining the partitioning coefficients are however debated. DREAM originally used the K_d coefficient derived based on equilibrium between seawater and barite only, as outlined in Neff (2007). It is unclear which coefficients are used today for the sediment, as these values can’t be altered or seen by the user of DREAM. The aforementioned method intuitively seems unrepresentative when neglecting the interaction between barite-sediment and barite-porewater. The experimental setup of Schaanning et al. (2011) through a mescosome seems more appropriate for assessing these interactions.

The burial threshold value was mostly determined based on organisms escape potentials. The studies by Schaanning et al. (2008) and Trannum et al. (2009) indicated that burial from uncontaminated cuttings did not have any relevant impact other than increased bioturbation after the initial deposition phase. This suggests that burial by itself have no, or limited impact on the benthic community. However, in both reports bioturbation created a rapid mixing of the natural sediment and the freshly added layers, causing an influx of oxygen and organic matter. This sudden spike led to an eutrophication phase, resulting in anoxic conditions in the sediment. A suggestion would be to include an increased influx of oxygen and chemicals at the start of the deposition, where the flux is reduced as a function of the deposition thickness until the activity stops influencing the top layer.

As previously mentioned, the drill chemical volumes used for the simulations are probably low compared to the other components. This is also confirmed for the sediment, where the toxicity is very low. Hence, there should also be a low amount of biological activity and oxygen consumption. As can be seen from Figure 8-9 oxygen depletion is hardly noticeable.

Figures 8-10 & 8-11 presents half normal plots showing the main contributing factors to the EIF and restitution time for the sediment, respectively. The results are similar; hence they will be discussed together.

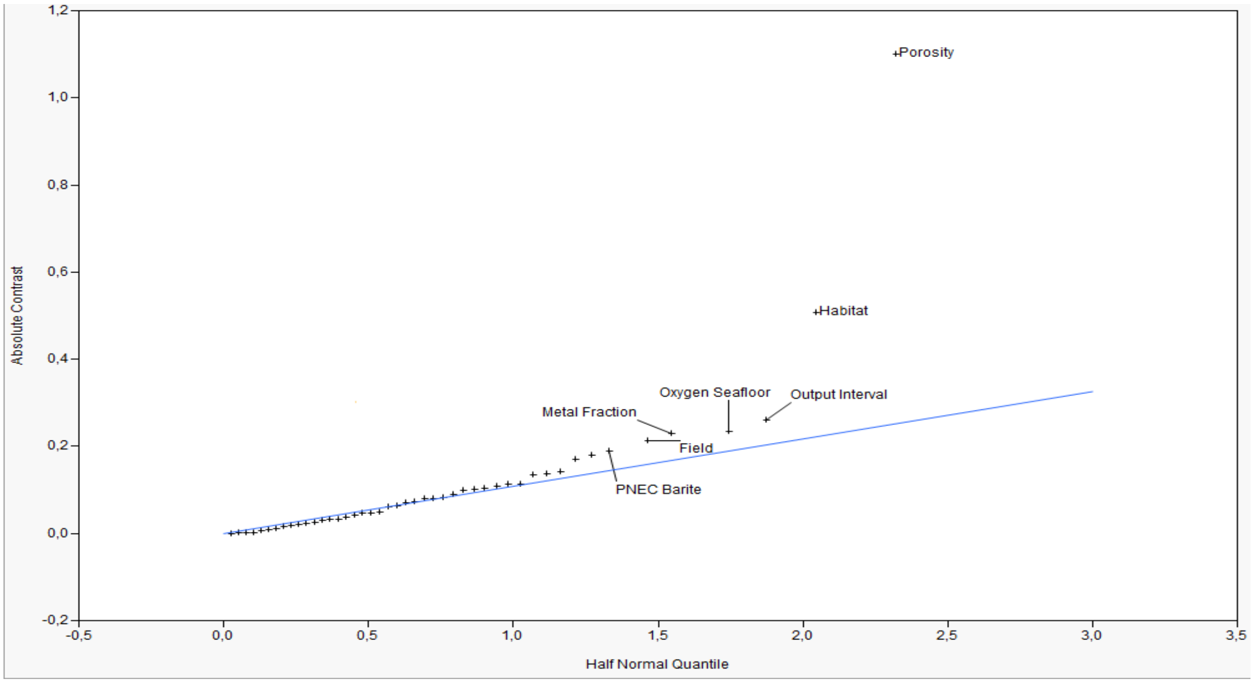


Figure 8-10: Half normal plot identifying the main contributing factors for the sediment EIF.

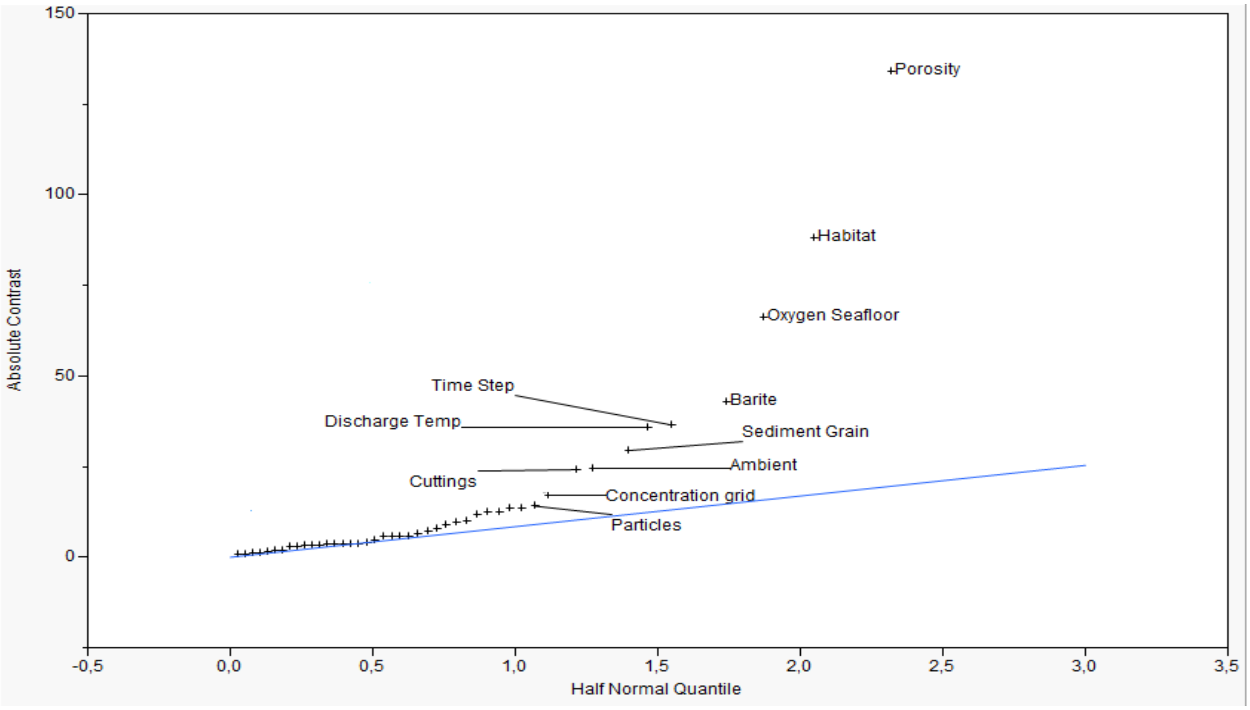


Figure 8-11: Half normal plot identifying the main contributing factors for the sediment restitution time.

The sediment porosity has the largest influence on both results. The required reporting scheme for DREAM modeling (Appendix B) does not include this factor. The constant porosity assumption was also argued by Meysman et al. (2007) to not affect the sediment mixing coefficient. However, it might influence diffusive processes. A reasonable assumption is that porosity may change extensively based on geographical location. Hence, porosity should be included in the reporting regime.

The habitat factor shows a significant contribution to the EIF. This parameter was not clearly defined numerically in the DREAM manual. The oxygen concentration above the seafloor is more significant in the restitution model. Most likely this is related to the diffusion mechanism where more oxygen reduces the time until the sediment is regarded healthy again.

8.2.3 Model Stability

Based on the results from Table 8-3, the DREAM model shows a high goodness of fit. Only the sediment EIF shows some discrepancy from the other results. The sediment is modeled over a ten year period. Consequently the time step for the iteration procedure is quite large when compared to the water column. Most likely, some results might have been bypassed before it was written out.

Table 8-3: The goodness of fit (Rsquare) for the model based on the EIF and restitution time results.

Phase	**Water Colum**		**Sediment**	
Parameter	**EIF**	**Restitution Time**	**EIF**	**Restitution Time**
R^2	0.96	0.97	0.84	0.94

9. Conclusions & Recommendations

9.1 Conclusions

Particle settling velocity is to a large degree determined by its density. The particle size distribution of cuttings and barite used in the revised DREAM model is solely based on a single study. This can potentially result in a non-representative fate prediction. In addition, the DOE indicates that the particle distributions do not have an associated PNEC value for each size interval. If discharged particles are small and angular, they might more easily accumulate in biota and cause damage through obstruction.

The DOE revealed that the threshold value (PNEC) for barite was the second most significant factor for the water column EIF. The PNEC for barite have been derived based on few experimental results. This has led to the use of extrapolation techniques to cover for uncertainties. The currently used value is most likely too low.

The burial of benthic organisms is represented by the thickness of the deposited drill cutting layer. The threshold value is based on an organism's ability to escape the affected area. Newer studies suggest that particle deposition also induces bioturbation activity, where the effect from this can potentially create a larger impact through increased influx of oxygen and substrate in the sediment.

The sensitivity result shows that the DREAM model's "Goodness of fit" is high. The Water column EIF and restitution time results have a R^2 of 0.96 and 0.97, respectively. The sediment EIF and restitution results have a R^2 of 0.84 and 0.94, respectively. The lower fit for the sediment EIF is most likely due to that some results are lost in the iteration procedure.

9.2 Recommendations

- For modeling the TCC effluent it is imperative to obtain a correct particle size distribution of the effluent. Each size interval should also be associated with a PNEC. It is also recommended to implement additional distributions in DREAM for traditional operations based on the formation that are being drilled.

- Improve the burial effect by including an influx of oxygen and chemicals, based on the bioturbation response from the deposition phase. More research should also be performed to confirm the thickness where the activity seems to stop influencing the flux of oxygen and substrate.
- A suggestion for future assessment of the DREAM model would be to perform a full factorial sensitivity analysis, designed to check for inter-variation between factors and substances. This would provide information regarding how different factors influence each other.

References

THE ACTIVITIES REGULATIONS [Online]. 2010. Norway. Available: http://www.ptil.no/activities/category399.html [Accessed 28.02 2012].

ANTONY, J. 2003. *Design of Experiments for Engineers and Scientists*, Elsevier Science & Technology Books.

ASME 2004. *Drilling fluids processing handbook,* Amsterdam, Elsevier.

BEYER, J. 2011. Lecture in Aquatic Ecotoxicology. *Toxicity testing of cheimcals and risk assessment.* University of Stavanger.

BJØRGESÆTER, A. 2006. Field Based Predicted No Effect Concentrations (F-PNECs) for macro benthos on the Norwegian Continental Shelf. *ERMS.*

CRECELIUS, E., TREFRY, J., MCKINLEY, J., LASORSA, B. & TROCINE, R. 2007. Study of Barite Solubility and the Release of Trace Components to the Marine Environment. Battelle Northwest Division.

EC 2003. Technical Guidance Document on risk assessment in support of

Commission Directive 93/67/EEC on risk assessment for new notified substances

and Commission Regulation (EC) No 1488/94 on risk assessment for existing

substances and Directive 98/8/EC of the European parliament and of the council

concerning the placing of biocidal products on the market. *In:* PROTECTION, I. F. H. A. C. (ed.).

FROST, T. K. 06.03 2012. *RE: Input data for drilling* Type to BREIVIK, S.

FROST, T. K., NILSSEN, I., NEFF, J., ALTIN, D. & LUNDE, K. R. 2006. Toxicity of Drilling Discharge. *ERMS.*

GREENWOOD, N., PARKER, E. R., FERNAND, L., SIVYER, D. B., WESTON, K., PAINTING, S. J., KRÖGER, S., FORSTER, R. M., LEES, H. E., MILLS, D. K. & LAANE, W. P. M. 2010. Detection of low bottom water oxygen concentrations in the North Sea; implications for monitoring and assessment of ecosystem health. European Geosciences Union.

KLIF. 2010. *Status og oppfølging av lekkasjer fra kaksinjeksjonsbrønner* [Online]. Available: http://www.klif.no/nyheter/dokumenter/kaksinjeksjon_rapport210510.pdf [Accessed 28.02 2012].

KLIF. 2011. *Borevæsker* [Online]. Available: http://www.miljostatus.no/Tema/Hav-og-vann/Pavirkninger-pa-livet-i-vann/Olje-og-gass/Utslipp-til-luft-og-sjo/Utslipp-til-sjo/Borevasker/ [Accessed 28.02 2012].

MEYSMAN, F. J. R., MALYUGA, V. S., BOUDREAU, B. P. & MIDDELBURG, J. J. 2007. The influense of porosity gradients on mixing coefficients in sediments. *Geochimica et Cosmochimica Acta*, 71**,** 961-973.

NAGELKERKE, N.J.D. 1991. A note on a general definition of the coefficient of determination. *Biometrica*, 78, 691-692.

NEFF, J. 2007. Estimation of the Bioavailability of Metals from Drilling Mud Barite. *Integrated Environmental Assessment and Management.*

NEFF, J. 2010. Fate and effects of water based drilling muds and cuttings in cold water environments. Duxbury, MA 02332, USA: Neff & Associates LLC.

NIST/SEMATECH 2003. e-Handbook of Statistical Methods [Online]. Available: http://www.itl.nist.gov/div898/handbook/ [Accessed 15.03 2012].

OLJEDIREKTORATET 2011. Miljøteknologi [Online]. Available: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Rapporter/Mi%C3%B8j%C3%B8teknologi/Nordsj%C3%B8-Milj%C3%B8teknologirapport%202011.pdf [Accessed 25.03 2012].

ORSZULIK, S. T. 2008. *Environmental technology in the oil industry,* Hampshire, UK, Springer.

OSPAR. *About OSPAR* [Online]. Available: http://www.ospar.org/content/content.asp?menu=00010100000000_000000_000000 [Accessed 13.03 2012].

REED, M., HØVERSTAD, B., RYE, H., DURGUT, I., JOHANSEN, Ø., BRÖNNER, U., HETLAND, B., DITLEVSEN, M. K., ARSLANOĞLU, Y., RØNNINGEN, P. & DAAE, R. L. 2011. MEMW Users Manual version 6.1. *In:* SINTEF (ed.).

RYE, H. 2005. The influence of flocculation processes on the deposition of drill cuttings and mud on the sea floor. *8th International Marine Environmental Modeling Seminar.* Helsinki.

RYE, H., REED, M., DURGUT, I. & DITLEVSEN, M. K. 2006a. Documentation report for the revised DREAM model. *ERMS.* SINTEF.

RYE, H., REED, M., T.K., F., SMIT, M. G. D., DURGUT, I., JOHANSEN, Ø. & DITLEVSEN, M. K. 2008. Development of a Numerical Model for Calculating Exposureto Toxic and Nontoxic Stressors in the Water Column and Sediment from Drilling Discharges. *Integrated Environmental Assessment and Management,* 4**,** 194-203.

RYE, H., REED, M., T.K., F. & T.R., U. 2006b. Comparison of the ParTrack mud/cuttings release model with field data based on use of synthetic-based drilling fluids. *Environmental Modelling & Software,* 21**,** 190-203.

SCHAANNING, M. T. 2012. *RE: Borekaks.* Type to BREIVIK, S.

SCHAANNING, M. T., TRANNUM, C., PINTURUER, L. & RYE, H. 2011. Metal Partitioning in Ilmenite- and Barite-Based Drill Cuttings on Seabed Sections in a Mesocosm Laboratory. *SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production.* Rio De Janeiro, Brazil.

SCHAANNING, M. T., TRANNUM, C., ØXNEVAD, S., CARROLL, J. & BAKKE, T. 2008. Effects of drill cuttings on biogeochemical fluxes and macrobenthos of marine sediments.

SHEN, L. & CHEN, Z. 2007. Critical review of the impact of tortuosity on diffusion. *Chemical Engineering Science,* 62**,** 3748-3755.

SINGSAAS, I., GARPESTAD, I. E., SKARE, I., BAKKE, K., FALCAO, L., VEIGA, BUFFAGNI, M., FOLLUM, O. A., JOHNSEN, S. & MOLTU, U. E. 2007. Environmental Risk Management System (ERMS) – development of a risk-based environmental management tool for drilling discharges. A Summary paper.

SMIT, M. G. D., HOLTHAUS, K. I. E., KAAG, N. B. H. M. & JAK, R. G. 2006a. The derivation of a PNECwater for weighting agents in drilling mud. *ERMS.*

SMIT, M. G. D., JAK, R. G., RYE, H. & FROST, T. K. 2006b. Framework for the Environmental Impact Factor for drilling discharges.

STRAALEN, N. M. 2002. Threshold models for species sensitivity distribution applied to aquatic risk assessment for zinc. *Environmental Toxicology and Pharmacology.* Amsterdam: Elsevier.

SVENSEN, T. & TAUGBOL, K. 2011. Drilling Waste Handling in Challenging Offshore Operations. *Arctic and Extreme Environments Conference and Exhibition.* Moscow, Russia: SPE.

TRANNUM, C., NILSSON, H. C., SCHAANNING, M. T. & ØXNEVAD, S. 2009. Effects of sedimentation from water-based drill cuttings and natural sediment on benthic macrofaunal community structure and ecosystem processes.

TWMA. 2010. *TCC Rotomill* [Online]. Available: http://www.twma.co.uk/images/downloads/TCC_Rotomill.pdf.

VALEUR, J. R. 2011. Environmental Impacts of NORM Disposal--With Emphasis on Discharges to Sea. *SPE Projects, Facilities & Construction*.

WHEELER, J. R., GRIST, E. P. M., LEUNG, K. M. Y., MORRITT, D. & CRANE, M. 2002. Species sensitivity distribution: data and model choise. Hong Kong.

Appendix A

Table A-1: Candidate chemicals for use in the risk calculations (EIF) for drilling discharges, as described by ERMS.

Metals	**Comments**
Arsenic, Barium, Cadmium, Chromium, Copper, Mercury, Nickel, Lead and Zinc.	Both free-available and attached form of the metal needs to be considered.
Natural Organic Compounds	**Comments**
BTEX	Might be present in the water column following oily cuttings.
Naphthalenes	Includes naphthalene and C1 – through C3-naphthalenes.
Other 2-3 Ring PAH	Includes 12 analyte groups, including fluorenes, phenanthrenes and dibenzothiophenes.
>= 4-Ring PAH	Includes 10 unalkylated PAH, including benzo(a)pyrene.
Aliphatic Hydrocarbons	Total petroleum hydrocarbons measured by IR or GC/FID. Sometimes high in cutting piles.
C0-C3 Phenols	Might be present in solution in drilling waste plume in water column.
C4-C5 Phenols	Might be present in solution in drilling waste plume in water column.
>= C6 Phenols	Might be present if the mud contains alkylphenol polyethoxylate detergents. Focus on C8- & C9-phenols
Added Chemicals (PLONOR)	Does not require a discharge permit (Green Chemicals)
Barite	Weighting chemical (Barium sulfate). Most abundant solid ingredient in most muds.
Carboxymethyl cellulose	Clay deflocculent. Major solid ingredient in most muds.
Bentonite	Montmorillonite clay. Normally a major solid ingredient in muds.
Portland cement class G	Used in setting casing. Normally not discharged intentionally.
Quartz	Silica. Considered toxicologically inert.
Xanthan Gum	Natural plant material for viscosity control.
Added Chemicals (non-PLONOR)	Yellow substances should be evaluated. Red and/or black substances will be evaluated if use is proved to be necessary from a safety or a

Source: Smith et al. 2006b, p18

Appendix B

This section described the reporting scheme for risk assessment of drilling discharge modelled in DREAM (Frost, 2012).

Input data for drilling discharges (exploration well)

- **Date:**
- **Name of location:**

Coordinates, ….. … degrees, …… minutes and ….. seconds N (or S)
…degrees, …… minutes and …... seconds E (or W)

- **Ambient conditions:**

Median grain size on location before drilling: (mm)

Table B-1: Ambient water column stratification.

Depth, m	Temperature, deg. C	Salinity, ppt
0		
10		
30		
…..		

- **Ambient currents**

Measured ?? (yes/no)
Numerically simulated ? (yes/no)
Other (or no currents):

- **Ambient winds**

Specify if available

- **Water depth on location (m)**:

Table B-1: Details of the drilling program.

Drilling section: (example) 1)		**36” drilling**	**26” drilling**	**17.5” drilling**	**12.25” drilling**	**8.5” drilling**
Start of discharge, (month)						
Section length, m:						
Drilling (penetration) rate, m/h						
Discharge depth, m 4)						
Diameter of outlet opening, m						
Orientation of outlet opening (N, E, S, W)						
	Compound	**Amounts**	**Amounts**	**Amounts**	**Amounts**	**Amounts**
Components	**In discharge**	**tonnes**	**tonnes**	**tonnes**	**tonnes**	**Tonnes**
Particles	Cuttings					
Particles	Bentonite					
Particles	Barite					
Particles	Other….					
Chemical 1	Chemicals can be specified on a component level as well 2)					
Chemical 2						
Chemical 3						
Chemical…….						
	Sum MUD 3)					

1) Batch discharges can be included as well.
2) Only non-PLONOR chemicals or components need to be included.
3) Includes water and PLONOR chemicals in addition
4) Could be distance from sea surface or distance from sea floor

Table B-3: Properties of chemicals added, either on a product or a component level:

	Compound	*Density*	*PNEC ***	*Biodegradation*	*Log Pow*	Comments
	in discharge	*SG*	*ppb*	*% over 28 days*		
Particle groups						
Cuttings				-	-	Defaults available
Particles 1	**Bentonite**			-	-	Defaults available
Particles 2	**Barite**			-	-	Defaults available
……..						
Drilling chemicals						

(non-PLONOR)						
Chemical/component 1						
……						

Table B-4: Heavy metal content in particle matter

Heavy metals in natural sediment, bentonite and barite (mg/kg)				
	Natural sediment	**mg/kg bentonite**	**mg/kg barite**	**Other particle matter**
Cd				
Cr				
Cu				
Hg				
Pb				
Zn				

- **Grain size distributions particle materials**

Preferably, the calculations should be based upon site specific particle size distributions of all the different groups of particle matter involved.

If no such information is available, default particle size distributions are available for some particle groups.

- **Other matter of specific interests:**

This information should relate to site specific information: Specific details in drilling discharge arrangements (say discharge depth above sea surface) of specific resources on the drill site (say, the presence of corals and/or sponges). In such cases, details of the specific conditions should be provided.

Appendix C

Table C-1: Complete matrix of all factors and simulation used for the sensitivity analyze.

Pattern	Number of Particles	Output Interval	Time Step	Outlet Diameter	Discharge Depth	Sediment Median Grain Size	Sediment Porosity	PNEC Barite	Metal Fraction in Barite	Effluent Temperature	Oxygen Concentration Seafloor	**Ambient Data**	**Wind Profile**	**Size Distribution Barite**	**Size Distribution Cuttings**	**Concentration Grid Size**	**Habitat Grid Size**
+––––++––+––++++–	0,5	-0,5	-0,6	-0,333	-1	0,333	0,333	-0,5	-0,5	0,333	-0,444	0	1	1	1	1	0
––++––+––++++–+–+	-0,5	-0,5	0,6	0,333	-1	-0,333	0,333	-0,5	-0,5	0,333	0	1	1	0	1	0	1
+++++++++++++++++	0,5	0,5	0,6	0,333	1	0,333	0,333	0,5	0,5	0,333	0	1	1	1	1	1	1
++++–+–+––––++––+	0,5	0,5	0,6	0,333	-1	0,333	-0,333	0,5	-0,5	-0,333	-0,444	0	1	1	0	0	1
+––++++–+–+––––++	0,5	-0,5	-0,6	0,333	1	0,333	0,333	-0,5	0,5	-0,333	0	1	0	0	0	1	1
+––+––++++–+–+–––	0,5	-0,5	-0,6	0,333	-1	-0,333	0,333	0,5	0,5	0,333	-0,444	1	0	1	0	0	0
+––––++––+––++++–	0,5	-0,5	-0,6	-0,333	-1	0,333	0,333	-0,5	-0,5	0,333	-0,444	0	1	1	1	1	0
111112	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	0	1
+––+––++++–+–+–––	0,5	-0,5	-0,6	0,333	-1	-0,333	0,333	0,5	0,5	0,333	-0,444	1	0	1	0	0	0
–––++––+––++++–+–	-0,5	-0,5	-0,6	0,333	1	-0,333	-0,333	0,5	-0,5	-0,333	0	1	1	1	0	1	0
111122	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	1	1
111121	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	1	0
++–+–+––––++––+––	0,5	0,5	-0,6	0,333	-1	0,333	-0,333	-0,5	-0,5	-0,333	0	1	0	0	1	0	0
–++++–+–+––––++––	-0,5	0,5	0,6	0,333	1	-0,333	0,333	-0,5	0,5	-0,333	-0,444	0	0	1	1	0	0
111211	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	1	0	0
+––++++–+–+––––++	0,5	-0,5	-0,6	0,333	1	0,333	0,333	-0,5	0,5	-0,333	0	0	0	0	0	1	1
111121	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	1	0
++––+––++++–+–+––	0,5	0,5	-0,6	-0,333	1	-0,333	-0,333	0,5	0,5	0,333	0	0	1	0	1	0	0
––+––++++–+–+––––	-0,5	-0,5	0,6	-0,333	-1	0,333	0,333	0,5	0,5	-0,333	0	0	1	0	0	0	0
+–+–+––––++––+––+	0,5	-0,5	0,6	-0,333	1	-0,333	-0,333	-0,5	-0,5	0,333	0	0	0	1	0	0	1
––++++–+–+––––++–	-0,5	-0,5	0,6	0,333	1	0,333	-0,333	0,5	-0,5	0,333	-0,444	0	0	0	1	1	0
––++++–+–+––––++–	-0,5	-0,5	0,6	0,333	1	0,333	-0,333	0,5	-0,5	0,333	-0,444	0	0	0	1	1	0
–+–+––––++––+––++	-0,5	0,5	-0,6	0,333	-1	-0,333	-0,333	-0,5	0,5	0,333	-0,444	0	1	0	0	1	1
++–+–+––––++––+––	0,5	0,5	-0,6	0,333	-1	0,333	-0,333	-0,5	-0,5	-0,333	0	1	0	0	1	0	0
111111	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	0	0
+–+––––++––+––+++	0,5	-0,5	0,6	-0,333	-1	-0,333	-0,333	0,5	0,5	-0,333	-0,444	1	0	0	1	1	1
111122	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	1	1
––––++––+––++++–+	-0,5	-0,5	-0,6	-0,333	1	0,333	-0,333	-0,5	0,5	-0,333	-0,444	1	1	1	1	0	1
–+––––++––+––++++	-0,5	0,5	-0,6	-0,333	-1	-0,333	0,333	0,5	-0,5	-0,333	0	0	0	1	1	1	1
111111	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	0	0
+++–+–+––––++––+–	0,5	0,5	0,6	-0,333	1	-0,333	0,333	-0,5	-0,5	-0,333	-0,444	1	1	0	0	1	0
+–+––––++––+––+++	0,5	-0,5	0,6	-0,333	-1	-0,333	-0,333	0,5	0,5	-0,333	-0,444	1	0	0	1	1	1
+–+–+––––++––+––+	0,5	-0,5	0,6	-0,333	1	-0,333	-0,333	-0,5	-0,5	0,333	0	0	0	1	0	0	1
++++–+–+––––++––+	0,5	0,5	0,6	0,333	-1	0,333	-0,333	0,5	-0,5	-0,333	-0,444	0	1	1	0	0	1
–+–+––––++––+––++	-0,5	0,5	-0,6	0,333	-1	-0,333	-0,333	-0,5	0,5	0,333	-0,444	0	1	0	0	1	1
111112	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	0	0	1
111211	0	0	0	0	0	0	0	0	0	0	-0,222	0	0	0	1	0	0
+++–+–+––––++––+–	0,5	0,5	0,6	-0,333	1	-0,333	0,333	-0,5	-0,5	-0,333	-0,444	1	1	0	0	1	0
––+––++++–+–+––––	-0,5	-0,5	0,6	-0,333	-1	0,333	0,333	0,5	0,5	-0,333	0	0	1	0	0	0	0
++––+––++++–+–+––	0,5	0,5	-0,6	-0,333	1	-0,333	-0,333	0,5	0,5	0,333	0	0	1	0	1	0	0
+++++++++++++++++	0,5	0,5	0,6	0,333	1	0,333	0,333	0,5	0,5	0,333	0	1	1	1	1	1	1
––––++––+––++++–+	-0,5	-0,5	-0,6	-0,333	1	0,333	-0,333	-0,5	0,5	-0,333	-0,444	1	1	1	1	0	1
––++––+––++++–+–+	-0,5	-0,5	0,6	0,333	-1	-0,333	0,333	-0,5	-0,5	0,333	0	1	1	0	1	0	1
–––++––+––++++–+–	-0,5	-0,5	-0,6	0,333	1	-0,333	-0,333	0,5	-0,5	-0,333	0	1	1	1	0	1	0
–+––++++–+–+––––+	-0,5	0,5	-0,6	-0,333	1	0,333	0,333	0,5	-0,5	0,333	-0,444	1	0	0	0	0	1
–++––+––++++–+–+–	-0,5	0,5	0,6	-0,333	-1	0,333	-0,333	-0,5	0,5	0,333	0	1	0	1	0	1	0
–+––––++––+––++++	-0,5	0,5	-0,6	-0,333	-1	-0,333	0,333	0,5	-0,5	-0,333	0	0	0	1	1	1	1
–++++–+–+––––++––	-0,5	0,5	0,6	0,333	1	-0,333	0,333	-0,5	0,5	-0,333	-0,444	0	0	1	1	0	0
–++––+––++++–+–+–	-0,5	0,5	0,6	-0,333	-1	0,333	-0,333	-0,5	0,5	0,333	0	1	0	1	0	1	0
–+––++++–+–+––––+	-0,5	0,5	-0,6	-0,333	1	0,333	0,333	0,5	-0,5	0,333	-0,444	1	0	0	0	0	1

Table C-2: Numerical results for EIF and restitution time for all simulations.

Case	EIFWaterColum	EIFSediment	Restitution Time in the Water Column (d)	Restitution Time in the Sediment (d)	Case	EIFWaterColum	EIFSediment	Restitution Time in the Water Column (d)	Restitution Time in the Sediment (d)
Base	552	3,8	2,5	1689	26	228	3,0	2,25	1490
1	1659	5,9	2,75	2090	27	651	5,0	3	1659
2	1569	6,0	2,75	1699	28	17	4,0	1,25	1490
3	6	6,0	2,25	1673	29	438	7,0	3	1673
4	214	4,0	3	1523	30	563	3,0	2,5	1659
5	23	6,0	2	1699	31	17	7,0	2,25	1913
6	248	5,8	2	2300	32	229	3,0	2,25	1460
7	1590	5,3	2,75	2090	33	34	4,0	1,25	1520
8	566	5,0	2,5	1659	34	234	5,0	3	1553
9	232	6,0	2	2330	35	1777	5,0	3,75	1613
10	11	2,5	1,75	1700	36	599	5,0	2,5	1659
11	591	5,9	3	1659	37	569	3,8	2,5	1689
12	608	3,9	3	1659	38	15	7,5	2,25	2033
13	1170	3,5	3	1613	39	298	5,0	2,25	1700
14	17	5,3	3	2213	40	0	2,5	0	1673
15	597	3,0	2,5	1629	41	8	6,0	2,25	1643
16	17	4,3	0,75	1700	42	17	4,0	1,25	1520
17	615	3,0	3	1689	43	1792	7,0	2,75	1700
18	0	2,8	0	1673	44	11	2,3	1,75	1700
19	298	5,0	2,25	1700	45	0	7,0	0	1943
20	17	4,0	1,5	1550	46	1297	3,5	3,75	1673
21	13	3,3	2,25	1613	47	426	6,0	3	1673
22	9	2,8	3	1673	48	17	5,0	3	1973
23	1676	5,0	3,75	1583	49	1376	2,8	3,75	1643
24	1189	3,8	3	1613	50	0	6,0	0	1973
25	529	3,0	2,5	1659					

Table C-3: Contribution from each effect to the sediment EIF.

Case	Drill-chem-1	EIF_Cadmium Barite	EIF_Chromium Barite	EIF_Copper Barite	EIF_Lead Barite	EIF_Mercury Barite	EIF_Zinc Barite	Thickness	Oxygen	Grain size
Base	0	0	0	0	0	0	0	2,58	0	97,42
1	0	0	0	0	0	0	0	3	0	96
2	0	0	0	0	0	0	0	3,06	0	96,94
3	0	0	0	0	0	0	0	2,75	0	97,25
4	0	0	0	0	0	0	0	0,59	0	99,41
5	0	0	0	0	0	0	0	5,53	0	94,47
6	0	0	0	0	0	0	0	4,1	0,39	95,51
7	0	0	0	0	0	0	0	3,96	0,14	95,9
8	0	0	0	0	0	0	0	1	0	98
9	0	0	0	0	0	0	0	4,12	0,43	95,45
10	0	0	0	0	0	0	0	2,16	0	97,84
11	0	0	0	0	0	0	0	1	0	98
12	0	0	0	0	0	0	0	1	0	98
13	0	0	0	0	0	0	0	1,16	0	98,84
14	0	0	0	0	0	0	0	5,08	0,32	94,6
15	0	0	0	0	0	0	0	2	0	97
16	0	0	0	0	0	0	0	7,58	0,02	92,4
17	0	0	0	0	0	0	0	2	0	97
18	0	0	0	0	0	0	0	1,81	0	98,19
19	0	0	0	0	0	0	0	5	0	94
20	0	0	0	0	0	0	0	0,64	0	99,36
21	0	0	0	0	0	0	0	1,49	0	98,51
22	0	0	0	0	0	0	0	1,51	0	98,49
23	0	0	0	0	0	0	0	0,62	0	99,38
24	0	0	0	0	0	0	0	1,16	0	98,84
25	0	0	0	0	0	0	0	2	0	97
26	0	0	0	0	0	0	0	0	0	99
27	0	0	0	0	0	0	0	1	0	98
28	0	0	0	0	0	0	0	1,09	0	98,91
29	0	0	0	0	0	0	0	2	0	98
30	0	0	0	0	0	0	0	2	0	97
31	0	0	0	0	0	0	0	4,13	0,05	95,81
32	0	0	0	0	0	0	0	0,7	0	99,3
33	0	0	0	0	0	0	0	0,63	0	99,37
34	0	0	0	0	0	0	0	0,75	0	99,25
35	0	0	0	0	0	0	0	0,63	0	99,37
36	0	0	0	0	0	0	0	1	0	98
37	0	0	0	0	0	0	0	2,44	0	97,56
38	0	0	0	0	0	0	0	3,71	0,06	96,22
39	0	0	0	0	0	0	0	5	0	94
40	0	0	0	0	0	0	0	1,89	0	98,11
41	0	0	0	0	0	0	0	2,72	0	97,28
42	0	0	0	0	0	0	0	1,09	0	98,91
43	0	0	0	0	0	0	0	2,98	0	97,02
44	0	0	0	0	0	0	0	1,94	0	98,06
45	0	0	0	0	0	0	0	4,49	0,08	95,43
46	0	0	0	0	0	0	0	1,38	0	98,62
47	0	0	0	0	0	0	0	2,29	0	97,71
48	0	0	0	0	0	0	0	4,64	0,1	95,25
49	0	0	0	0	0	0	0	1,27	0	98,73
50	0	0	0	0	0	0	0	4,48	0,14	95,38

Table C-4: Contribution from each component to the water column EIF.

Case	Drill-chem-1	EIF_Cadmium _Barite	EIF_Chromium _Barite	EIF_Copper _Barite	EIF_Lead _Barite	EIF_Mercury _Barite	EIF_Zinc _Barite	Cuttings	Bentonite	Barite
1	2	0	0	0	0	0	0	0	1	95
2	2,6	0	0	0,01	0	0	0	0,31	1,67	95,41
3	8,21	0,01	0,09	0,66	0	0	0,02	1,46	4,93	84,63
4	5,61	0	0	0,01	0	0	0	0,57	3,57	90,24
5	1,69	0	0	0,01	0	0	0	0,15	0,49	97,66
6	4,49	0	0,01	0,06	0	0	0	0,55	3,5	91,39
7	2,28	0	0	0,01	0	0	0	0,31	1,59	95,8
8	3	0	0	0	0	0	0	0	2	94
9	4,47	0	0,01	0,06	0	0	0	0,54	3,43	91,5
10	8,34	0	0,01	0,05	0	0	0	2,59	5,1	83,92
11	3	0	0	0	0	0	0	0	2	94
12	3	0	0	0	0	0	0	0	2	94
13	1,74	0	0	0	0	0	0	0,23	1,34	96,69
14	0,95	0	0	0	0	0	0	0,29	0,22	98,54
15	3	0	0	0	0	0	0	0	2	94
16	1,71	0	0	0	0	0	0	0,14	0,47	97,67
17	3	0	0	0	0	0	0	0	2	94
18	3,11	0	0	0	0	0	0	0,26	0,94	95,67
19	6	0	0	0	0	0	0	0	3	88
20	0,91	0	0	0	0	0	0	0,19	0,3	98,6
21	3,98	0	0	0	0	0	0	1,05	2,02	92,95
22	2,43	0	0	0	0	0	0	0,99	0,32	96,25
23	2,34	0	0,01	0,08	0	0	0	0,3	1,66	95,61
24	1,75	0	0	0	0	0	0	0,24	1,35	96,66
25	3	0	0	0	0	0	0	0	2	94
26	4	0	0	0	0	0	0	0	3	91
27	3	0	0	0	0	0	0	0	2	94
28	2,36	0	0,01	0,04	0	0	0	0,66	1,61	95,33
29	4,93	0	0	0,01	0	0	0	0,71	3,77	90,57
30	3	0	0	0	0	0	0	0	2	94
31	4,2	0	0	0,02	0	0	0	1,35	2,7	91,72
32	4,65	0	0,01	0,08	0	0	0	0,66	3,5	91,11
33	1,03	0	0	0	0	0	0	0,21	0,45	98,3
34	5,6	0	0	0,01	0	0	0	0,56	3,61	90,22
35	2,3	0	0,01	0,07	0	0	0	0,3	1,65	95,66
36	3	0	0	0	0	0	0	0	2	94
37	3,18	0	0	0,01	0	0	0	0,35	2,18	94,28
38	5,18	0	0	0,02	0	0	0	1,77	2,71	90,32
39	6	0	0	0	0	0	0	0	3	88
40	3,87	0	0	0	0	0	0	0,34	1,61	94,17
41	7,71	0,01	0,07	0,48	0	0	0,01	2,48	5,94	83,3
42	2,44	0	0,01	0,04	0	0	0	0,67	1,67	95,17
43	2,59	0	0	0,01	0	0	0	0,31	1,63	95,46
44	8,94	0	0,01	0,05	0	0	0	2,41	4,9	83,69
45	4,96	0	0	0,01	0	0	0	1,71	4,14	89,17
46	1,84	0	0,01	0,04	0	0	0	0,23	1,41	96,47
47	4,82	0	0	0,01	0	0	0	0,71	3,71	90,75
48	0,7	0	0	0	0	0	0	0,19	0,13	98,99
49	1,9	0	0,01	0,04	0	0	0	0,23	1,44	96,37
50	5,53	0	0	0,01	0	0	0	1,55	3,49	89,42