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The model develo	pment has been m	ade as a part of the ERMS JIP.
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## SUMMARY

The present report contains a description of the revised DREAM model to calculate environmental risks and impacts from drill cuttings and mud (and produced water) discharged to the sea. Impacts and risks are calculated for both the water column and for the sediment.

The model development has been carried out as a part of the ERMS Joint Industry Project.

It should be noted that the purpose of the model is to provide a tool for operators offshore to predict potential risk for environmental injury caused by discharges to the sea. The model is aimed at guiding operators in selection of chemicals that can minimize environmental risk, and also to calculate potential environmental risk caused by natural compounds.

Parts of the model documentation are also included in the "Near field report" (ERMS report No. 23) and the "Restitution report" for the sediment (including description of the re-suspension, ERMS report No. 21). These two documents are each rather comprehensive, and are therefore reported separately.

Trondheim, 31 August 2006,

Henrik Rye.



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# Abbreviations

BOP	Blow-Out Preventer
СВ	Background concentration of metal in sediment
DREAM	Dose related Risk and Effect Assessment Model
EC50	The concentration where a specific effect is observed for 50% of the test specimen
EIF	Environmental Impact Factor
ERMS	Environment Risk Management System
HOCNF	Harmonized Offshore Chemical Notification Format
LC50	The concentration which causes lethality for 50% of the test specimen
LOEC	Lowest Observed Effect Concentration
MPA	Maximum Permissible Addition
MPC	Maximum Permissible Concentration
NCS	Norwegian Continental Shelf
NOEC	No Observed Effect Concentration
OBM	Oil Based Mud
РАН	Poly-Aromatic Hydrocarbons
PEC	Predicted Environmental Concentration/Change
PNEC	Predicted No Effect Concentration/Change
PLONOR	Pose Little or No Risk to the environment
SBM	Synthethic Based Mud
SFT	Norwegian State Pollution Control Authority
SPM	Suspended Particle Matter
SSD	Species Sensitive Distributions
TGD	Technical Guideline Document (EC 1996)
THC	Total HydroCarbons in sediment
WBM	Water Based Mud

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# **1** Introduction

In the former DREAM project (DREAM = Dose related Risk and Effect Assessment Model), a model was developed to calculate PEC's (PEC = Predicted Environmental Concentration) for produced water discharged into the sea. The DREAM project developed a system for calculating water volumes impacted by concentrations (PEC's) where the associated sum of risks of damage caused by the concentrations exceeded 5 % probability of damage. For such a case, an EIF (EIF = Environmental Impact Factor) was calculated as an indicator for potential damage caused by the discharge. The 5 % probability risk level was chosen to represent the PNEC (PNEC = Predicted No Effect Concentration) level. The method developed in the DREAM project is therefore denoted a "PEC/PNEC" approach, where PEC/PNEC > 1 expresses a state where potential damage might be encountered.

The ERMS project (*ERMS* = *Environment Risk Management System*) is a "follow-up" of the DREAM project, extending the method developed to be valid for discharges during drilling operations as well. The present report documents the method developed to arrive at a system for calculating environmental risks caused by drilling discharges. It is developed along the same lines as for the produced water discharges, defining water volumes (and sediment areas) with PEC/PNEC > 1.

However, some features are different from the produced water case:

- The duration of the drilling discharges is generally short
- The cuttings and mud discharges have large contents of mineral particles
- The discharges may cause deposits on the sea floor
- Non-toxic environmental impacts have to be considered as well

All these factors have to be accounted for in the revised/extended EIF method for drilling discharges. The present report accounts for how this has been done and implemented in the revised DREAM model as a part of the ERMS project.

This report is organized as follows:

Chapter 2 and 3 outline how the concentration fields (Chapter 2) and the corresponding risks (Chapter 3) are accounted for in the water column, including both toxic as well as non-toxic stressors.

The sediment is a new compartment that has to be accounted for separately. Chapter 4 outlines how the PEC's for the sediment have been approached in general. Chapter 5 explains the principles and the use of the "diagenetic equations" to calculate toxic as well as the non-toxic stressors in the sediment.

Chapter 6 outlines how the PEC's and the risks for the sediment are accounted for, including both toxic stressors (chemicals, heavy metals) as well as the non-toxic stressors (burial, oxygen depletion and change of grain size). Chapter 7 presents one case example, while Chapter 8 contains the references.

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# 2 Calculation of concentration fields in the water column

## 2.1 General

The EIF for the water column applied to drilling discharges has been developed along the same lines as has been practiced for the produced water discharges. In the following, a brief outline of the present approach for the water column is therefore given.

The operators on the Norwegian Continental Shelf (NCS) have developed a method for evaluating potential environmental risks from produced water discharges. The method gives a quantitative measure of the potential risks, and is thus able to form a basis for reduction of impacts in a systematic and a quantitative manner. This method is based on the calculation of the EIF by means of the (former) DREAM model.

The EIF method is based on a PEC/PNEC approach. That is, the concentration PEC for some compound discharged into the recipient is compared to some concentration threshold limit PNEC for that compound. When PEC is larger than the threshold PNEC, there may be a potential risk for damage on the biota in the recipient. When the PEC is lower than the PNEC threshold, the risk for damage is considered to be "acceptable".

Details of the PEC/PNEC approach is outlined in the ERMS "toxicity" report (Frost et. al., 2006, ERMS report No. 4) and will not be elaborated further here. The present report will focus on how the PEC's are arrived at in the revised DREAM model.

## 2.2 Discharges during the drilling process

The cuttings and mud discharges originate from the drilling process, including cementing, maintenance and testing operations. Different types of mud are used, mainly

- Oil based mud (OBM)
- Synthetic base mud (SBM)
- Water based mud (WBM)

Other types of discharges or ingredients of interest are:

- Dope (for lubricating the drill string)
- Contingency chemicals
- Cementing chemicals
- Chemicals for testing the Blowout preventer (BOP)
- Completion chemicals
- Weight materials like barite

The cuttings and the chemicals may also be discharged in various ways:

- For the shallow drilling sections (typically 36" and 26"), the discharges normally go to the sea floor directly from the drilling well
- For the deeper sections (typically 17 <sup>1</sup>/<sub>2</sub>" section diameter and less), the discharges go normally to the sea after separating the mud from the cuttings at the shaker on the drilling rig



- At the end of a drilling operation, the excess mud may go to the sea as a "batch" discharge from the rig
- Liquid from testing of a BOP is discharged close to the sea floor

The time duration of the various discharges may also vary:

- Batch discharges and cementing chemical discharges are of short duration (within one hour)
- Drilling discharges and testing of BOP are usually of a longer duration (some days, if only effective drilling time period is considered).

The model should cover all these aspects in order to realistically assess the concentration fields (the PEC's) in the sea.

### 2.3 Behavior of the discharges in the sea

In principle, the same approach has been adapted for the drilling discharges that have been used for calculating produced water concentrations. However, some features are different:

- Cuttings is the only "natural compound" in the discharge
- The discharges are generally of a relative short duration
- The discharges contain ingredients of particle nature
- Some of the chemicals may "attach" to the mineral particles in the discharge
- The chemicals/particles may be "sticky", causing "agglomeration"
- The density of the discharge is generally large, which will cause the discharge to sink

These features have to be built into the simulation model in order to have a proper description of the behaviour of the different cuttings and mud compounds in the water column.

The model concept applied is a "particle" (or Lagrangian) approach. The model generates particles at the discharge point, which are then transported with the currents and turbulence in the sea. Different properties of the particles (representing properties like mass of various compounds, densities and sinking velocities) are associated with each particle as shown in Figure 2.1.

These particles are not the "real" particles in the sea, but are representing the properties of the discharge. As an example, the particles may represent the concentration of dissolved compounds in the discharge. This is the case for the discharge of produced water, where all compounds in the discharge are assumed to be totally dissolved into the water. The particles in the model are therefore not "real", only representing compounds that are assumed to be dissolved.

Model particles are representing different state variables, such as gas bubbles, droplets, dissolved matter and solid matter. For discharges of drill cuttings and mud, solid particles and dissolved matter will be of particular interest. Figure 2.1 shows one example of solid particles (denoted "spillets") represented in the model.





Figure 2.1. An example of particle representation in the DREAM model. One solid "spillet" case is shown, representing the properties of solid particles in a discharge.





Figure 2.2. The spreading of model particles in the recipient caused by turbulence and ocean currents. WBC = Water Based Cuttings particles. WBM = Water Based Mud particles (barite). From Rye et. al. (2004).

Figure 2.2 shows one case where the solid particles in the model have been spread in the recipient due to ocean currents and turbulence. Solid particles of different types (cuttings particles WBC, and barite particles WBM) and with varying sinking velocities (due to differences in size and sinking velocities) are shown.

For WBM in particular, many of the chemicals discharged are water soluble. For these chemicals, the same assumption is used as for the produced water dissolved compounds. They are assumed completely dissolved into the water column. The concentration for each compound can then be calculated from the mass and the number of particles within a unit volume of water for each of the compounds included.

The model is able to include effects on the concentration levels due to biodegradation and evaporation, adsorption to natural particles in the water and additions due to background concentrations in the water. The model can include these factors for each chemical or component group modeled, dependent on the information available.

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### 2.4 Calculation rules for PEC in the water column

### **Dissolved** compounds

The EU technical Guidance Document (TGD, 2003) provides recommendations on how the concentrations (the PEC's) are to be calculated for discharges to sea. This chapter compares the proposed ERMS method of calculation of the PEC's in the water column to the TGD recommendations.

For dissolved chemicals in the water column, TGD (2003) recommends the following formula:

Equation 1 Calculation of local PEC seawater for the marine environment (TGD approach) PEC seawater =  $C_{discharge}$ / DILUTION \* (1+ Kp<sub>susp</sub>\* SUSP<sub>seawater</sub>\*10<sup>-6</sup>) + PEC <sub>seawater</sub>, regional in which: PEC seawater = local concentration in seawater during emission episode [mg\*f<sup>-1</sup>] PEC <sub>seawater</sub>, regional = regional concentration in seawater [mg\*f<sup>-1</sup>] C discharge = concentration of the substance in the discharge [mg\*f<sup>-1</sup>] Kp <sub>susp-water</sub> = solid-water partition coefficient for suspended matter [1\*kg<sup>-1</sup>] SUSP<sub>seawater</sub> = concentration of suspended matter in seawater [mg\*f<sup>-1</sup>] DILUTION = dilution factor [-]

The concentration at the regional scale (PEC <sub>seawater, regional</sub>) is used as background concentration in seawater for the local scale.

The DILUTION factor can be estimated analytically for certain cases (say, discharges into rivers). In the ERMS project, the DILUTION is calculated with the revised *DREAM* model. For using this formula for PEC calculations, information must be available on the suspended matter in the sea water and on background concentrations (denoted "regional concentrations in sea water" in Equation 1 bracket). These contributions can be calculated with the *DREAM* model if needed. However, experience has shown that it may be difficult to obtain good data on these factors. The content of suspended matter undergoes usually seasonal variations, in particular the organic part of the particle matter. Therefore, in the ERMS approach (for the time being), the concentrations of the discharge compounds (the PEC's) are calculated without the contributions from background concentrations and natural particle matter present in the recipient.

Reduction of concentrations due to biodegradation of the chemicals dissolved is included in the ERMS approach. The formula used in the ERMS approach can thus be written:



Equation 2. Calculation of local PEC <sub>seawater</sub> for the marine environment (ERMS approach)

PEC seawater = C discharge \* exp (- kt) /DILUTION

in which:

PEC <sub>seawater</sub> = local concentration in seawater during emission episode  $[mg^*\Gamma^1]$   $C_{discharge}$  = concentration of the substance in the discharge  $[mg^*\Gamma^1]$  k = biodegradation factor (days<sup>-1</sup>) t = time (days) DILUTION = dilution factor [-]

The ERMS approach only includes chemicals with a partition coefficient  $logP_{ow}$  smaller than 3 as dissolved in the water column. Chemicals with  $logP_{ow}$  coefficient larger than 3 are assumed to be "attached" to particles or to form "agglomerated particles". These particles will to a large extent descend down on the sea floor and impact on the sediment. The fates of these are treated in Chapters 4 - 6.

For the present ERMS approach, the DILUTION factor given in Equation 2 includes the effects from

- near field mixing, driven by the momentum and the negative buoyancy of the discharge
- far field mixing, driven by the natural turbulence and transport in the recipient
- evaporation into the atmosphere (only for compounds where relevant information is available)

#### Particle matter

The ERMS approach also includes PEC's from particle matter discharged into the water column (including barite particles). The formula used for particle matter can be written as:

Equation 3. Calculation of local PEC <sub>seawater</sub> for the particle matter discharged into the marine environment (ERMS approach)

PEC <sub>seawater</sub> = C<sub>discharge</sub> /DILUTION

in which:

PEC <sub>seawater</sub> = local concentration of discharged particles in seawater during emission episode  $[mg^*\Gamma^1]$   $C_{discharge}$  = concentration of the substance or particles in the discharge  $[mg^*\Gamma^1]$ DILUTION = dilution factor [-]

The DILUTION factor is the same as in Equation 2, except that the DILUTION factor in Equation 3 also includes fall-out of particles from the plume and down on the sea floor (due to gravity). For particles, the biodegradation factor k in Equation 2 is assumed to be zero (no biodegradation of particles).



The equation 3 is applied for all particle contents in the discharge (cuttings, barite, bentonite, ...). The fall-out of particles due to the particle density represent an extra "dilution" of the discharge because the content of the particle matter in the discharge plume is reduced due to the fallout.

### Barite heavy metals

The concentration of dissolved metals originating from barite in the water column is estimated from the Equation 4:

Equation 4. Calculation of local PEC <sub>seawater</sub> for dissolved metals from barite in the marine environment (ERMS approach)

PEC seawater = (C discharge /DILUTION) \* (FRACTION /Kpmetal)

in which:

 $\begin{aligned} & PEC_{seawater} = local \ concentration \ in \ seawater \ of \ dissolved \ metal \ [mg*\Gamma^1] \\ & C_{discharge} = concentration \ of \ barite \ particles \ in \ the \ discharge \ [mg*\Gamma^1] \\ & DILUTION = \ dilution \ factor \ for \ dilution \ of \ the \ discharge \ in \ recipient \ water \ (-) \\ & FRACTION = \ fraction \ of \ the \ metal \ in \ barite \ (kg \ metal/kg \ barite) \\ & K\rho_{metal} = \ partition \ coefficient \ between \ the \ metal \ in \ barite \ and \ dissolved \ metal, \ see \ equation \ 5 \ (box \ below) \end{aligned}$ 

The partition coefficient Kp<sub>metal</sub> is given by (Frost et. al., 2006):

#### Equation 5. Calculation of Kp metal (TGD approach)

 $Kp_{metal} = C_{sol}/C_{aqu}$ 

in which:

Csol = Total available metal concentration in the solid phase [mg\*kg-1] Caqu = Available metal concentration in the aqueous phase [mg\*kg-1]

The first expression in the bracket in equation 4 above is identical with the PEC in the seawater for barite as given by Equation 3. However, the dissolved metal concentrations originating from barite is influenced by two other factors in addition:

- The part of the barite that consists of the metal in question (denoted FRACTION)
- The part of the metal in the barite that is bioavailable (that is, dissolved in the ambient water, denoted Kp<sub>metal</sub>).

These two factors are therefore built into the Equation 4 above (see the last bracket) for the calculation of the concentration of the dissolved metals originating from barite (ERMS approach).

At present, only metals originating from barite are included in the ERMS approach. Cuttings and other particle matter may contain heavy metals as well, but the barite is currently assumed to contain the most dominant contributions to the heavy metal risks for discharges of drill cuttings and mud.



In the toxicity report (Frost et. al., 2006), guidance on how to choose the metals to be included and the numbers for the parameters FRACTION and  $Kp_{metals}$  are given. For convenience, the metals and the numbers are given in Table 2.1.

Table 2.1. Partition coefficients (log  $K_p$ ) for metals in barite applied to the water column. The data are according to the ERMS toxicity report (Frost et. al., 2006). The column to the right shows the factor to multiply with the barite concentrations in the water column in order to arrive at the concentrations of the dissolved metals for the water column.

Metal	Log Kp	Metal content in	Factor to multiply with
		barite (mg/kg or	barite concentrations in
	(-)	FRACTION*10 <sup>6</sup> )	water (-)
Cadmium (Cd)	2.60 - 3.78	0.04 - 1.7	4.3 10 <sup>-9</sup>
Chromium (Cr)	4.11 – 4.34	9.8 - 14.3	1.1 10 <sup>-9</sup>
Copper (Cu)	4.30 - 4.90	76.6 – 104.7	5.3 10-9
Mercury (Hg)	5.48 - 6.11	0.31 - 0.69	2.3 10 <sup>-12</sup>
Lead (Pb)	4.30 - 4.48	48.7 – 116.7	5.9 10 <sup>-9</sup>
Zinc (Zn)	3.30 - 4.30	42.9 - 138.9	7.0 10 <sup>-8</sup>

The column on the right hand side shows how the dissolved concentrations of metals from barite in the water column have been estimated in the ERMS project. These numbers represent the bracket (FRACTION/Kp<sub>metal</sub>) as given in Equation 4. In order to be conservative, numbers for Kp are chosen on the low side, while numbers for the FRACTION for metals in barite are chosen on the high side in the Table 2.1 value intervals. When these numbers are multiplied together according to the last bracket in equation 4, the expected reduction factor to be used in order to arrive at the dissolved metal concentration estimates appears. These factors should be used for multiplication with the barite concentrations in the water column calculated with the revised DREAM model.

The combination of expected content of metals in barite with realistic partitioning coefficients causes the actual concentrations of dissolved metals from barite in sea water to be significantly lower than the PNEC's presently applied for the metals in the water column as defined in the ERMS "toxicity" report (Frost et. al., 2006) for all practical cases. Therefore, the risks from dissolved metals in barite for the water column have been assumed negligible in the ERMS approach. Similarly, impacts from dissolved metals from cuttings particles (and other particle matter) are neglected as well.

PNEC's presently used for heavy metals dissolved in the water column originating from barite is given in Table 6.1 (column to the left). For further details regarding PNEC's for the water column, see Frost et. al., 2006 (the ERMS toxicity report).

#### Non-toxic stressors for the water column:

Non-toxic stresses caused by particle matter are included in the ERMS approach. The concentrations of the particles in the water column are calculated from Equation 3. Further details are given in Chapter 2.7.

#### Relations between Koc, Kow and Pow partition coefficients for non-ionic substances

Another relation that is recommended by the TGD (2003) is a relation between the partition coefficients  $K_{oc}$  and  $K_{ow}$  for non-ionic substances (see Equation 4 in Frost et. al. 2006, chapter 2):



Formula 6. Calculation of  $K_{oc}$  partition coefficients for non-ionic substances (TGD approach): Log  $K_{oc}$  = 0,00028 + 0,983 \* log  $K_{ow}$ 

in which:

 $K_{oc}$  = partition coefficient organic carbon-water [l\*kg-1]  $K_{ow}$  = octanol-water partioning coefficient (l\*kg-1)

This relation has been approximated with  $K_{oc} = K_{ow}$  in the ERMS project. The reason for this is shown in Figure 2.3. For all practical purposes, these two coefficients may be considered to be equal, as is apparent from this figure.



Figure 2.3. A graphical presentation of the relation between the partition coefficients  $K_{oc}$  and  $K_{ow}$  for non-ionic organic chemicals according to DiToro et. al. (1991). Also given in TGD (2003).

To sum up, in the ERMS approach, the partition coefficients  $P_{ow}$ ,  $K_{ow}$  and  $K_{oc}$  are all considered to be equivalent and equal, see the equation 7 below:

Formula 7. Relations between  $K_{oc}$ ,  $K_{ow}$  and  $P_{ow}$  partition coefficients (ERMS approach): Log  $K_{oc}$  = Log  $K_{ow}$  = Log  $P_{ow}$ in which:  $K_{oc}$  = partition coefficient organic carbon-water [l\*kg-1]  $K_{ow}$  = octanol-water partitioning coefficient (l\*kg-1)  $P_{ow}$  = partition coefficient determined from the HOCNF testing procedure [l\*kg-1]

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### 2.5 The deposition of the matter on the sea floor.

As a part of the ERMS project, the DREAM model has been extended to include:

- Inclusion of a near field plume for the descent of the discharge
- Inclusion of solid particles to sink down through the water column
- Inclusion of solid particle size distributions for various particle types

## Near-field plume

Discharges of drill cuttings and mud have densities that are significantly heavier than the ambient water. A near field plume is therefore included in order to account for the descent of the plume. This descent will cease to occur when the density of the descending plume equals to the density of the ambient water. The plume path is governed by the ocean current velocities (and directions) and also by the vertical variation of the ambient salinity and temperature (stratification). The combination of these factors causes the plume to level out at some depth (the "depth of trapping") or sink down on the sea floor and level out there. A utility has been made available in the model to specify the vertical distribution of the temperature and salinity (depth intervals to be specified by the user). The ocean currents available in the model are also utilized, such that a new near field plume is calculated each time a new ocean current profile is loaded into the model system (typically each second hour). Therefore, the depth of trapping is updated at regular time intervals, dependent on the ocean currents on the discharge site. Mineral particles (cuttings, weight material) are allowed to fall out of the plume, dependent on the sinking velocity and the rate of entrainment of water into the plume. For produced water, gas bubbles are allowed to influence on the density of the plume. The bubbles are also allowed to leave the plume.

These features are built into the near field model (plume phase of the discharge) which can be run for produced water discharges, drill cuttings and mud discharges and accidental discharges (including the presence of oil or oil droplets). The ERMS near field plume model is presented in a separate ERMS report (Johansen, 2006).

## Descent of particles down on the sea floor

Figure 2.4 shows a vertical cross section of an underwater plume on the downstream side of the release calculated with the revised *DREAM* model. The "depth of trapping" in the case shown indicates that this appears at about 20 m depth (discharge depth is about 5 m in this case). At this depth, the discharge separates into two parts:

- One of the parts appears to spread horizontally at the depth of trapping. This part consists of dissolved compounds (not sinking) and of solid particles (basically barite) that are so small in diameters that sinking velocities are negligible.
- The other part of the discharge appears to sink down on the sea floor. This part may consist of coarser particles (like cuttings particles with relatively large diameters) and may be of other particles that are "agglomerated" (see chapter 2.7).





*Figure 2.4. Vertical cross section of the near field plume and the deposition of particles on the sea floor. Example calculation. Discharge point at the upper left corner of the figure.* 

Defaults for the size distributions of the cuttings and barite particles are given in Rye et. al. (2004) and are also shown in Chapter 7, Tables 7.1 and 7.2. These values can be changed by the user. The particle sinking velocities are assumed to be made up by two contributions in the model. The first contribution is the laminar Stokes sinking velocity for smaller particles:

$$W_1 = \frac{d^2 g'}{18\nu}$$
(2.1)

where

 $W_1$  = laminar Stokes sinking velocity of a particle

- d = particle diameter
- g' = reduced gravity =  $g(\rho_{particle} \rho_{water})/\rho_{water}$
- g = standard gravity
- $\rho$  = density of particle or sea water
- v = kinematic viscosity = 1.358 x 10<sup>-6</sup> m<sup>2</sup>/s at 10 °C for sea water

For simplicity, the kinematic viscosity coefficient v is kept constant with temperature (negligible influence on the results).



The second contribution to the sinking of the particles is the friction dominated (that is, interval dominated by constant drag coefficient) sinking velocity for larger particles:

$$W_2 = K\sqrt{d g'} \tag{2.2}$$

where

 $W_2$  = friction dominated sinking velocity K = a dimensionless empirical constant = 1.054

The total sinking velocity W is thus estimated by a combination of the two velocities:

$$W = \frac{1}{\left(\frac{1}{W_1} + \frac{1}{W_2}\right)}$$
(2.3)

The empirical constant K is chosen so that correspondence is reached between the friction dominated sinking velocity as given in US Army Corps of Engineers (1984) and the formula (2.3) above. This formula takes into account that grains are usually *non-spherical* and have therefore generally lower sinking velocities than grains with spherical shapes.

Details of the near field module implemented in the *DREAM* model are given in a separate ERMS report (Johansen, 2006).

#### 2.6 Deposition of chemicals on the sea floor

Fates of chemicals in the water column are included in the present *DREAM* model. Chemicals in produced water discharge are dissolved in the water column, as described in the former DREAM model (Reed et. al., 2001). In water based mud (WBM), the added chemicals are mainly expected to dissolve in the water column. These chemicals may be treated as chemicals in the produced water. For other types of mud (say, OBM), the dissolution of the chemicals in the water column may be slow. The chemicals of this type (typically with high partition coefficient K<sub>oc</sub>) may also have a large ability to adsorb to organic matter in the sediment or in the water column. This type of chemicals may also have "sticky" properties that cause the chemical to form "agglomerated" particles.

According to the EU TGD (2003), substances with  $K_{oc} < 500 - 1000$  L/kg are not likely sorbed to sediment. The EU TGD (2003) states that "To avoid extensive testing of chemicals, a log  $K_{oc}$  or log  $K_{ow}$  of  $\geq$  3 can be used as a trigger value for sediment effects assessment".

This rule has been adapted in the present study. For low  $P_{ow}$ ,  $K_{ow}$  or  $K_{oc}$  values (< 1000), the chemicals are assumed to dissolve (completely) in the water column, as for the chemicals in the produced water. For large  $P_{ow}$ ,  $K_{ow}$  or  $K_{oc}$  values ( $\geq$  1000), the chemicals are assumed to deposit on the sea floor.

All chemicals with low  $P_{ow}$ ,  $K_{ow}$  or  $K_{oc}$  values (the HOCNF scheme reports the  $P_{ow}$  value) are therefore treated as the produced water discharge, except that the chemical is assumed to spread in the recipient at the depth of trapping (where the near field plume levels out in the recipient). No adsorption of the dissolved compounds in the discharge to organic matter, either in the water



column or in the sediment, is assumed. This assumption may be in conflict with the TGD (2003) recommendations, where a formula is given (see the Equation 8 in the bracket in chapter 4.2 in the present report) for the case when the discharge plume hits the sediments on the sea floor. In such a case, the dissolved chemicals may attach to the organic carbon in the sediment. On the other hand, the TGD (2003) also states that the impact on the sediment caused by plumes or concentrations in the water column can be neglected for chemicals with  $K_{ow}$  or  $K_{oc}$  lower than order 1000. This recommendation is followed here.

All chemicals with large  $P_{ow}$ ,  $K_{ow}$  or  $K_{oc}$  values ( $\geq 1000$ ) are assumed to be deposited on the sea floor. This process may take place through

"agglomeration", forming new particles "attachment" of chemicals to cuttings (or other mineral) particles.

Both these processes will bring the chemicals (with logPow > 3) down on the sea floor. The "agglomeration" process is a well-known fact for OBM and (most) SBM types of mud. The base fluids in OBM and SBM usually have large partition coefficients. These chemicals tend to form large "clumps" consisting of the chemical, cuttings and other particle matter in the clump (barite). Due to the content of the particles, they will sink down on the sea floor relatively fast.

Examples of chemicals with typical log Pow > 3 are:

- Dope for lubrication of the drill string
- OBM
- Some types of SBM
- Oil attached to cuttings
- Oil based chemicals used for contingency

Delvigne (1996) showed that oil based drilling fluid (OBM) clumped (formed agglomerated particles) when the cuttings contained more than about 5 w% of OBM drilling mud. Therefore, agglomerated particles consisting of OBM, cuttings and particle barite (when OBM is present in the discharge) have been implemented in the model. The computer program is generalized so that all chemicals in the discharge with  $P_{ow}$ ,  $K_{ow}$  or  $K_{oc}$  values  $\geq 1000$  form agglomerates. The agglomerated particles are formed such that for the case with 5 w% of the chemicals (including the cuttings) forming agglomerates, all cuttings and the barite are to be found within the agglomerated particles.

If the amount of chemicals (with logPow > 3) is small compared to the amount of cuttings, the chemical is recommended to be "attached" to the cuttings particles (as for dope, lubricating the drill string). The "attachment" routine is such that the chemical follows the fate of the particle that the chemical is attached to. Because most of the cuttings will sink down on the sea floor, the chemical attached to it will experience the same fate.

The agglomerated particles will in general have a relatively large density and sink down on the sea floor rather immediately. Delvigne (1996) has performed laboratory studies on their sizes and sinking velocities, and found that the size of the clumps ranged from about 2 mm to 50 mm. Their settling velocities were in the range 10 - 60 cm/s. These numbers are implemented in the model.

For the solid particles that are not agglomerated, these are assumed to sink due to their individual sizes and densities, see the formulas 2.1 - 2.3. No adjustments for possible flocculation processes of the free particles of cuttings and barite in the water column are accounted for in the present



model version. Some of the particle matter in the discharge do have flocculation properties (like bentonite), but bentonite is generally discharged directly to the sea floor. Due to the descent of the plume, it will end up in the sediment anyway. But discharged from a platform, the bentonite particle distribution should be specified to reflect the flocculation properties of the bentonite. Some support for the non-flocculating properties of the barite in field data is reported in Rye et. al., (2004), who compared the barium concentrations measured in the sediment (originating from barite) in the vicinity of a discharge point with model simulations of the deposition of the barite on the sea floor from the same discharge. A reasonably good correspondence was found between the field data and the model simulations when the barite was assumed *not* to flocculate in the numerical simulations. Other observational and experimental data have also been reviewed that support this assumption (Rye, 2005).

### 2.7 Particle stress from barite

The discharges of drilling mud and cuttings will result in increased concentrations of suspended particle matter (SPM) in the water column. These particles may cause impact on the water column organisms. This impact is not caused by toxicity, but by the presence of (non-spherical) particles in the water column. The stresses from such particles are therefore included in the model for the potential impact in the water column.

In estuaries and coastal areas, natural concentrations of particles in the sea water (SPM = *Suspended Particle Matter*) may go up to 400 mg/L. In open North Sea areas, the typical concentrations are lower, usually < 20 mg/L (TNO, 2006b). Particularly in water systems with relatively low natural suspended sediment concentrations (< 10 mg/L), an increase of the SPM concentrations may lead to an increase in ecological effects.

TNO (2006b) has made a review of the stresses imposed by particles in the mud discharged to the sea, based on Species Sensitive Distributions (SSD's). They have arrived at a set of PNEC's and risk functions for various groups of particles matter. These risks are included in the risk calculations for the water column. The following particle groups are presently implemented:

- Barite
- Bentonite
- WBM in general

The risks from these are added to the toxicity-based risks caused by dissolved chemicals in the water column. Therefore the risks caused by particle stress are presently treated in the same way as the risks caused by toxicity. The PNEC's and the risk functions are assumed not to be particle size dependent (except that large particles will tend to descend to the sea floor and thus not contribute to the risks in the water column).

### 2.8 Summary of impacts from drilling discharges in the water column

To sum up, the following impacts in the water column are included in the present version of the *DREAM* model:

1. Chemicals that are water soluble with relatively small partitioning coefficient ( $K_{ow}$ ,  $K_{oc}$  or  $P_{ow} < 1000$ ) are all included as totally dissolved into the water column, as for produced water.



- Chemicals that are not (or negligible) water soluble (with partitioning coefficient ≥ 1000) are assumed to accumulate in the sediment on the sea floor. Impacts in the water column from these chemicals are neglected. (Impacts from these on the sediment are treated in chapters 5 7).
- 3. Particle stress from particle matter in the discharge (barite, bentonite, attapulgite and WBM in general) is also included for impact calculations in the water column.
- 4. Metals in barite dissolve in the water column to a very small extent. Impacts from these are therefore neglected. However, metals from barite may cause toxic stresses in the sediment. The calculation of PEC's from these on the sediment is treated in chapter 6.
- 5. Impacts from cuttings particles in the water column are neglected. Cuttings are considered to be a natural ingredient in the water column, like other mineral particles.

The following Table 2.2 contains an overview of the various factors involved in calculating the PEC's for the water column.

	WATE	<u>R COLUM</u> N I	MPACT	
	Stressor:	PEC:	PNEC:	Details in:
Produced water	1. Dispersed oil	Assumed dissolved	Concentration	Reed et. al., 2001
discharge	2. Natural HC compounds	Dissolved	Concentration	Reed et. al., 2001
	3. Heavy metals	Dissolved	Concentration	Reed et. al., 2001
	4. Added chemicals	Dissolved	Concentration	Reed et. al., 2001
Drill cuttings and	5. Cuttings	No impact		See sediment impact
mud discharge	6. Particles in mud	Spreading and deposition	Particle concentration	Chapter 2.7.
	7. Metals in barite	Equilibrium partitioning metal – sea water	Concentration of dissolved fraction based on equilibrium partitioning	Chapter 2.4.
	8. Added chemicals, Pow < 1000	Dissolved	Concentration	Chapter 2.4.
	9. Added chemicals, Pow > 1000	No impact		See sediment impact
	10. Oil on cuttings	No impact		See sediment impact

Table 2.2. Overview of the various factors involved in calculation of the stressors for the water column.



Note that the case "oil on cuttings" is a case that involves a discharge of cuttings originating from drilling in a reservoir containing oil (see row No. 10 in Table 2.2). This discharge is containing oil that will "attach" to the cuttings particles in the case that the cuttings are discharged and when the amount of oil is lower than 5 w% of the cuttings (looking at the "oil" as a bulk chemical, the  $logP_{ow}$  for oil is generally larger than 3). In the case that the amount of oil is larger than 5 w% of the cuttings, the discharge is assumed to "agglomerate". In both cases, the oil will end up on the sea floor, with a corresponding impact on the sediment.

For such a case, no impact is calculated for the water column by the revised DREAM model. This case may be contrasted to the case where dispersed oil is discharged with the produced water (see row No. 1 in Table 2.2). For the produced water case, the discharge will not contain any mineral particles that the oil can "attach" to, or "agglomerate" with. In the present model version, the dispersed oil in produced water is assumed to dissolve and impact on the water column, with no impact on the sediment.

An interesting case may appear when jetted sand is discharged along with the produce water stream. In this case, the dispersed oil may agglomerate or attach to the sand particles. For such a case, the oil should not be (completely) dissolved into the water column, but should be brought down (may be in parts) to the sea floor, attached to (or may be agglomerated with) the sand. The ERMS project does not cover this particular case in their scope of work, but this case may represent an interesting case where the model capabilities developed for both the produced water discharges and the drill cuttings and mud discharges may be combined in another way.

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## 3 Risks and EIF for the water column.

### 3.1 PEC/PNEC for water soluble drilling discharges

Two different types of stressors are included for the impacts in the water column caused by drilling discharges, as explained in chapter 2. These are:

- Impacts from chemicals with  $P_{ow}$ ,  $K_{oc}$  or  $K_{ow} < 1000$
- Impacts from particle stress caused by weighting material in the mud

Risks are related to the PEC/PNEC ratio, where the PEC is the "*Predicted Environmental Concentration*" and the PNEC is the "*Predicted No Effect Concentration*".

The impacts from the chemicals are treated in the same way as for the chemicals in the produced water. Assuming only non-PLONOR chemicals to be included for the risk calculations, the HOCNF scheme (or similar) contains the information necessary (in principle) for characterizing the biodegradability (matter biodegraded over 28 days), the partition coefficient (P<sub>ow</sub>) and the NOEC's, EC50's and LC50's for assignment of a proper PNEC value. The risks caused by the chemicals are related to the ratio PEC/PNEC for each chemical. For the PEC values, the revised DREAM model is run in order to determine the PEC values of the chemical in the recipient (for all grid points and at all times). The PEC/PNEC ratio is then determined accordingly.

The PEC/PNEC ratio for the chemical or compound in question is then used to determine the probability of impact on the recipient in terms of probability of risk for damage. For produced water, this is presently done according to a method developed by Karman et. al., 1994 (and also published in Karman and Reerink, 1997). When PEC/PNEC = 1, this corresponds to a level of probability of damage equal to 5 %. When PEC/PNEC < 1, the probability of damage (risk) is lower than 5 %. When PEC/PNEC > 1, the risk is correspondingly higher than 5 %.

### 3.2 Calculation of risks for the water column.

Figure 3.1 shows an example of the relation between the PEC/PNEC ratio and the probability of damage (risk). The curve is determined from the formula (Karman and Reerink, 1997):

Risk = 
$$\int_{0}^{\ln PEC/PNEC} \left\{ \frac{1}{S_m \sqrt{2\pi}} \exp \frac{-(y - X_m)^2}{2S_m^2} \right\} dy$$
 (3.1)

where

Risk = the probability that a species will be affected

 $X_m = a$  mean of the logarithmically transformed data

 $S_m$  = a standard deviation of the logarithmically transformed data

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

The data that are referred to represents data on damage on particular species determined from laboratory experiments.





Figure 3.1. The relation between the PEC/PNEC level and the risk level (in %) for damage on biota. Note that at level PEC/PNEC = 1, the probability of damage is 5 %. Based on Karman et. al., 1994.

The risk curve used for chemicals and natural compounds in produced water is based on Karman and Reerink (1997), with:

 $S_m = 1.74$  and  $X_m = 2.85$ 

The parameters Sm and Xm express the shape of the risk function shown in Figure 3.1. The numbers given by Karman and Reerink (1997) are also presently used for the risk calculations of the chemicals in the water column caused by drilling discharges. The constants are therefore presently used for all dissolved compounds in the water column for both drilling discharges and produced water discharges. These numbers may be revised later based on results from the ERMS project.

The curve shown in Figure 3.1 relates the calculated PEC/PNEC ratio to the probability of risk in a unique way. This can then be done for any compound of chemical in the discharge.

For each time instant and for each grid cell, it is possible to calculate the sum of environmental risk for all compounds in the discharge. For the total risk for two compounds in the discharge, the sum of risks can be calculated from the formula

$$P(A+B) = P(A) + P(B) - P(A) * P(B)$$
(3.2)

where P(A) is the probability of environmental risk for compound A and P(B) is the probability of risk for compound B. For small risks (that is, P(A) and P(B) are both small), the risks can be considered to be linearly additive, approximately. For a larger number of compounds, the sum of risks can be calculated from the generalized formula for the sum of probabilities P(A), P(B), ..... P(i) ...:



$$P(\text{sum } i) = 1 - \prod \{1 - P(i)\}$$
(3.3)

The total risk for a given discharge is then calculated by means of the revised DREAM model. The total risk contribution (in %) is calculated by the model for every point (grid) in space and time instant within the model domain. The sum of risks (for every point in space and time) is then summarized with the use of formula 3.3 and converted back to a corresponding PEC/PNEC value with the aid of Figure 3.1. The results are then presented as shown in Figure 3.2 (snapshot in time). The water volume indicated by the dark color then indicates the water volume where the ratio PEC/PNEC is larger than one (risk is larger than 5 %) for all compound (or compound groups) considered. Within this water volume, the risk contribution is calculated to be larger than the 5 % limit (corresponding to a total PEC/PNEC > 1) for the sum risk of all compounds.



Figure 3.2. Calculation of PEC/PNEC for the sum risks of various compounds in produced water. Snapshot in time. Horizontal extent (upper figure) and vertical extent (lower figure) are both shown. From Rye et. al. (2004b).



### **3.3** Calculation and presentation of the EIF for water soluble drilling chemicals

For the water soluble drilling chemicals in the water column, the EIF (*Environmental Impact Factor*) is defined in the same way as for the produced water. EIF is defined as the water volume where the PEC/PNEC > 1, divided by a unit volume equal to  $(100m \times 100m \times 10m =) 10^5 \text{ m}^3$  of recipient water.

Although the same calculation rules for the risks and the EIF are adapted for the water soluble drilling discharges, some aspects are different. As an example, one case with EIF's calculated for drilling discharges dissolved into the water column is given, based on Rye and Frost (2003).

Assuming a case where the chemicals are discharged from the rig and then spread out in the surface layers of the sea (expect for the BOP testing, which is usually discharged at the sea floor), the EIF's have been calculated as shown in Figure 3.3. The figure shows that the drilling chemicals are contributing moderately to the EIF values. Inclusion of the contingency chemicals enhances the EIF's, while the contribution from cementing chemicals and chemicals used for BOP testing is negligible.

Also note the time variability of the EIF value. Because the duration of the drilling discharges are limited, the EIF will be a time variable quantity. This is different from the produced water case, where the discharge rate is more or less constant though the simulation time (typical one month). Therefore, not only the actual (maximum) EIF value should be reported, but also the *duration* of the period where the EIF value is larger than zero. In the case shown in Figure 3.3, the maximum EIF is close to 700 (for the drilling including contingency chemicals case), and the time duration where EIF is larger than zero is close to 50 hours (for the same case).



EIF for an exploration drilling

Figure 3.3. Time development of the EIF's for various discharges of drilling chemicals during an exploration drilling. From Rye and Frost, 2003.

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### 3.4 EIF for particle stresses

One special feature of discharges of drill cuttings and mud is the presence of particles. In the revised DREAM model, stresses from particles in the water column have been included in the same way as for the dissolved chemicals. TNO (2006b) has considered environmental stresses imposed by (non-spherical) particles in the water column based on Species Sensitive Distributions (SSD's). They arrived at PNEC's and risk functions ( $X_m$ 's and  $S_m$ 's) for different particle types. Four particle types or particle groups have been included as described in chapter 2.7.

The risk functions and the PNEC's for the different particle types or groups are assumed to be independent of their particle size distributions. The shape of the risk functions for the particle stresses is different from the risk function shown in Figure 3.1. That is to say, the risk function parameters  $X_m$  and  $S_m$  are different from the risk function parameters used by Karman and Reerink (1997), as shown in chapter 3.2.

The risks from the non-toxic stressors are added to the risks from the toxic stressors to arrive at the total EIF for the water column. This addition implies that the risks caused by physical stresses from particles are considered "equivalent" to chemical stresses for the water column. The ERMS project has not considered the justification for this assumption. Users may feel uncomfortable with adding risks caused by chemical stresses with risks caused by physical (particle effect). The users may wish to calculate these stresses separately, without adding them together. But conceptually they are equivalent in the sense that they are both the origin of stresses (and environmental risks) on the biota in the recipient, and the EIF's are anyway calculated based on the same methodology.

For details of the actual risk functions and the PNEC's for the particle stresses in the water column, it is referred to the TNO report (TNO, 2006b).

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## 4 Design of the bottom sediment module

## 4.1 General

Due to the particle content of the discharge, parts of the discharge sink down on the sea floor. Chemicals in the discharge may attach to the particles and thus end up on the sea floor as well, even though the density of the chemicals may be smaller than the ambient water. The chemicals may also form larger particle "agglomerates" due to the sticky properties of the chemical (OBM, SBM). The bottom sediment model must therefore be able to calculate the impacts on the original sediment layer caused by the parts of the discharge that deposit on the sea floor.

The parts of the discharge that remain in the water column are treated in chapter 2 and 3. The present chapter deals with the approach selected for the part of the discharge that ends up on the sea floor.

The following contains a lay-out of the bottom sediment module for simulation of the impact and recovery (restitution) time of the benthic biota.

### 4.2 Results from the TNO design study, comparison with EU's TGD.

A sediment bottom module is needed for the risk assessment of the drill cuttings and mud discharges that deposit on the sea floor. The deposits may have different types of impact: The deposits may cause *burial* effects by covering existing biota on the sea floor. The grain size of the deposit may cause a *change in characteristic (median) grain size* of the sediment that may favor other species on that location on the expense of the natural habitat (effects of adding "exotic sediment"). Chemicals that attach on the particles that are depositing may have *toxic effects* on the biota on the sea floor. Biodegradation of the added chemicals attached to the added sediment may cause *oxygen depletion* in the sediment layer. Heavy metals in barite may also contribute to the toxicity in the sediment.

TNO (2006c) has proposed risk factors for drilling discharges on the sea floor as a part of the ERMS project. The bottom sediment module should include four different "stressors", namely

- changes in grain size
- oxygen depletion
- burial
- toxicity

The following contains an outline of the approach chosen for calculating these stressors based on simulations of the physical/chemical processes in the sediment.

The TGD (2003) also recommends a formula for calculating PEC's for chemicals in the sediment. This formula relates the concentration of a chemical in the sediment to the concentration in "surface water during emission episode". The concentration in bulk sediments can be derived from the corresponding concentration in the water column by predictions from Equation 8, assuming thermo-dynamic partitioning equilibrium (DiToro et al., 2001):



Equation 8 Calculation of local PEC<sub>sediment</sub> for the marine environment (TGD approach)

PEC sediment = [Kp susp-water / RHO susp] \* PEC seawater \* 1000

in which:

PEC <sub>seawater</sub> = local concentration in seawater during emission episode [mg\*l-1] Kp <sub>susp-water</sub> = suspended matter-water partitioning coefficient [m3\*m-3] RHO <sub>susp</sub> = bulk density of suspended matter [kg\*m-3] PEC <sub>sediment</sub> = predicted environmental concentration in sediment [mg\*kg-1]

Highly adsorptive or insoluble, solid substances may not be considered subsequently with the approach described above, as they are not in equilibrium distribution between water and suspended matter because of their strong association with suspended matter; however they may be desorbed or dissolved after ingestion by benthic organisms.

The concentrations in the ambient water may show large vertical concentrations except for very shallow areas or in rivers. For coastal waters where the water depths may vary down to the range 50 - 500 m, there may be no ambient concentration at the sea floor (interacting with the sediment) at all. Therefore, this formula will not give any impact on the sediment for many cases, in particular for most offshore applications.

However, experience has shown that there are in fact impacts on sediment in areas with larger depths than, say, 30 - 50 m, caused by drilling discharges. Experience has shown that sediment may be strongly impacted by discharges of drill cuttings and mud, even though the plume concentrations (the PEC <sub>seawater</sub>) are not in touch with the sea floor at all. This case is not covered by the TGD (2003). The mechanisms that will bring the discharges down on the sea floor will be sinking particles and/or chemicals attached to the particles (or chemicals that agglomerate to form particles). These processes are accounted for in the revised DREAM model that has been developed.

To put these processes into a more formal framework, the deposition of the discharges for larger depths can be expressed as:

#### Equation 9. Calculation of local PEC<sub>sediment</sub> for the marine environment (ERMS approach)

PEC sediment = [1000 / RHO susp] \* PEC discharge /DEPOSITION

in which:

PEC <sub>discharge</sub> = concentration in discharge pipe [mg\*l-1] DEPOSITION = deposition factor calculated by the model (-) RHO <sub>susp</sub> = bulk density of suspended matter in sediment [kg\*m-3] PEC <sub>sediment</sub> = predicted environmental concentration in sediment [mg\*kg-1]

This formula applies to both chemicals and particles (cuttings, barite, ...) in the discharge. The chemicals included are only those with a  $logP_{ow} \ge 3$  (that is, those chemicals who are not assumed to be dissolved in the water column).



The "DEPOSITION" factor represents the spreading of the discharge in the ambient, transport by the currents, the sinking down and deposition of the particles (including chemicals) on the sea floor. Then the average concentration over the upper 3 cm of the sediment layer is calculated, represented by the quantity PEC sediment. All these calculation steps are taken care of by the revised DREAM model.

No biodegradation or other processes are involved in the deposition calculations, because these processes are assumed to take place over a relatively short period of time, generally. Once the chemicals are deposited on the sea floor, they may start to biodegrade.

The TGD (2003) applies only to substances that are assumed to be toxic. The non-toxic stressors oxygen, burial and grain size change for the sediment layer are not treated in the TGD. The environmental risks from the non-toxic stressors in the sediment have therefore been developed as a part of the ERMS project.

Further reference to the TGD (2003) formulas for sediment is made in chapter 6.3.

### 4.3 Separation in the time scales

The four stressors to be calculated for the sediment layer comes in addition to the stressors already defined for the water column (see chapters 2 and 3):

- toxicity in the water column
- suspended particles in the water column

We have therefore to deal with all together 6 different stressors for the drilling impacts, compared to the one stressor only for produced water discharge (toxicity) in the water column. (Any impacts on the sea floor caused by the produced water plume impacting on the sea floor directly have so far been neglected). Also, we have to face the complication that the impacts on the sediment have time scales that are much longer than the time scales involved for the impacts in the water column. The time duration for the discharge and the build-up of the layer at the sea floor will in general be much shorter (within weeks or months), compared to the time scales for the restitution of the new sediment layer on the sea floor (years or decades). This makes it necessary to include different time scales for the two compartments. This also leads to use of different time steps in the model for the water column and the sediment impact in order to be able to calculate the full restitution time of the sediment layer (within reasonable time limits).

So far, the deposition and the impacts from one deposited layer only have been included in the simulations ("mono-layer" version of the model).

#### 4.4 Design of the sediment module

The description of the bottom sediment module layout is divided into the following sections:

- Discharge characterization and deposition calculations (chapter 4.5)
- Natural bottom sediment characterization before discharge (chapter 4.6)
- Calculation of sediment impacted area/volume (chapter 4.7)
- Calculation of restitution time and re-suspension (chapter 4.8)

The model development enters as an essential part within a conceptual frame for the ERMS project described by TNO (2006a). Figure 4.1 illustrates the structural elements for the development work that has taken place as a part of the ERMS project. The model development



work (as described here) enters into the scheme as the "yellow part" of Figure 4.1. The "hazard identification" includes the 6 stressors that have been defined. The "exposure modeling" involves the model development described in the present report (the description of the PEC's). The "1<sup>st</sup> step thresholds" involve establishment of the PNEC's to be used. The "risk assessments" involve the risks calculated (the PEC/PNEC's) for the 6 stressors. Details on the relation between the environmental risks and the PEC/PNEC's are given in TNO (2005).

The actual derivations of the equations used to describe the PEC's in the sediment are shown in chapter 5. The actual PEC calculations for the sediment (and risks) are treated in chapter 6.



Figure 4.1. Procedure for development of the EIF for drilling discharges. From TNO's concept report (TNO, 2006a).

### 4.5 Discharge characterization and deposition calculations

The modeling of the discharges comprises the fates of the

- cuttings
- particles in mud (barite, bentonite, other..)
- non-particulate chemicals in the mud

Both WBM, SBM and OBM types of mud are included.

Particles will sink down on the sea floor with sinking velocities dependent on their size and density. Chemicals may form "agglomerated particles" dependent on the "sticky" properties of the chemicals (SBM, OBM). A near field descending plume is included. Further details are given in chapter 2.

The inclusion of a three-dimensional (3D) and time variable ocean current field will cause a spread of the deposits on the sea floor, resulting into a deposition with characteristics dependent on the horizontal co-ordinates x and y. Each grid point cell on the sea floor then contains the amount of drill cuttings and mud (particles, chemicals) deposited on the sea floor within that cell.



The layer deposited is assumed to be well mixed (homogeneous) and aerated (oxygen content equal to that close to the sea floor initially) during the deposition time ("mono-layer" is assumed).

#### 4.6 Natural bottom sediment characterization before discharge

Because one of the stressors defined involves the *change* of oxygen content in the sediment layer due to the discharge, we need to calculate the content of the oxygen in the sediment layer both before and after the discharge has taken place.

Because the oxygen content vary with the sediment depth, the whole oxygen profile in the vertical needs to be calculated (before discharge) and the time variation of the oxygen content in the sediment as well (during and after discharge). This has to be done for every horizontal grid point at the sea floor due to the fact that the deposition on the sea floor will vary with geographic location (x and y). We thus have to establish a full 3D and time variable picture of the oxygen content in the (pore water) sediment before, under and after the discharge.

This is a rather comprehensive task. The processes that influence on the oxygen profile in the sediment are the amounts of biodegradable matter (mostly biodegradable carbon) in the sediment, the diffusion of the free oxygen downwards through the pore water in the sediment and the consumption of the free oxygen due to the presence of biodegradable organic matter in the sediment. The biodegradable matter itself (comprising carbon, nitrogen and phosphorus compounds, basically) spreads downwards into the sediment layer due to natural burial and bioturbation (that is, mixing within the sediment layer due to the presence of sediment re-workers).

An approach that is able to describe these processes is the use of the so-called "diagenetic equations". These are differential equations which have to be solved numerically. One example of such an equation can be written as (simplified version):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z} \left( D \ \frac{\partial C}{\partial z} \right) - K_C \ C + Q_C \tag{4.1}$$

where the two last terms on the right hand side are reaction or source terms. The first term on the right hand side is a diffusion term (could represent bioturbation in the sediment or molecular diffusion through pore water), while the term on the left hand side expresses the rate of change of the concentration C (which could be a chemical, organic matter in the sediment, oxygen or some content of solid matter). The equation(s) can be used in its 1-dimensional form (vertical co-ordinate z included only), but has then to be solved for each horizontal grid.

These types of equations have been used to calculate the oxygen balance in the sediment layer before the discharge. An illustration is shown in Figure 4.2. The actual equations used are written down and explained in chapter 5.





Figure 4.2. Illustration of a typical free oxygen profile for the sediment before discharge. The figure illustrates the calculated oxygen profile before discharge. The depth of the bioturbation layer indicated is to illustrate that biota may be present within the whole bioturbated layer. However, the depth of the bioturbated layer may occasionally extend below the depth of the oxygenated layer (not shown). The 4 mg/L oxygen concentration limit is for illustration of the fact that the availability of the oxygen in the sediment may have some impact on the depth of the bioturbation layer. The activity of the bioturbating organisms are dependent on the oxygen concentration (respiration).

#### 4.7 Calculation of sediment impacted area/volume

During and after the discharge, the four stressors defined for the sediment layer has to be calculated (burial, free oxygen depletion, toxicity and change of grain size).

These four parameters are calculated for the new sediment layer (including the added deposition on the top) as follows:

- *The burial* is represented by the thickness of the new layer added. This parameter is calculated from the depositions of the discharge compounds only.
- *The toxicity* of the new sediment layer is simply calculated from the content (concentration) of the chemical(s) in the added sediment. These chemicals may however bioturbate into the original sediment layer, causing a mixing between the new and the old sediment.

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- *The free oxygen depletion* is calculated from re-calculating the new free oxygen profile after discharge. The biodegradation from the added chemicals in the new sediment layer must then be included in addition to the natural biodegradation (present in the sediment layer before discharge). This biodegradation may then cause a reduction of the free oxygen content in the pore water of the sediment layer. The actual reduction of the free oxygen content in the pore water of the sediment layer is calculated by taking the difference between the new oxygen content in the pore water of the sediment layer of the sediment after discharge and the oxygen content before discharge.
- *The change of grain size* (introduction of "exotic" sediment) is illustrated in Figure 4.3. A new layer with another median grain size is added on the top of the former (natural) sediment layer. These two layers may then start to mix into one another due to bioturbation, causing a distribution of the median grain size in the vertical.



Figure 4.3. Illustration of the addition of a new layer with a different particle size. The new layer may contain cuttings, barite (or other weighing material) and chemicals.

All these sediment processes are described in the model by means of an implementation of the diagenetic equations. In order to describe the processes in sufficient detail, four diagenetic equations are used:

- One for the free oxygen content in the pore water
- One for the natural organic matter in sediment
- One for the added organic matter (chemicals) due to the discharge
- One for the change of the grain size in the sediment.

Details on how this is done are described in more detail in chapter 5.

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### 4.8 Calculation of restitution time and re-suspension of matter

One of the requirements for the sediment impact model is to calculate the restitution time or the recovery time of the sediment layer after deposition. Examples of processes that will contribute to the recovery of the sediment layer will be

- Burial by natural deposition after discharge (dilution effect)
- Bioturbation after discharge (dilution effect)
- Biodegradation of the chemicals (removal of chemicals)
- Re-suspension of deposited matter (re-distribution and removal)

The first three of these processes are modeled by means of the diagenetic equations. Both burial, bioturbation and biodegradation effects are included in these equations, including toxicity (which is reduced as a consequence of the biodegradation) and free oxygen depletion (which may occur during the biodegradation of the chemicals). Details are given in chapter 5.

Re-suspension is modeled by a separate routine. The deposition on the sea floor may be redistributed due to the presence of waves and/or strong bottom currents. For such a case, a criterion for re-suspension has been built into the model system. Once the matter has been re-suspended, the particles in the suspension may re-distribute into a new geographical (x and y) location.

Details of the re-suspension formulas used and its implementation in the revised DREAM model are given in a separate ERMS report (SINTEF, 2006).

As a final summary, Figure 4.4 illustrates some of the processes involved in the simulation of drilling discharges. Also, the various processes included in the model system can be summarized as follows:

### Ambient and initial conditions:

- Configuration of the outlet opening
- Near field plume
- Ambient stratification
- Ambient ocean current field





Figure 4.4. An illustration of the processes involved in the revised DREAM model. Note that the figure has only illustrative purposes, and therefore some of the processes shown may contain details that may not be correct in detail.

### Fates in the water column:

- Transport and dissolution of chemicals
- Transport and deposition of particles
- Particle stress
- Biodegradation of chemicals
- Formation of "agglomerated" particles

### Fates in the sediment

- Deposition of cuttings, weight material and chemicals
- Burial
- Oxygen depletion
- Effects of exotic sediment (change of grain size)
- Toxicity of chemicals in the sediment
- Toxicity of heavy metals in barite in the sediment
- Effects from biodegradation of chemicals
- Effects from bioturbation
- Effects from natural burial
- Re-suspension
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## 5 The diagenetic equations

#### 5.1 Model requirements

The sediment model is designed to include four stressors:

- Burial
- Change of grain size
- Oxygen depletion
- Toxicity from added chemicals

This formulation requires that processes that involve free oxygen balance and effects from bioturbation (sediment mixing) must be included.

Because the free oxygen depletion is involved, both the free oxygen content of the sediment before and after the discharge must be included.

The time development of the sediment impact must be included as well, because the restitution time of the sediment is required. The sediment processes (like bioturbation) are acting in the vertical dimension (z). Therefore, the model must simulate the time development of the different stressors with time and as a function of the sediment depth (z).

The model must also be fully three-dimensional, because the deposits are spreading geographically over some area (x,y). Therefore, all these processes are modeled in the vertical and as a function of time for each horizontal cell. This means that processes acting in the horizontal direction within each cell (grid point) are neglected. This is acceptable, because vertical variations take place over a very short distance (order 0.1 m), while the horizontal grids used for the sediment are typically of order 10 - 100 m size. This means that horizontal variations are slow, (negligible) compared to the vertical variations.

The processes are all described by means of the "diagenetic equations" for free oxygen, organic matter and particle matter. These equations are solved in a fixed grid ("Eulerian") system. The equations are formulated as partial differential (partly non-linear) equations, and solved with numerical differential (implicit) schemes.

In the following, the formulation of the equations is based on the report by Berner (1980) which formulated the basic "diagenetic equations" to be applied for processes in sediment in general. In addition, the textbook by Bernard Boudreau (1997), Boudreau (1998) and direct consultations with Bernard Boudreau about the issues raised in the present project form the basis for the actual equations used.

### 5.2 The equations used for modeling natural sediment

The free oxygen balance in natural sediment may as a first approximation be expressed as a balance between added biodegradable organic matter depositing on the sea floor, consumed by the free oxygen in the sediment layer. The biodegradable organic matter depositing on the sea floor appears as (attacted to) particles, and is distributed within the sediment layer, partly by bioturbation and partly by vertical advection (caused by natural burial, adding new layers of sediment continuously on the top of the former sediment). The free oxygen diffuses downward from the free water masses through the pore water, and is consumed by the biodegradable organic



matter (forming  $CO_2$ ). The free oxygen flux from above is thus essentially balanced by the organic matter consumption in the sediment.

The processes involved in this balance are modeled with the following equations:

$$\frac{\partial O_2}{\partial t} = \frac{D_0}{\theta^2} \frac{\partial^2 O_2}{\partial z^2} - \frac{1-\varphi}{\varphi} [\gamma_1 k_1 C_1] \frac{O_2}{K_{02} + O_2}$$
(5.1)

for the free oxygen O<sub>2</sub>, and

$$\frac{\partial C_1}{\partial t} = \frac{\partial}{\partial z} \left( D_B \frac{\partial C_1}{\partial z} - w C_1 \right) - \left[ k_1 C_1 \right] \frac{O_2}{K_{02} + O_2}$$
(5.2)

for the biodegradable natural organic matter C<sub>1</sub> in the sediment.

The symbols are:

 $\partial$  = the partial derivative symbol

t = time dimension

z = the vertical dimension

 $O_2(z, t)$  = the free oxygen pore water concentration, g/m<sup>3</sup> (or mg/L) pore water

 $C_1(z, t)$  = concentration of biodegradable organic matter in the sediment, kg/m<sup>3</sup> dry weight

 $D_0$  = diffusion coefficient for oxygen in pore water, cm<sup>2</sup>/hour

 $\theta$  = tortuosity of the sediment (-)

 $D_B(z, t) =$  bioturbation coefficient, cm<sup>2</sup>/hour

 $\varphi$  = porosity of the sediment (-)

w = burial velocity from natural sediment deposition, mm/year (cm/hour in model)

 $\gamma_1$  = Redfield number, combined with mol weights of C<sub>1</sub> and O<sub>2</sub> (-)

 $k_1$  = biodegradation (respiration) rate of natural organic matter, per hour

 $K_{O2}$  = "Monod-type" saturation constant, mg/L (Boudreau 1997, chapter 4.4.2)

The equations are non-linear and coupled, and must therefore be solved simultaneously. For establishment of the vertical profiles of the  $O_2$  and the natural biodegradable organic matter  $C_1$  before the discharge, stationary conditions are assumed ( $\partial / \partial t = 0$ ) by assuming both left-hand sides of the equations to be zero. Then the equations can be solved by numerical iteration. Thus,  $O_2(z)$  and  $C_1(z)$  are established for all horizontal grid points on the sediment floor before discharge.

The physical interpretation of the equations formulated is:

The left-hand sides of the equations express the rate of change of the  $O_2$  (z,t) and the  $C_1(z,t)$  for each grid point (distributed in the horizontal, x and y). These changes are caused by the contributions from the right hand sides of the equations. The first terms on the right hand sides express the changes caused by diffusion of the free oxygen through the pore water (for  $O_2$ ) and the bioturbation effect combined with the natural burial effect (for  $C_1$ ). The last terms on the right hand sides of the equations are equal, and express the oxygen consumption (for  $O_2$ ) and the respiration/biodegradation of the organic matter (for  $C_1$ ), forming  $CO_2$  basically. The term containing the porosity factor  $\varphi$  expresses that the equation for  $C_1$  is acting on the sediment compartment, while the equation for  $O_2$  is acting on the pore water compartment.



A number of approximations are made in order to arrive at these equations.

Strictly, the bioturbation term and the natural burial term in formula (5.2) should be included in the oxygen equation as well. However, the diffusion term in the free oxygen equation is generally much larger than the natural burial term and the bioturbation term when these are applied for the free oxygen equation (Boudreau 1997, chapter 3.7). These terms are therefore omitted in the oxygen equation. The simplification of the free oxygen equation (5.1) is also treated in more detail below (see also Figure 5.1).

The equations formulated are based on the assumption of constant porosity throughout the sediment layer. This is only partly true, because porosity has a tendency to decrease with sediment depth. Also, the porosity has a tendency to increase with *decreasing* grain size (Berner 1980, chapter 3). The porosity factor can be selected by the user, but based on Berner (1980), a value of 0.6 appears to be typical or representative for sediments close to the sediment surface.

The tortuosity factor appears because the molecular diffusion in the pore water is slowed down due to the presence of the grains. This is accounted for by dividing the diffusion coefficient with the tortuosity squared  $\theta^2$ . The tortuosity is often related to the porosity  $\varphi$  by means of an empirical relationship. Boudreau (1997, chapter 4.2.5) reviews these, and recommends the following relationship:

$$\theta^2 = 1 - \ln(\varphi^2) \tag{5.3}$$

This relationship has been used in the present model. This also means that if constant porosity is assumed, constant tortuosity results as well. The relation (5.3) is built into the model. As an example, for a porosity  $\varphi$  chosen equal to 0.6, tortuosity squared  $\theta^2$  will be calculated by relation (5.3) to be close to 2.

#### Actual formulas for the constants in the diagenetic equations

#### $D_0$ = diffusion coefficient for oxygen in pore water.

The actual diffusion coefficient for the oxygen in the pore water is taken from Boudreau 1997, chapter 4.2:

$$D_0 = (0.2604 + 0.006383^*(T/\mu))^* 10^{-5}$$
(5.4)

where T is the absolute temperature in the pore water and  $\mu$  is the dynamic viscosity of water given in centipoise. D<sub>0</sub> is given here in cm<sup>2</sup> s<sup>-1</sup>.  $\mu$  is approximated by

$$\mu = 1.7910 - 0.06144 * \text{temp} + 0.001451 * \text{temp}^2$$
 (5.5)

where "temp" is the temperature in °C in the pore water and  $\mu$  is given in centipoise (10<sup>-2</sup> g cm<sup>-1</sup> s<sup>-1</sup>). These formulas generate a universal and temperature dependent molecular diffusion coefficient for the free oxygen in the pore water. The pore water temperature is assumed to be equal to the temperature of the sea water close to the bottom (to be specified in the input menu).



#### *w* = *burial velocity from natural sediment deposition*

The natural burial velocity is generally increasing close to river entrances and at locations where sediment build-up is taking place. Boudreau (1997, chapter 4.6) points out that the natural burial tends in general to decrease with the water depth. The user is free to specify the burial rate, but the following "default" relations are recommended, based on an interpretation of results presented in ERMS report No. 12 (Akvaplan-niva, 2005):

w = 3.5/H;	H > 35 m depth	(5.6)
w = 0.1  cm/year;	H < 35 m depth	(5.7)

where H is the water depth given in m and w is the burial rate given in cm/year. This formula gives the natural burial equal to 0.1 cm/year at 35 m depth and 0.01 cm/year at 350 m depth. This is in reasonable agreement with the observed burial rates in Akvaplan-niva (2005). The formulas above will be practical to use, because water depth is a piece of information easily available for any site where drilling is planned. If numbers for burial rates are available for the site considered, the model can use these. The relations (5.6) and (5.7) are automatically selected by the model, unless otherwise stated.

#### $D_B = bioturbation \ coefficient$

The bioturbation coefficient is assumed to be water depth dependent as well as dependent on the sediment depth. The coefficient is assumed to be largest at the sediment surface and then decreasing monotonically downwards. The following expression is used (Boudreau, 1998):

$$D_{\rm B}(z) = 3D_{Bave} \left(1 - \frac{z}{L}\right)^2$$
(5.8)

where  $D_{Bave}$  is the average bioturbation coefficient over the bioturbated layer depth L, denoted the bioturbation depth. Experience shows that the parameter L is on the average close to 10 cm, but may show large variations (see the Figures 5.2 and 5.3 shown later in the chapter 5). The value of L appears to be invariant for varying water depth (Boudreau, 1998) and for varying natural burial velocities w (Boudreau 1997, chapter 4.2). L = 9.7 cm is recommended as a default (Boudreau, 1998), but a value of 10 cm will serve equally well.

The average bioturbation coefficient  $D_{Bave}$  however, has been shown to vary with the natural burial rate w. An increasing burial rate w enhances the bioturbation activity. The relation

$$D_{Bave} = 15.7 \text{ w}^{0.6} \tag{5.9}$$

is used (Boudreau 1997, chapter 4.2), which is based on a best fit line drawn through data collected from a large variety of different oceanic conditions. w is here given in cm/year and the bioturbation coefficient is given in  $cm^2$  per year. Since the burial rate is depth dependent (see the relations 5.6 and 5.7), the bioturbation coefficient also becomes depth dependent, with decreasing values with increasing depth.

The figure 5.1 is reproduced from Boudreau's book (1997), showing the variation of the bioturbation coefficient with the burial rate. The equation 4.147 indicated in the figure 5.1 is identical to the formula (5.9) above. The formula shows the bioturbation coefficient to decrease



with increasing burial rate. A rate or order 0.1 - 0.01 cm/year corresponds to a bioturbation coefficient of order 1 - 10 cm<sup>2</sup>/year on the average, but the variations are large. Values are varying between order 0.01 - 100 cm<sup>2</sup>/year for the bioturbation coefficient within the actual range of the burial rate, reflecting the variability of oceanic conditions.

It may be noted here that the diffusion coefficient for the oxygen is significantly larger than the typical values for the bioturbation coefficients, in particular for low burial rates. The oxygen diffusion coefficient is about  $470 \text{ cm}^2$ /year and above (temperature dependent, see the relations 5.4 and 5.5), which is above the range of the bioturbation coefficients shown in Figure 5.1. This justifies the assumption of neglecting the bioturbation term in the oxygen diffusion formula (5.1) for the free oxygen diffusion in the pore water. Therefore, the free oxygen mixing in the sediment is dominated by pore water diffusion and not by bioturbation when the burial rates are small.



**Figure 4.13.** Plot of mixing coefficient, DB, against corresponding burial velocities, w, cited in the sources listed in Boudreau (1994). The solid line is the best power-law fit given by Eq. (4.147). The different symbols identify the tracer, i.e.  $\blacklozenge$  for 137Cs and 239,240Pu, O for 32Si,  $\bigcirc$  for 234Th and 228Th, X for 210Pb, + for tektites and ash,  $\blacktriangle$  for <sup>7</sup>Be, and  $\blacksquare$  for miscellaneous tracers and techniques. (Reproduced with the kind permission of Elsevier Science Ltd.)

Figure 5.1. The bioturbation coefficient used in the diagenetic equations for sediment mixing. Reproduced from (Boudreau, 1997). References shown in the figure can be found in Boudreau's book from 1997. Equation 4.147 mentioned in the figure is identical to formula (5.9) shown above in the present report.



The content of the natural organic matter in the sediment.

The natural burial w represents deposits of both organic and inorganic matter. The organic matter may in turn be divided into parts that are biodegradable (or respirable) in the oxic zone and parts that are not. The resulting concentration  $C_1$  for the organic matter (TOM) in the formulas (5.1 – 5.2) must not be confused with the concentration of TOC (Total Organic Carbon). The total organic matter TOM consists of many different contributions (private communication with Jerry Neff, Battelle, USA, quotation of mail from him):

"There are four classes of humic substances, based on molecular weight and solubility behavior (Jonasson, 1977; Aiken et al., 1985):

 Humins are high molecular weight polymers that are insoluble in water at any pH;
 Humic acids are extremely complex medium molecular weight organics that are not watersoluble at a pH of 2 or lower, but are soluble at higher pH.

3. Fulvic acids have molecular weights of about 700 to 1000 and are less condensed precursors of humic acids. They are completely soluble at all pHs.

4. Yellow organic acids are low molecular weight soluble acids, probably representing, in part, the final stages of microbial degradation of humic substances in sediments.

Class 4 is the most biodegradable and biodegradability decreases with increasing molecular weight and decreasing solubility. Humins often are considered relatively inert. In fact humins are the main precursors of fossil fuels, kerogen and petroleum".

The biodegradable/respirable part of the TOM is the one that impacts on the free oxygen profile in the pore water and is thus modeled. This is the part that is denoted  $C_1$  in the formulas (5.1 - 5.2) above. However, the content of this part will be substantially lower than the TOM content typically observed offshore (typical values for TOM are of order 1 - 10 w% of the sediment dry weight). It is usual to find oxygen profiles with oxygen substantially above zero down to order 3 - 5 cm on the Norwegian Continental Shelf (private communication with Odd Gunnar Brakstad, SINTEF). The content of TOM that will result into such oxygen profiles can be specified through the size of the downward flux of TOM of the biodegradable/respirable matter at the sediment surface (through the upper boundary condition for the  $C_1$  equation, see below).

### $\gamma_1$ = Redfield number, combined with mol weights of $C_1$ and $O_2$

This factor is to be included because 32 grams of O<sub>2</sub> reacts with 12 grams of C to form CO<sub>2</sub>. A factor is therefore to be included to account for the different mol weights. In addition, some reactions involving both N and P compounds cause the  $\gamma_1$  factor to be equal to (138/106)\*(32/12) = 3.47, approximately. The complete equation formulation (*the aerobic respiration equation*) for this reaction can be found in Shimmield et. al. (2000).

#### $k_1$ = biodegradation (respiration) rate of natural organic matter

The biodegradation rate has been found to be dependent on the burial velocity w. In addition, the biodegradation rate comprises two types of contributions (Boudreau 1997, chapter 4.4.3):



- A reactive fraction that decays within the top 10 20 cm of the sediments and that characterizes the part of the organic matter that biodegrades on a relatively short time scale
- A refractory component that oxidizes on a much longer time scale

Based on Boudreau (1997 and 1998), the following expression is used for the  $k_1$  biodegradation rate of TOM:

$$k_1 = 3.0w^{0.6} + 0.4w^{0.6}$$
(5.10)

where w is the burial velocity (cm per year) and  $k_1$  is given in per year. The first term in the equation above represents the reactive fraction, and the second term represents the refractory fraction. These numbers are based on straight line plots through observed data from a variety of oceanic conditions.

#### $K_{O2} = Monod$ -type saturation constant

The last fraction included in the last right-hand term of the formulas (5.1 - 5.2) includes the oxygen concentration in both the nominator and in the denominator. Based on a recommendation by Bernard Boudreau, so-called *Monod kinetics* were adapted to deal with the biodegradation term in the organic matter formula (5.2).

Boudreau (1997, chapter 4.4.2) points out that reaction kinetics may involve nonlinear processes. Also, from a modeling point of view, it may be advantageous to involve nonlinear processes for the biodegradation processes, because troubles may arise with zero or negative oxygen concentrations in the numerical solutions of the equations used. The use of the *Monod kinetics* secure that negative  $O_2$  values will not occur.

The *Monod kinetics* express that a reaction (like biodegradation or respiration) may be expressed as:

$$\left(\frac{\partial C}{\partial t}\right)_{reaction} = -kC\frac{O_2}{K_{O2}+O_2}$$
(5.11)

where the  $K_{O2}$  is a "saturation constant". This constant is generally small, compared to normal  $O_2$  values. The expression above says that the reaction is first order (linear) in the organic matter concentration and hyperbolic in the concentration of the oxygen (oxidant). The latter means that the reaction is essentially independent of  $O_2$  when  $O_2 >> K_{O2}$ , and it is first order in  $O_2$  when  $O_2 << K_{O2}$  (Boudreau 1997, chapter 4.4.2).

The value of the  $K_{02}$  is chosen 0.1 mg/L. The value of this constant is not well known, but it should be chosen to be a low value (positive and close to zero) in order to avoid the oxygen values in the formulas (5.1 and 5.2) to pass below zero oxygen content (private communication with Bernard Boudreau, Halifax, Canada).

#### Boundary and initial conditions

The differential formulas (5.1 - 5.2) must have both boundary and initial conditions formulated in order to be solved numerically. The boundary conditions will here be represented as the



conditions at the sea floor (the sediment surface) and at the bottom of the sediment layer modeled (typically just below the bioturbation depth L of the sediment layer, 10 cm depth are typically used). In addition, initial conditions (at time t = 0) must be specified.

The upper boundary conditions for the oxygen (see formula 5.1) will be a representative value of the oxygen concentration just above the sea floor. Default value may be 9 mg/L. At the lower end of the sediment modeled, an oxygen concentration close to zero can be used (0.01 mg/L is the recommended default).

The boundary condition at the sea surface for the organic matter formula (5.2) will be a flux type condition (a *Robin's condition*, see Boudreau 1997 chapter 5.2.2). The term w in formula (5.2) represent an advection term, which means that the origin in the z coordinate (z = 0 at the sea floor, with z pointing positive downwards) is moving upwards with a rate corresponding to the natural burial velocity w. For such an equation, the boundary condition is expressed as a flux of organic matter from above adding to the sediment layer:

Flux = 
$$wC_0 = -\left(D_B \frac{\partial C_1}{\partial z} - wC_1\right)$$
 valid at  $z = 0$  (sediment surface) (5.12)

Note that  $C_0$  will be different from the  $C_1$  organic matter content at the sediment surface (z = 0) for the case that the bioturbation coefficient  $D_B$  is larger than zero at z = 0. The  $C_0$  term expresses the amount of biodegradable organic matter that has to be supplied in order to balance the content of free oxygen in the pore water of the sediment layer. Similarly, for the boundary condition at the bottom of the sediment layer, the organic matter  $C_1$  (at  $z = z_{max}$ ) is simply advected away with the w term (Flux at  $z_{max} = -wC_1$ ).

As initial conditions, vertical profiles for both  $O_2$  and  $C_1$  are specified. Then  $\partial/\partial t$  terms are assumed zero, and an iteration is performed in order to make the formulas (5.1 - 5.2) converge towards the stationary solutions of  $O_2(z)$  and  $C_1(z)$ . This will then represent the stationary solution of the present-day state in the sediment, before the discharge is starting to impact on the natural sediment.

#### 5.3 The diagenetic equations for modeling the discharge

The diagenetic equations to be used during and after the discharge will be different from the ones used to simulate the present state of the sediment before the discharge.

The reason for this extension will be:

- The grain size of the deposit may be different from the grain size of the original sediment. An extra diagenetic equation is therefore needed to describe the median grain size of the new sediment layer (which will be mixed into the old sediment layer due to the bioturbation).
- Also, another diagenetic equation is needed to describe the behavior of the biodegradable (organic) matter following the new sediment added.

Therefore, four different diagenetic equations are needed to describe the behavior of the new sediment layer. These equations are:



- One for the new free oxygen distribution in the pore water
- One for the behavior of the original biodegradable organic matter in the sediment
- One for the behavior of the biodegradable (organic) matter added
- One for the change of median grain size of the sediment.

These equations are written as:

$$\frac{\partial O_2}{\partial t} = \frac{D_0}{\theta^2} \frac{\partial^2 O_2}{\partial z^2} - \frac{1-\varphi}{\varphi} \left[ \gamma_1 k_1 C_1 + \gamma_2 k_2 C_2 \right] \frac{O_2}{K_{02} + O_2}$$
(5.23)

for the oxygen O<sub>2</sub>, and

$$\frac{\partial C_1}{\partial t} = \frac{\partial}{\partial z} \left( D_B \frac{\partial C_1}{\partial z} - w C_1 \right) - \left[ k_1 C_1 \right] \frac{O_2}{K_{02} + O_2}$$
(5.24)

for the biodegradable natural organic matter C1 in the sediment, and

$$\frac{\partial C_2}{\partial t} = \frac{\partial}{\partial z} \left( D_B \frac{\partial C_2}{\partial z} - w C_2 \right) - \left[ k_2 C_2 \right] \frac{O_2}{K_{02} + O_2}$$
(5.25)

for the biodegradable added organic matter C2 to the sediment, and finally

$$\frac{\partial R_{ave}}{\partial t} = \frac{\partial}{\partial z} \left( D_B \frac{\partial R_{ave}}{\partial z} - w R_{ave} \right)$$
(5.26)

for the median grain size Rave of the new mixed sediment.

The symbols used are the same as for the formulas (5.1) - (5.2). The additional symbols are:

 $C_2$  (z, t) = added biodegradable organic matter in the sediment, kg/m<sup>3</sup> dry weight  $\gamma_2$  = Redfield number for added organic matter –  $O_2$  reaction (-)  $k_2$  = biodegradation (respiration) rate of added organic matter, per hour  $R_{ave}$  (z, t)= median grain size of new sediment, mm

The formulas 5.23 - 5.25 are coupled, and must be solved simultaneously. The free oxygen concentrations in the pore water are involved in all three of the equations, and both organic matter concentrations  $C_1$  and  $C_2$  appear in the free oxygen equation.

Some new assumptions are involved in formulating the formulas (5.23 - 5.26).

The new  $O_2$  equation includes now an extra sink term due to the biodegradation of the new organic matter added (examples are the biodegradable matter in SBM or OBM).

#### The formula (5.25) for the added organic matter

The added deposit comprises particle matter (cuttings, barite) and chemicals that are following the particle matter down on the sea floor. This deposition will cause the burial velocity to increase.



This added burial velocity is calculated by the model from the particle deposition rate on the sea floor. However, since the natural burial velocity w is fixed in the equations for all times, the added burial is accounted for by adding new grid cells on the top of the natural sediment layer.

The equation for the added organic matter  $C_2(z,t)$  is activated after the discharge is initiated. The added organic matter content in the sediment layer will be assumed to be zero prior to the discharge. During the discharge, the amount of added organic matter is calculated for the grid points that are added due to the discharge. After the discharge is ended, the added organic matter concentration influx at the new sediment surface will be zero.

The added organic matter concentration  $C_2(z,t)$  will typically comprise:

- Dope for lubrication of a drill string or casing
- Contingency chemicals containing biodegradable oil
- Oil from reservoir attached to the cuttings discharged
- Main ingredients of oil based mud
- Some ingredients in synthetic based mud

These types of chemicals may form "agglomerated" particles in the discharge (the model recommends that chemicals are agglomerated when Log  $P_{ow}$  coefficient is > 3 and when the amounts of chemicals with Log $P_{ow}$  > 3 are larger than 5 w% of the cuttings). The agglomeration (or "clumping") of the chemicals will bring the chemicals relatively fast down on the sea floor. The biodegradation and oxygen consumption of all these (after being deposited in the sediment) can then be calculated by means of the formula (5.25) for C<sub>2</sub>.

The new organic matter equation for  $C_2$  is formally the same as for the natural organic matter equation except that Redfield numbers and biodegradation properties may be different from the original natural organic matter (biodegradable part). Also, the added organic matter may comprise different contributions  $C_i$ , each with its own biodegradability  $k_i$ . The added organic matter component  $C_2$  is therefore defined as

$$C_2 = \sum_i C_i \tag{5.27}$$

and the term in the bracket to the right in formula (5.25) is defined:

$$k_2 C_2 = \sum_{i} (k_i C_i)$$
(5.28)

which form the basis for calculating the total added organic matter  $C_2$  and its average biodegradation properties.

Strictly, a new diagenetic equation is needed for each added organic matter component that is included if we wish to calculate for each added organic matter component. In order to avoid excessive calculations, an approximate method is therefore used for the biodegradation of the added organic matter that will also be able to maintain the identity of each added organic matter  $C_i$  included. The biodegradation coefficient  $k_i$  is therefore reduced for each added organic matter according to the oxygen deficit calculated for each time step and each grid point. This is done by reducing the biodegradation coefficient  $k_i$  for each of the chemicals included according to the amounts remaining of the free oxygen in the pore water, compared to the oxygen available before the discharge.



The average Redfield number for the added organic matter compounds is denoted  $\gamma_2$  in the free oxygen formula (5.23).

#### The formula (5.26) for the median diameter particle change:

This equation is new. It is solved independently of the other equations. Because one of the stressors for the sediment layer is defined as the change in grain size, one extra equation is needed to account for this factor.

When the discharge is taking place, cuttings and other particles will deposit on the sea floor. These will add on the top of the existing sediment. The bioturbation will then start to act on the added particles, causing a mixing between the added particles and the original sediment. The formula (5.26) accounts for this through the bioturbation factor  $D_B$ . The added particles may have diameters that are different from the original sediment. Thus, a vertical distribution of the median particle size will result. This vertical distribution of the median particle size (radius or diameter) is modeled by means of the formula (5.26) for the median size particle parameter  $R_{ave}$ .

The natural burial causes the particles in the sediment to be advected downwards, assuming that the origin is always placed at the sediment surface (surface is moving upwards, looking from a fixed depth coordinate system). The added layer will also be advected downwards due to the natural burial, in the same rate as for the natural burial. This is accounted for through the w term in the equation for  $R_{ave}$ . Added sediment is represented by adding new grid points on the top of the old sediment. After the discharge, original sediment will start to deposit again on top of the added sediment that deposited. The added sediment will then be bioturbated as well into the natural sediment that deposits after the discharge has ceased to occur. The last term of formula (5.26) secures that this process is included as well.

The formula for the median diameter expresses the results from the volumetric mixing of the sediment (due to bioturbation). The median diameter or radius  $R_{ave}$  is defined as

$$\sum_{i} (Vol_i R_i) = R_{ave} \sum_{i} Vol_i$$
(5.29)

where  $Vol_i$  are the volumes of the particles with the diameter  $R_i$ . The volume of the added particles for each class  $R_i$  are calculated based on the mass deposited (calculated by the model) divided by the density of the particles for each class. The mass of particles for each particle size group  $R_i$  is calculated by the model for each cell from the deposition calculations.

Because the added particles are mixed with natural sediment particles (due to bioturbation), also natural particles are included in the calculations with the formula (5.29) as well. However, for the natural sediment, only median particle size is used, which then has to be specified by the user.

In general, all volume averaged properties (that is, "median" properties) that satisfies the relation above (percentage volume of added sediment, median radii and median diameters of particles in the sediment etc...) can be calculated with this equation.



#### Actual values or formulas for the constants in the added diagenetic equations

 $\gamma_2$  = Redfield number of the reaction  $O_2$  – added organic matter  $C_2$ 

A Redfield type number for the added chemicals will express the balance between the free oxygen consumption in the pore water and the organic matter consumption, as for the C<sub>1</sub> organic matter component. At present, no other factor for this reaction has been made available except for the factor used for the natural organic matter in the sediment. Therefore, the factor  $\gamma_2$  in the free oxygen formula (5.23) is assumed to be equal to  $\gamma_1$  for the time being. This assumption is also used for estimates of organic matter consumption in OBM piles in Shimmield et. al. (2000).

#### $k_2$ = biodegradation (respiration) rate of the added organic matter

Similar as for the natural organic matter, the added organic matter formula (5.25) also includes a biodegradation constant, expressing the expected reduction of organic matter on a yearly basis. Numerous laboratory experiments exist on this factor. NIVA (2005) summarizes the results from laboratory experiments on the biodegradation of OBM's and SBM's carried out at Solbergstrand, Norway. Also, NIVA (2005) includes results from observations of biodegradation of PAO (poly alpha olefins) and THC (total hydrocarbons) on the NCS (Norwegian Continental Shelf). Their findings indicate that the biodegradation rates are dependent on the free oxygen available in the pore water. NIVA (2005) report that half-lives tend to increase with amounts of the biodegradable matter deposited in the experiment. These are processes that the model is able to account for by means of the equations used. Examples of comparisons between model simulations and laboratory experiments on biodegradation are given in SINTEF (2006).

#### Boundary and initial conditions

Boundary conditions for the oxygen formula (5.23) remain the same as for the oxygen equation before discharge. During the addition of new layers (grids) on the top of the old sediment, the oxygen concentration in the pore water of the new layer added is assumed to be the same as the oxygen concentration just above the sea floor in the free water masses.

Boundary conditions for the natural organic matter content  $C_1$  remains the same during and after the deposit of the new layer. Because new layers (grids) are added during the discharge period, the concentration of the natural organic matter within the added layer will be scaled down with the factor

 $\frac{w}{w+W} \tag{5.30}$ 

where the w is the natural burial velocity and W is the burial velocity imposed by the new deposition.

Except for the organic matter concentration  $C_1$  within the added layer given above, the flux boundary conditions for  $C_1$  remain the same as for the formula (5.2) for the natural organic matter before discharge.



The boundary conditions for the added organic matter equation for  $C_2$  will be zero influx at the sediment surface. The added organic matter concentration will be given initially by the concentration of the added organic matter within the added layer. At the lower boundary (at the location  $z_{max}$ ), the outflux is specified by the product of w and  $C_2$ .

The boundary conditions for the particle size equation are also given by flux conditions at the sea floor and at the lower boundary on the model domain. Structurally, the median particle size formula (5.26) is identical to the two organic matter formulas (5.24) and (5.25), except that the biodegradation term is left out (sediment particles do not biodegrade).

The boundary flux condition of the particle size equation will be

Flux = 
$$wR_{median0} = -\left(D_B \frac{\partial R_{ave}}{\partial z} - wR_{ave}\right)$$
 for  $z = 0$  (5.31)

where  $R_{median0}$  is the median particle size of the natural depositing sediment. This boundary flux condition will be valid after discharge period is completed. During discharge, new grid points are added that will contain particles with the median particle size of the deposit. At the lower boundary, the outward flux is given by the product of w and  $R_{ave}$  (after the completion of the discharge).

For initial conditions, the calculated distributions of  $O_2(z)$  and  $C_1(z)$  generated prior to the discharge are used for the formulas (5.23) and (5.24). For the added organic matter,  $C_2$  is assumed to be zero for the grid points below the added layer. For the median particle size  $R_{ave}$  is assumed to be constant and equal to  $R_{median0}$  representing the particles size in the natural sediment before the discharge.

#### 5.4 Numerical methods applied for solution of the differential equations

The system equations (Eq'ns 5.23 to 5.26) cannot be solved analytically because they are nonlinear with respect to the state variables ( $O_2$ ,  $C_1$ ,  $C_2$ , and  $R_{ave}$ ) and the parameters ( $D_0$ ,  $D_B$ ,  $\gamma$ 's, and k's). In order to achieve an analytical solution some simplification and/or assumptions with some specific set of initial-boundary conditions and parameters should be utilized. However those limited solutions do not usually represent the reality properly. Therefore equations for advectiondiffusion problem must be solved by an approximate technique.

A finite difference method is used to discretize the system equations. The method applied utilizes an implicit / central differencing. The problem domain x = [0, L] is divided into N elements (N+1 points). The finite difference approximations of the system equations (Eq'ns 5.23-5.26) are given by

$$\frac{O_i^{k+1} - O_i^k}{\Delta t} = \frac{D_O}{\theta^2} \frac{O_{i+1}^{k+1} - 2O_i^{k+1} + O_{i-1}^{k+1}}{\left(\Delta x\right)^2} - \frac{1 - \varphi}{\varphi} [\gamma_C k_C C_i^{k+1} + \gamma_E k_E E_i^{k+1}] \frac{O_i^{k+1}}{K_O + O_i^k}$$

for the oxygen  $O_2(O's)$ , and

$$\frac{C_i^{k+1} - C_i^k}{\Delta t} = D_B \frac{C_{i+1}^{k+1} - 2C_i^{k+1} + C_{i-1}^{k+1}}{\left(\Delta x\right)^2} + \left(\frac{dD_B}{dx}\Big|_{x_i} - w\right) \left(\frac{C_{i+1}^{k+1} + C_{i-1}^{k+1}}{2\Delta x}\right) - k_C C_i^{k+1} \frac{O_i^{k+1}}{K_O + O_i^k}$$



for the biodegradable natural organic matter  $C_1(C's)$  in the sediment, and

$$\frac{E_i^{k+1} - E_i^k}{\Delta t} = D_B \frac{E_{i+1}^{k+1} - 2E_i^{k+1} + E_{i-1}^{k+1}}{(\Delta x)^2} + \left(\frac{dD_B}{dx}\Big|_{x_i} - w\right) \left(\frac{E_{i+1}^{k+1} + E_{i-1}^{k+1}}{2\Delta x}\right) - k_E E_i^{k+1} \frac{O_i^{k+1}}{K_O + O_i^k}$$

for the biodegradable added organic matter  $C_2(E's)$  to the sediment, and finally

$$\frac{R_i^{k+1} - R_i^k}{\Delta t} = D_B \frac{R_{i+1}^{k+1} - 2R_i^{k+1} + R_{i-1}^{k+1}}{(\Delta x)^2} + \left(\frac{dD_B}{dx}\Big|_{x_i} - w\right) \left(\frac{R_{i+1}^{k+1} + R_{i-1}^{k+1}}{2\Delta x}\right)$$

for the median grain size  $R_{ave}(R's)$  of the new mixed sediment.

The difference equations are implicit of state variables because there are tree unknowns of each variable  $(O_{i+1}^{k+1}, O_i^{k+1}, \text{and } O_{i-1}^{k+1}$  in oxygen equation,  $C_{i+1}^{k+1}, C_i^{k+1}$ , and  $C_{i-1}^{k+1}$  in natural organic matter equation, and the others). A set of algebraic equations for a given variable is generated when the difference equation is applied at each point. The set of equations can be written in a matrix form, which has non-zeros only in three diagonals (therefore it is called tri-diagonal). The method applied to solve such a matrices is a well-known algorithm: Gaussian elimination. This method simultaneously provides all unknowns  $(O_i^{k+1}, i = 1, 2, 3, ..., n$  i.e. the oxygen profile in the sediment,  $C_i^{k+1}, i = 1, 2, 3, ..., n$  i.e. the natural organic matter concentration profile, and the others) for a given system equation.

Since the system equations are coupled and need to be solved simultaneously, they are solved by an iterative algorithm which starts from the profiles in the previous time step (or from the profiles of the initial condition) and calculates the profiles in the new time step by substituting the previous iteration values while checking covergence of state variables.

#### 5.5 Budget equations

In order to ensure that the equations are calculated right, extra integral quantities are included for control purposes. These are calculated in selected horizontal grid points and for each time step. These include the free oxygen influx to the sediment layer and the amount of the total organic matter (both added organic matter and the natural organic matter) that has been biodegraded since the last time step. These two quantities should approximately balance each other during the simulations. The influx of the free oxygen at the sea floor can be approximated from

Influx of free O<sub>2</sub> = 
$$\varphi \frac{D_0}{\theta^2} \frac{\partial O_2}{\partial z}$$
 (5.32)

where the oxygen gradient is estimated at the sediment surface and the influx is given per time step and per unit area of the sediment surface (adjusted for the porosity). In Boudreau (1997, chapter 8.13), these fluxes can be estimated based on the vertical distribution of  $O_2(z)$ . This flux should then equal (approximately) the rate of organic matter biodegraded when the oxygen flux is divided with the Redfield number (close to 3.47).



In the ERMS "Restitution" report (SINTEF, 2006), an application of formula (5.32) has been made on the influx of oxygen measured during testing of biodegradation of chemicals in the laboratory. Details can be found in (SINTEF, 2006).

#### 5.6 A comment on the natural variability of the natural sediment

Natural sediment appears with a large natural variability. A number of external factors impact on the sediment characteristics. Factors that have an influence on the sediment characteristics and can be varied through the model input menus are:

- Water depth and temperature regimes
- Natural deposition rates
- Ocean current regimes
- Seasonal variations of the currents
- Substrate (grain size and porosity)
- Benthic fauna on the site \*\*
- Possible influence due to anthropogenic causes (discharges)

\*\* cannot be varied in the input menu, but the size of the bioturbation coefficient is assumed to be water depth dependent in the model. A separate NFR (that is, The Norwegian Research Council) project is initiated that is aimed at relating the size of the bioturbation coefficient to the actual biota on the site.

As an example, the depth of the bioturbation layer L may vary from order one cm to 20 - 30 cm for marine sediments as a result of such factors. See Figures 5.2 and 5.3 as examples of measured depths of the bioturbation depth L (copied from Boudreau 1997 and 1998).

The model developed as a part of the ERMS project will be able to model such variability by changing values on the parameter input list. However, this model is basically designed to be used for management purposes and not for scientific purposes in particular. Ideally, all the parameters listed above should be made available to model the existing sediment layer properly. This would be the best basis to predict the impact from the discharge on the sea floor.

In practice, the real situation will not be like the ideal one. When a drilling operation is planned, information will basically (or at best) be available from surveys of the sediment collected on the site. Other parameters will have to be estimated or represented as "default" values. Therefore, the model is designed so that impacts can be calculated even though all necessary (or desirable) information is not available. This is achieved by recommending "default" values of the parameters where no information is ordinarily available.

As an example, the default value in the model for the bioturbation depth L is close to 10 cm sediment depth, which turns out to be a reasonable average for the typical bioturbation depths measured. This default value seems to be representative, irrespective of water column depth and size of the natural burial velocity w, see the Figures 5.2 and 5.3. However, the user is free to choose other values for the bioturbation depth parameter L (or for other sediment parameters). Default values are given in the program menus.

Also, it might be an advantage to operate with a common or uniform set of input parameters for the model in order to compare calculated impact factors (EIF's) from different geographical areas as well as different composition of the releases. On the other hand, the sediment parameter variability is indeed large, and it may therefore be that the choice of sediment parameters should



be made more site dependent (as for the selection of median grain size of the sediment on the location).



Figures 5.2 and 5.3.

Upper figure (Figure 5.2) shows the bioturbation depth as a function of the burial velocity w. The figure is copied from Boudreau (1997, chapter 4.2.7). Different symbols represent different tracer techniques used to determine the bioturbation depth.

Lower figure (Figure 5.3) shows the bioturbation depth as a function of the water depth at the location of the sediment. The figure is copied from Boudreau (1998). The dashed line represents a worldwide mean value close to 10 cm.

# **()** SINTEF

## 6 The PEC's and risks calculated for the sediment

This chapter deals with how the deposition and the subsequent concentrations (the PEC's and the Predicted Environmental Changes for the non-toxic stressors) are calculated for the sediment layer. The PEC's, combined with the PNEC's given, form then the basis for calculating the risks associated with the depositions on the sea floor.

### 6.1 The deposition on the sea floor.

As explained in chapter 2, the depositions are caused by different contributions:

- *The cuttings particles* are sinking down in the sea floor in accordance with their sinking velocity (given by their size and density).
- *The particles in the weighting material* (an example is barite) are also assumed to be sinking down on the sea floor in accordance with the sinking velocity of the particles (given by their size and density).
- *The chemicals* in the discharge with log  $P_{ow}$  (or log  $K_{ow}$  or log  $K_{oc}$ ) > 3. These are assumed to deposit on the sea floor, either as "attached" to cuttings particles (or to other particle groups) or as "agglomerates" (that is, particles formed as clusters consisting of the chemicals, the cuttings particles and the particles in the weighting material).

In addition, *the heavy metals in the barite* are assumed to be "attached" to the barite particles and will thus move along with the barite. For the part of the barite that deposits within the model domain, the toxicity of the metals (in the barite) is calculated for the sediment. The toxicity of the metals in the cuttings particles is neglected.

6 metals in the barite are included. These are:

- Cadmium (Cd)
- Chromium (Cr)
- Copper (Cu)
- Lead (Pb)
- Mercury (Hg)
- Zinc (Zn)

Chemicals that typically deposit in the sediment (have logPow coefficient factor > 3, typically) are as given in chapter 2:

- Dope for lubrication of the drill string or casing
- OBM
- Some types of SBM
- Oil attached to cuttings
- Oil based chemicals used for contingency

These are the factors that are presently included in the sediment model for calculation of the impact (and the subsequent recovery time) of the sediment layer.



#### 6.2 Definition of stressors for the sediment layer:

Based on the TNO conceptual report (TNO, 2006a), the following stressors are included for the sediment layer:

- Burial
- Grain size change
- Oxygen depletion
- Toxicity

For the water column, the two stressors chosen (toxicity and particle concentrations) are both three-dimensional, given in units of  $g/m^3$  of water (or mg/L). It would therefore be practical that the stressors for the sediment compartment were defined in a similar manner. This is however not been done. The "burial" parameter is not a three-dimensional parameter, but is simply a "thickness" parameter (with a length dimension), expressing the thickness of the added layer on the top of the original (natural) sediment. This parameter is not three-dimensional, but two-dimensional, expressing the variations of the thickness (deposition) in the two horizontal dimensions (x and y).

Because the burial parameter is two-dimensional (that is, area dependent only), it would be practical that the other three parameters for the sediment stresses be expressed in terms of area dependent (two-dimensional) quantities as well. This can best be achieved by integrating the other three parameters in the vertical, converting the three-dimensional quantities (grain size change, oxygen concentration and sediment concentration) into two-dimensional ones. The following vertical integrations were chosen:

- Grain size change: Average over the upper 3 cm of the sediment layer
- Oxygen depletion: Average over the bioturbation depth (L) of the sediment layer
- Toxicity: Average the concentration over the upper 3 cm of the sediment layer

In this way, the three-dimensional stressors are converted into two-dimensional ones. We arrive in this way with a total of two 3D stressors for the water column and four 2D stressors for the sediment.

The choice of vertical integration interval of 3, L and 3 cm, respectively, may seem somewhat arbitrary. Sediment concentrations are usually measured over the upper 1 or 3 cm of the sediment layer during surveillance. For comparison with field data, the choice of either 1 or 3 cm vertical integration interval would ease the comparison with field data (for verification purposes). The three cm interval was chosen, because the biota is mainly concentrated within this interval. This argument goes for both the toxicity and the change of grain size (introduction of exotic sediment). For the oxygen content, The bioturbation depth L was chosen in order to ensure that it is integrated over mostly all free oxygen content available in the sediment. This gives a better estimate than selecting a 3 cm vertical integration of the free oxygen content. However, the parameters are free to be chosen in the input menu.

The four 2D stressors defined for the sediment can thus be expressed as follows:

*Burial is defined as the total thickness* of the added layer caused by the deposition. This build-up is caused by the particles (grains) in the discharge (cuttings and particles in the weight material). The thickness is calculated from



$$Burial = \frac{1}{1 - \varphi} \sum_{i} \frac{M_i}{\rho_i}$$
(6.1)

where  $\varphi$  is the porosity, M<sub>i</sub> is the mass of particle component *i* deposited pr. m<sup>2</sup> of the sediment area, and  $\rho_i$  is the density of the particles of class *i*. The summation is carried out over all particle classes *i* deposited on the sea floor. As an example of calculation, assume a porosity of 0.6 and a density of cuttings particles equal to 2500 kg/m<sup>3</sup>, then the thickness of 1 kg of cuttings deposited over 1 m<sup>2</sup> will result into a thickness (burial) of about 1 mm. The porosity factor is included because the particles are only occupying a part of the total volume of the sediment.

*Grain size change is defined as the change of the median grain size* in the sediment, averaged over the upper three cm of the sediment layer (including the added sediment). The parameter is defined as (absolute value is used only)

Grain size change = 
$$\frac{1}{3cm} \int_{0}^{3cm} D(z) dz - D_{original}$$
 (6.2)

where D(z) is the median grain size parameter (diameter) after discharge defined as in formula 5.29 in chapter 5.  $D_{original}$  is the median grain size of the natural sediment on the site before the deposition has taken place (constant value). The new grain size parameter after discharge D(z) may have a sediment depth dependency due to effects from bioturbation. This definition secures that the environmental stress imposed by a finer grain size added on top of coarser sediment, will be similar as for the stress imposed by coarser sediment added on top of a finer grain sized sediment.

*The oxygen depletion* parameter is calculated as the reduction of the oxygen content (%) in the sediment layer due to the discharge, integrated over the layer where bioturbation is taking place (that is, the bioturbation depth parameter L, see formula 5.6 in chapter 5). The integrated free oxygen content of the layer has unit g  $O_2$  in pore water/m<sup>2</sup> sediment surface. Generally, the free oxygen content in the layer is close to zero at the sediment depth L. This secures that approximately all the free oxygen in the sediment is included in the oxygen depletion parameter, defined as

$$O_2 \text{ depletion (\%)} = 100 \frac{\int_{0}^{L} \varphi O_2(z) dz}{\int_{0}^{L} \varphi O_2(z) dz}_{before discharg e}$$
(6.3)

where  $O_2(z)$  is the oxygen concentration in the pore water (mg/L or g/m<sup>3</sup>) and  $\varphi$  is the porosity included to account for the fact that only a part of the space (given by the porosity) is occupied by the pore water.

*The concentration* of a chemical in the sediment is specified by averaging the content of chemical over the upper three cm of the sediment layer (including the added layer):

Sediment chemical concentration = 
$$\frac{1}{3cm} \int_{0}^{3cm} C(z) dz$$
 (6.4)



where C(z) is the concentration of the chemical deposited on the sea floor along with the cuttings (or other type) particles. The concentration of the chemical is allowed to have a sediment depth dependency due to the effects from bioturbation (as for the grain size change).

An alternative approach would be to integrate over the upper three cm for all the three stressors in question. This was not chosen because the main biologic activity is concentrated within the upper parts of the sediment, see the shape of the bioturbation function used in the model (formula 5.8 in chapter 5.2, which indicates a very rapid decrease of the bioturbation activity with the sediment depth). However, other formulations or definitions are possible.

All chemicals are assumed to enter the non-dissolved phase, as for the grains and the natural organic matter. The toxicity of the chemicals are calculated based on partitioning (that is, only the part of the chemical that dissolves into the pore water is assumed to be bioavailable and therefore toxic). For HOCNF chemicals, the partition coefficient is assumed to be given by the log  $P_{ow}$  coefficient.

In addition to the chemicals in the sediment, the heavy metals "attached" to the barite particles will also contribute to the toxicity in the sediment. The concentrations from these are calculated in the same way as for the chemicals in the sediment, averaging the content of the metals over the upper three cm of the sediment layer (formula 6.4).

All "agglomerated" particles or chemicals "attached" are assumed to resolve into its separate compounds (chemicals, cuttings, barite) when entering the sediment layer. All "particles" in the sediment layer will undergo the same "fate" once they are deposited on the sea floor, agglomerated or not. This may have some influence on how grain size distributions are determined (either contributing to the distributions as "agglomerated" particles or as individual particles originating from the former agglomerated particles may generally be larger and more difficult to re-suspend, compared to individual particles.

Three of the four stressors defined are non-toxic stressors. These cannot be said to represent "concentrations". The terms PEC and PNEC must therefore be redefined. This is most easily done by rephrasing the PEC as the "*Predicted Environmental Change*" and the PNEC as the "*Predicted No Effect Change*" for the non-toxic stressors.

#### 6.3 Calculation of the PEC's for the sediment layer.

Two of the non-toxic stressors (the grain size change and the oxygen depletion) and the toxicity stressor (the concentrations) are all defined in terms of the vertical variation of the parameters through the sediment layer. The vertical distributions of these stressors must therefore be known.

These vertical distributions are calculated by solving the "diagenetic equations" as explained in chapter 5. The oxygen depletion is calculated by solving the diagenetic formula (5.23) for the oxygen balance. The concentration of the chemical(s) is calculated by solving the "added organic matter" formula (5.25). The change of grain size distribution D(z) is calculated by solving formula (5.26). The free oxygen content in the natural sediment before discharge is calculated by solving the formulas (5.1 and 5.2). Further details on how these parameters are calculated are given in chapter 5.

The median grain size of the natural sediment before discharge  $(D_{\text{original}})$  must however be specified from observations on the drilling site.



#### PEC's for added organic matter to the sediment layer:

The TGD (2003) does not give any formulas on how the chemicals are re-distributed in the sediment. Therefore, the ERMS project has developed a method for calculating time variable PEC's in the sediment for toxic stressors. Once the matter deposited is down on the sea floor, the PEC's in the sediment for chemicals (those with Log  $P_{ow} > 3$ ) are calculated according to the following formulas:

Equation 10. Calculation of local PEC<sub>sediment</sub> for organic chemicals in sediment (ERMS approach): PEC <sub>sediment</sub> = PEC (t =0)<sub>sediment</sub> \* exp (- kt) /BIOTURB in which:  $PEC_{sediment}$  = concentration of chemical in the sediment [mg\*kg<sup>-1</sup>] PEC (t =0)<sub>sediment</sub> = same as above for the initial time step t = 0.

k = biodegradation factor for chemical in the sediment [days<sup>-1</sup>]t = time [days]BIOTURB = dilution factor in the sediment due to effects from bioturbation [-]

The PEC  $(t = 0)_{sediment}$  for organic matter is calculated based on Equation 9 (see chapter 4.2). The k factor in Equation 10 is a biodegradation factor which is not a constant. This factor will vary with the availability of free oxygen in the pore water. If the free oxygen goes to zero, the k factor will go to zero as well. These effects are included in the model simulations through the use of the diagenetic equations, see chapter 5.

Equation 10 describes only the time development of the organic chemical concentration in the sediment. However, the PNEC's for organics in the sediment layer is related to the PNEC concentration level for the dissolved chemical in the pore water and not to the concentration of the chemical in the sediment. The pore water concentration of the organic chemical in the sediment is based on equilibrium partitioning:

Equation 11a. Calculation of local pore water concentration PEC<sub>porewater</sub> for organic chemicals (TGD approach):

PEC porewater = [RHO susp /1000] \* PEC sediment /Kpsusp-water

in which:

PEC  $_{porewater}$  = concentration of chemical in the pore water [mg\*l<sup>-1</sup>] PEC  $_{sediment}$  = concentration of chemical in the sediment [mg\*kg<sup>-1</sup>] RHO  $_{susp-water}$  = bulk density of suspended matter [kg/m<sup>-3</sup>] Kp  $_{susp-water}$  = suspended matter-water partitioning coefficient [m<sup>3</sup>\*m<sup>-3</sup>]

In the Equation 11a above, the Kp <sub>susp water</sub> is given in non-dimensional form  $(m^3*m^{-3})$ . Sometimes, the partition coefficient is given in dimensional form, like L/kg sediment (Di Toro et. al., 1991). The partitioning factor Kp <sub>susp water</sub> should in such a case be written as shown in Equation 11b:



Equation 11b. Calculation of local pore water concentration PEC<sub>porewater</sub> for organic chemicals (TGD approach):

PEC porewater = PEC sediment /Kpsusp-water

in which:

PEC <sub>porewater</sub> = concentration of chemical in the pore water [mg\* $\Gamma^{1}$ ] PEC <sub>sediment</sub> = concentration of chemical in the sediment [mg\*kg<sup>-1</sup>] Kp <sub>susp water</sub> = suspended matter-water partitioning coefficient [I\*kg<sup>-1</sup>]

And the Kp for the sediment is given by

Equation 12. Calculation of Kp sediment of non-ionic organic substances in sediment (TGD approach)

Kp <sub>sediment</sub> =  $F_{oc} * K_{oc}$ 

in which:

 $K_{oc}$  = partition coefficient organic carbon-water [I\*kg-1]  $Kp_{sediment}$  = partition coefficient for the sediment for non-ionic organic substances [I\*kg-1]  $F_{oc}$  = weight fraction of organic carbon in compartment [kg\*kg-1]

The Equations 10, 11b and 12 above explain how the organic chemicals in the discharge that deposit on the sea floor are diluted and biodegraded due to processes in the sediment. It also explains how the concentrations of the chemical in the pore water (PEC <sub>porewater</sub>) are calculated. These formulas are implemented in the revised DREAM model. The following comments can be made to the various factors that determine the PEC's of an organic chemical in the sediment:

 $K_{oc}$  is assumed to correspond to the  $P_{ow}$  coefficient that is given in the HOCNF scheme for non-PLONOR chemicals (Equation 12). *k* in Equation 10 is a biodegradation factor for reduction of the organic matter in the sediment due to biodegradation. This factor is not a constant, but is dependent on the content of oxygen in the sediment. If no free oxygen is available, k will approach to zero. The actual biodegradation is calculated by means of the diagenetic equations, as explained in Chapter 5 in this report. The factor BIOTURB in Equation 10 is a dilution factor caused by spreading of the organic matter down below 3 cm sediment depth due to the effects from the bioturbation.

At present, a default  $F_{oc}$  factor = 0.01 in Equation 12 is used (that is, the natural organic carbon (TOC) in the sediment is assumed to be 1 w% of the total sediment). This choice is corresponding to the number(s) for the content of total organic matter (TOM) typically observed in sediments is in the area of 1 - 10 w%. This percentage number is however typically water depth dependent and is also correlated to grain size. Smaller grain size favors the content of the organic matter. The depth dependency of TOM in the sediment for the Norwegian Continental Shelf is shown in Figure 6.1 (from Akvaplan-niva, 2005). The content of the TOC is usually only a fraction of the TOM, therefore a 1 w% choice for the F<sub>oc</sub> factor is a reasonable one.





TOM vs. depth, stations < 500 m

Figure 6.1. The relation between water depth and the TOM (Total Organic Matter) observed in the sediment on the Norwegian Continental Shelf. From Akvaplan-niva ERMS report No 12 (2005).

#### The PEC in sediment for the heavy metals in the barite

Heavy metals attached to the barite may enter the sediment layer along with the barite particles. These metals may impact on the biota in the sediment layer. In the model, the bioavailable part of the metals is determined through equilibrium partitioning, that is, a part of the metals is assumed to be bioavailable through dissolution of the metal into the pore water. In the following, the metal toxicity in the sediment is accounted for, as presently implemented in the model.

The concentration of barite deposited in the sediment initially during the release ( $PEC_{sediment}$ ) is calculated as explained in chapter 4.2, Equation 9. Once the barite is deposited in the sediment, the PEC's of the metal concentrations in the sediment due to the presence of the barite are calculated according to the following formula:

#### Equation 13. Calculation of local PEC<sub>metal</sub> for barite metals in sediment (ERMS approach):

PEC metal = PEC (t =0)sediment \* FRACTION /BIOTURB

in which:

PEC  $_{metal}$  = concentration of barite metal in the sediment [mg\*kg<sup>-1</sup>] PEC (t =0)<sub>sediment</sub> = concentration of deposited barite in the sediment at t = 0 [mg\*kg<sup>-1</sup>] FRACTION = content of the metal in barite [kg metal \* kg<sup>-1</sup> barite] BIOTURB = dilution factor in the sediment due to effects from bioturbation [-]

The FRACTION parameter is described in chapter 2.4 (Equation 4). The BIOTURB factor is calculated by the model, and represents the downward mixing of the metal in the sediment caused by the moving organisms in the sediment (bioturbation effect). The PEC (t = 0)<sub>sediment</sub> for deposited barite on the sea floor is based on Equation 9 (see chapter 4.2).



Equation 13 only describes the time development of the barite metal concentration in the sediment. However, the PNEC's for metals in the sediment layer is related to the PNEC concentration level for the dissolved metal in the pore water and not to the metal concentration in the sediment. The pore water concentration of the metal in the sediment is based on equilibrium partitioning (Frost et. al., 2006), as described by Equation 14:

Equation 14a. Calculation of local pore water concentration PEC<sub>porewater</sub> for barite metals (ERMS approach):

PEC porewater = [RHO susp /1000] \* PEC metal /Kp metal-porewater

in which:

PEC <sub>porewater</sub> = concentration of dissolved metal in the pore water [mg\* $\Gamma^{1}$ ] PEC <sub>metal</sub> = concentration of metal in the sediment [mg\*kg<sup>-1</sup>] RHO <sub>susp</sub> = bulk density of suspended matter [kg/m<sup>-3</sup>] Kp <sub>metal-porewater</sub> = barite metal-pore water partitioning coefficient [m<sup>3</sup>\*m<sup>-3</sup>]

In the Equation 14a above, the Kp <sub>metal-porewater</sub> is given in non-dimensional form  $(m^{3}*m^{-3})$ . Sometimes, the partition coefficient is given in dimensional form, like L/kg sediment (Di Toro et. al., 1991). The partitioning factor Kp <sub>metal-porewater</sub> should in such a case be written as shown in Equation 14b:

Equation 14b. Calculation of local pore water concentration PEC<sub>porewater</sub> for barite metals (ERMS approach):

PEC porewater = PEC metal /Kp metal-porewater

in which:

PEC <sub>porewater</sub> = concentration of dissolved metal in the pore water [mg\* $\Gamma^1$ ] PEC <sub>metal</sub> = concentration of metal in the sediment [mg\*kg<sup>-1</sup>] Kp <sub>metal-porewater</sub> = barite metal-pore water partitioning coefficient [I\*kg<sup>-1</sup>]

The Equations 13 and 14b above explain how the concentrations of the metals in the barite that deposit on the sea floor are arrived at. It also explains how the concentrations of the metals in the pore water (PEC <sub>porewater</sub>) are calculated. These formulas are presently implemented in the revised DREAM model.

The partitioning coefficient Kp for metals in the sediment is given in the Table 6.1 below (Frost et al., 2006). Note here that the Kp values for partition of metals in the sediment are all different from the Kp values specified for partition of metals in the water column, see chapter 2.4 (Table 2.1). Further details are given in the ERMS toxicity report (Frost et. al., 2006).

The PNEC's for the metals in the pore water is assumed to be equal to the MPA's (MPA = *Maximum Permissible Addition*) for heavy metals in water. The Equation 14b can also be used to relate PNEC's for dissolved heavy metals in pore water to the concentration PNEC for the heavy metals in the sediment. The corresponding MPA's for the heavy metals in the sediment are shown in Table 6.1 as well. Further details are given in the ERMS toxicity report (Frost et. al., 2006).

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Table 6.1. Actual values used for the 6 heavy metals in the sediment originating from barite<br/>implemented in the model. The MPA's for the pore water metal concentrations (MPA<br/>= Maximum Permissible Additions), the partition coefficients used (Kp), the MPA's<br/>for the heavy metals in the sediment, values selected for the background<br/>concentrations of the metals in the sediment ( $Cb_{sediment}$ ) and the MPC values (MPC =<br/>Maximum Permissible Concentrations) for the metals in the sediment are shown.<br/>Background values for metals in sediment ( $Cb_{sediment}$ ) represent mean background<br/>sediment concentrations for the Norwegian Continental Shelf. Further details are<br/>given in Frost et. al. (2006).

Metal	MPA water, ppb	Partition coefficient, log Kp	MPA for sediment, ppm	Background Cb <sub>sediment</sub> , ppm	MPC values for sediment, ppm
Cadmium Cd	0.34	1.46	0.01	0.037	0.047
Mercury (methyl) Hg	0.01	4.79	0.62	0.021	0.638
Lead Pb	11	1.9	0.87	10.7	11.57
Zinc Zn	6.6	1.84	0.46	20.7	21.16
Chromium Cr	8.5	3.24	14.77	14.6	29.37
Copper Cu	1.1	1.64	0.05	4.1	4.148

Note that the revised DREAM model only calculates the MPA values for the sediment (the maximum permissible addition of heavy metals due to the addition of the barite). The MPC values are not calculated by the revised DREAM model. These values are used for comparison with field data. The background values (the  $Cb_{sediment}$  values in Table 6.1) are site specific, and values for these should therefore be established for each region or location in question.

#### 6.4 The calculation of the restitution time of the sediment layer

The diagenetic equations also allow for including the time variations of the stressors defined. This is important, because the time variations form the basis for calculating the restitution time of the sediment layer. The diagenetic equations (as well as the definition of the stressors in chapter 6.2) include the time development of these stressors. The following factors are included in the sediment risk calculations in order to calculate the "restitution time" of the sediment layer, that is, the time needed to bring the EIF of the sediment layer back to "normal" (in terms of a time variable EIF calculated to be either zero or to pass below some prescribed limit).

Some of the factors involved in calculating the restitution time of the sediment (that is, oxygen flux into the sediment layer, the time for re-colonization of an impacted sediment and resuspension of the sediment) are treated in a separate ERMS report (ERMS report No. 21, SINTEF, 2006).

### Time variable burial and grain size change

The burial parameter based on formula (6.1) has no time dependency (except for the case of resuspension, where the mass deposited may be removed). This may not be realistic, because recolonization may lead to establishment of an alternative benthic fauna, favorizing the new sediment deposited ("exotic sediment" or alteration of sediment by the discharge). This new benthic fauna will then start to bioturbate the new sediment layer, bringing up the old sediment back to the surface (in the case that the layer deposited has a thickness lower than the bioturbation depth L). The new layer will thus be mixed into the former sediment layer. The old benthic fauna



may then be re-established, and "regain their territory" on the expense of the opportunistic "guest workers" that came in due to the exotic sediment in the discharge. In order to account for this effect, the burial parameter (thickness) is reduced according to the amount of the old sediment (in %) that has been bioturbated back to the sediment surface. This will allow the burial parameter to be reduced with time.

The change in grain size parameter will also be influenced by the return of the old sediment. However, when the upper 10 cm of the sediment (or so) has been mixed due to the bioturbation, the reduction of the grain size change will cease to occur. In such a case, the grain size change stress may last for a very long time.

In such a case, the following calculation rule has been introduced to reduce the risk contribution from the change of grain size. The rule expresses some kind of "acceptance" of the new community, assuming that the alteration of community represents no "harm" to the environment. In the case that the grid in question is not impacted by any other stress than the burial and the grain size change (that is, all toxicity and oxygen depletion effects have faded out), the grain size change effect (risk) is fading out over a time period of 5 years. The fading effect of the grain size change risk has been implemented according to the following calculation rules:

- The first year: Risk contribution from grain size change is reduced linearly in time from 100 % to 90 % of risk level calculated originally.
- For the three next years, the risk level is reduced linearly from 90 % to 10 % of grain size risk level calculated originally. This will give a 50 % reduction of risk after 2.5 years.
- For the last year (fifth year): Risk contribution from grain size change is reduced linearly in time from 10 % to 0 % of risk level calculated originally.

This calculation rule secures that the risks from grain size change turn to zero after a time period of 5 years when no oxygen depletion and toxicity are present. The method is based on the assumption that no species present that are assumed to be of any particular value (like corals) are influenced by the new community in an unfavourable way.

#### **Bioturbation**

The bioturbation will in general cause a "dilution effect" of the added matter deposited on the sea floor. The bioturbation will cause the chemicals and the barite deposited (included the heavy metals in the barite) to be bioturbated down below the three cm sediment depth level and down to the maximum bioturbation depth L. The time duration of this process will be dependent on the strength of the bioturbation factor  $D_B$  in the diagenetic equations, see chapter 5. The  $D_{Bave}$  factor in formula (5.7) is assumed to be dependent on the natural burial. In addition, the bioturbation coefficient is also assumed to be time dependent, because the deposition itself may reduce the extent of the bioturbation. As an example, the lack of oxygen in the sediment layer may reduce the bioturbation effect down to almost zero. This is accounted for by reducing the bioturbation coefficient  $D_{Bave}$  according to the risks estimated for the sediment layer. The risks are therefore estimated for the oxygen content, burial and the toxicity (the change in grain size risk parameter is not included here because "guest workers" may also cause bioturbation). The bioturbation reduction is assumed proportional to the risks imposed by the three sediment stressors as shown in Table 6.2:

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	Burial	Oxygen	Toxicity of oil
		depletion	in sediment
PNEC level	0.65 cm	20 %	56.4 mg/kg sed.
50 % risk	5.85 cm	60 %	9600 mg/kg sed.
$\mathbf{D}_{\text{Bave}} = 0$	11.05 cm	100 %	19 g/kg sed.

Table 6.2. Reduction of the  $D_{Bave}$  factor (bioturbation) due to various impacts on the sediment layer.

The reduction is carried out such that at the PNEC level, the  $D_{Bave}$  reduction is zero. At the 50 % risk level, the bioturbation is reduced by a factor of two. Based on a linear extrapolation, the bioturbation is turned off in the model (indicating no bioturbation effect) for the values shown in Table 6.5, bottom line.

#### **Biodegradation**

Another factor that may influence on the restitution time is the biodegradation of the chemicals added on the top of the natural sediment layer. The biodegradation will cause a reduction of the toxicity of the sediment layer. On the other hand, the biodegradation consumes oxygen that may cause oxygen depletion in the sediment, which is defined as another sediment stressor. These factors are all included in the model simulation through the use of the diagenetic equations, see chapter 5.

An overview of biodegradation results based on testing of chemicals in the laboratory (Solbergstrand) has been worked out by NIVA (2005). Also, the model has been validated against biodegradation results (that is, by comparing rates of oxygen consumption modeled and measured in the lab) from some of the laboratory results carried out at Solbergstrand. These results are reported in the "restitution" report (ERMS report No. 21, SINTEF, 2006).

#### **Re-colonization**

The typical time needed to re-colonize sediment that has suffered from toxicity or from oxygen depletion are included in the simulations as well. NIVA (2005) has estimated that the time period for this process is typically within three years time, while UKOOA (2003) has estimated a somewhat longer time span, typically 5 years. The difference here may be due to that the UKOOA report also includes successions of different benthic fauna in their considerations. 5 years re-colonization time is presently used in the model calculations (default value), which will be a somewhat conservative estimate. Further details here can also be found in the restitution report (ERMS report No. 21, SINTEF, 2006).

#### **Re-suspension**

Another effect that has been built into the model is the effects from re-suspension. This process will move deposited layers to other positions and thus re-distribute the deposit. The implementation and validation of these routines have been reported separately in the "restitution" report (ERMS report No. 21, SINTEF, 2006).

#### Natural deposition after discharge

After the discharge period is ended, natural deposition will continue to deposit, causing a "natural burial" of the deposit. This effect is also included in the simulations. The effect will cause a "dilution effect" on the added deposition (through the bioturbation activity), but the effect is generally working on a relatively long time scale.



#### 6.5 The definition of the risks and the EIF's for the sediment layer .

Based on the concentrations and the non-toxic stressor values, PNEC and risk functions have been established for the EIF calculations in the sediment layer. PNEC's and risk functions can be established in the same way as for the stressors in the water column. The risk functions for the non-toxic stressors in the sediment are based on SSD (Species Sensitive Distributions), TNO, 2006c). The PNEC for the change in oxygen content is based on (NIVA, 2005), by considering the effect of reduced redox potential (expressed through the Eh parameter for the sediment) on the diversity of the benthic fauna. A linear relationship between oxygen content and the Eh values was anticipated. For the toxicity, the Table 6.2 shows the PNEC value for oil in the sediment, based on data from the MOD database. Further details can be found in the TNO reports (2006a, b and c) and in the toxicity report (Frost et. al., 2006).

PNEC's for toxic substances in the sediment can be established from HOCNF testing of chemicals or similar. Details can be found in the ERMS toxicity report (Frost et. al., 2006). The PNEC concentrations applied in the risk calculations represent averages over the upper three cm of the sediment layer.

The total risk for the sediment is arrived at by adding the % risks calculated (for each time step and for each horizontal grid point) for each of the stressors, in the same way as outlined in chapter 3. See the formulas 3.2 and 3.3. Both toxic and non-toxic stressors are included. There is (in the present application) no weight or discrimination between the contributions from the toxic and non-toxic stressors. If more than one toxicity stressor is included (say, dope and oil in the same release, which have both log P<sub>ow</sub> coefficients larger than 3), the risks from both toxicity stressors are added as well. Also, risks from non-toxic and toxic stressors are added in the model, although there is no scientific foundation for this practice. Output graphics are however developed that separates the toxic risk contributions from the non-toxic contributions (optional).

TNO (2005) also provides risk functions for the dissolved metals in the sediment.

The EIF for the sediment is calculated by summing the risk contributions for all the risks defined for the sediment. If the sum of risks exceeds the 5 % level, then the "PEC/PNEC" level for the sediment is exceeded, and there is a contribution to the EIF for that sediment cell. The EIF unity for the sediment is temporarily chosen to 100m x 100m sediment area, in parallel to the definition of the EIF unity for the water column, which is defined 100m x 100m x 10m. Since the vertical dimension for the risks in the sediment layer is omitted, the definition of the EIF for the sediment layer grid becomes 2D instead of 3D.

#### 6.6 Overview for calculation of the stresses in the sediment.

Chapters 4, 5 and 6 presents the factors involved when the stressors for the sediment are calculated.

The various stressors included are many, and it may therefore be difficult to have a full overview of all of them. Therefore, Table 6.2 has been prepared to have a short overview of the stressors involved.

Note that the non-toxic stressors for the sediment (oxygen depletion, burial and grain size changes) are not included in the Table 6.2. The risk functions and the PNEC's for these are shown in ERMS report No. 9 (TNO, 2006c).



Table 6.2. Overview of the various toxic stressors involved for calculation of PEC's in the sediment layer. The non-toxic stressors for the sediment (oxygen depletion, burial and grain size change) are not included in the Table.

SEDIMENT IMPACT						
	Stressor:	PEC:	PNEC:	Details in:		
Produced	1. Dispersed oil	No impact		See water		
water				column impact		
discharge	2. Natural HC	No impact		See water		
	compounds			column impact		
	3. Heavy metals	No impact		See water		
				column impact		
	4. Added	No impact		See water		
	chemicals			column impact		
Drill	5. Cuttings	Deposits on	Contributes to	See chapter 6.2		
cuttings and		sea floor	non-toxic			
mud			stressors			
discharge	6. Particles in	Deposits on	Contributes to	See chapter 6.2		
	mud	sea floor	non-toxic			
			stressors			
	7. Metals in	Equilibrium	Concentration	See chapter 6.3		
	barite	partitioning	of pore water			
		between pore	fraction based			
		water and solid	on equilibrium			
		metals in barite	partitioning			
	8. Added	No impact		See water		
	chemicals,			column impact		
	Pow < 1000					
	9. Added	Attach to	Concentration	See chapter 6.3		
	chemicals,	particles or	of pore water			
	Pow > 1000	agglomerates,	fraction based			
		equilibrium	on equilibrium			
		partitioning	partitioning			
		between pore				
		water and				
		sediment				
	10. Oil on	Attach to	56.4 mg/kg	See chapter 6.4		
	cuttings	particles or	sediment based			
		agglomerates	on MOD data			

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## 7 Example calculation

### 7.1 Input data

One example calculations is shown in this chapter. The case consists of use of WBM for drilling an exploration well. 5 drilling sections are involved, including also two pilot holes and one P&A operation (P & A = *Plug and Abandonment*). The upper two drilling sections (36" and 26") are discharged directly on the sea floor, while the lower three drilling sections (17  $\frac{1}{2}$ ", 12  $\frac{3}{4}$ " and 8  $\frac{1}{2}$ ") are discharges from the drilling rig.

Grain size distributions for the cuttings and barite particles used in the calculations are shown in Tables 7.1 and 7.2. These particles are distributed on the sea floor and form the basis for calculating the stress caused by the change of grain size on the location. The median diameter of the natural sediment on site is about 0.03 mm.

Table 7.1. Grain size distributions of cuttings particles and their sinking velocities. In the model, a range of grain size is entered for each particle diameter group, so the table is only approximate. Particle sizes are generated randomly within each particle group interval. The sinking velocity is determined from particle diameter and density, see chapter 2.5. Based on Saga (1994).

DRILL CUTTINGS							
Diameter	Diameter Weight		Velocity	Velocity			
Mm	%	SG	m/s	m/day			
0.007	10	2.4	1.9E-05	1.7			
0.015	10	2.4	8.8E-05	7.6			
0.025	10	2.4	2.5E-04	21.2			
0.035	10	2.4	4.8E-04	41.6			
0.05	10	2.4	9.8E-04	84.9			
0.075	10	2.4	2.2E-03	191.0			
0.2	10	2.4	1.6E-02	1356.5			
0.6	10	2.4	5.7E-02	4898.9			
3	10	2.4	2.1E-01	17988.5			
7	10	2.4	3.2E-01	27483.8			

Table 7.2. Grain size distributions of barite particles and their sinking velocities. For details, see the figure text for Table 7.1. Based on Saga (1994).

DRILLING MUD							
Diameter	Weight,	Veight, Density,		Velocity,			
mm	%	tonnes/m3	m/s	m/day			
0.0007	10	4.2	4.4E-07	0.04			
0.001	10	4.2	9.1E-07	0.08			
0.002	10	4.2	3.6E-06	0.31			
0.003	10	4.2	8.2E-06	0.71			
0.005	10	4.2	2.3E-05	1.96			
0.009	10	4.2	7.4E-05	6.35			
0.014	10	4.2	1.8E-04	15.37			
0.018	10	4.2	2.9E-04	25.41			
0.028	10	4.2	7.1E-04	61.49			
0.05	10	4.2	2.3E-03	196.08			



The sediment model has been run for a total duration of 10 years (sediment impact part). Grids for both the water column and the sediment are chosen close to  $50 \times 50 \text{ m}^2$  in the horizontal. For the water column, a 10 m vertical resolution is used.

8 different discharges are defined for the exploration well. Each of these has its own composition of release and duration. In the simulations, only effective drilling is considered. The duration per drilled section is estimated from a penetration rate given by

- 10 m/h for 36" drilling section
- 20 m/h for 26" drilling section
- 25 m/h for 17 1/2" drilling section and smaller

Note that the actual duration of each drilling section in the simulations will be much shorter than the duration of the drilling section experienced in the field. The reason for this is that there is a lot of time needed in addition in between the actual drilling periods. The total duration for effective drilling in the example simulations is estimated to be about 10 days.

The discharge of the lubrication chemicals have been estimated based on consumption of the chemicals estimated per m drilled, both for drill string lubrication and for casing lubrication.

Amounts of chemicals discharged have been estimated for each drilling section. Only non-PLONOR chemicals have been included (in addition to cuttings and barite). These numbers have been recalculated to actual concentrations in the discharges and discharge rates, based on the assumptions accounted for above. The cuttings are assumed discharges along with the chemicals. The results are shown in Table 7.3.



Table 7.3Input data for the example calculation.

Drilling section:		9 7/8 Pilot 1	36"	26"	9 7/8 pilot 2	17 ½"	12 <sup>1</sup> / <sub>4</sub> "	8 <sup>1</sup> / <sub>2</sub> "	P & A
Discharge									
tons/day:		119.92	601.73	575.12	59.11	198.41	178.23	155.38	111.6
<b>Duration hours:</b>		25.84	8.4	28.1	24	11.2	37.6	19.6	24
	Compound	Concentration	Concentration	Concentration	Concentration	Concentration	Concentration	Concentration	Concentration
	in discharge	mg/kg (ppm)	mg/kg (ppm)	mg/kg (ppm)					
	Cuttings	687764.6	683747.6	691445.5	893259.2	544338.5	618867.8	340449.6	0.0
Weight material	Barite	0.0	0.0	0.0	47031.4	222141.9	256525.7	413843.3	819413.5
Viscosifier	Bentonite	18170.0	3846.1	5680.4	0.0	0.0	0.0	0.0	0.0
	Water +								
	PLONOR	294003.9	312401.4	302863.8	51041.0	193089.0	103069.4	226800.9	149467.3
	Bestolife 3010-								
Lubrication	NM	38.5	3.1	6.4	78.1	23.3	25.9	29.7	0.0
Lubrication	OCR 325 AG	23.1	1.8	3.9	46.8	14.0	15.5	17.8	0.0
Drilling fluid	Glydril MC	0.0	0.0	0.0	8543.5	40393.4	21495.6	18858.7	31119.2
Metals attached									
to Barite		Concentration	Concentration	Concentration	Concentration	Concentration	Concentration	Concentration	Concentration
		mg/kg (ppm)	mg/kg (ppm)	mg/kg (ppm)					
	Cadmium Cd	0.00	0.00	0.00	0.08	0.38	0.44	0.70	1.39
	Mercury Hg	0.00	0.00	0.00	0.03	0.15	0.18	0.29	0.57
	Lead Pb	0.00	0.00	0.00	5.49	25.92	29.94	48.30	95.63
	Zinc Zn	0.00	0.00	0.00	6.53	30.86	35.63	57.48	113.82
	Chromium Cr	0.00	0.00	0.00	0.67	3.18	3.67	5.92	11.72
	Copper Cu	0.00	0.00	0.00	4.92	23.26	26.86	43.33	85.79



#### 7.2 Stresses calculated for the sediment.

For the sediment layer, four stresses are calculated: Burial, toxicity, oxygen depletion and change of grain size. The results from the calculation of these are considered in the following.

The results are dependent on the actual PNEC's chosen for the various compounds in the discharge. The PNEC's for the most important contributors (non-toxic stressors only) are:

- Burial: 0.65 cm added thickness
- Oxygen depletion: 20 % reduction of the free oxygen content in the pore water
- Grain size change: 0.0325 mm median diameter change within the upper 3 cm

The sediment build-up is caused by particles depositing on the sea floor. All particle matter from the top hole sections (cuttings, bentonite) is discharged directly on the sea floor (discharge depth is assumed 1 m above sea floor). They will therefore deposit close to the discharge point. In addition, cuttings and barite (basically) will deposit on the sea floor discharged from the rig (discharges from the deeper well sections).

*Stress caused by burial.* Figure 7.1 shows the deposit (in mm thickness) on the sea floor after the completion of all the 8 releases from the various drilling sections.



*Figure 7.1. Deposition of discharge (layer thickness) at the end of the discharge period (at 10 days).* 



With a PNEC for burial equal to 0.65 cm, the stress induced by this deposition is shown in Figure 7.2. It will only be the grid points closest to the discharge point that will be impacted by burial stress:



Figure 7.2. Risks for the sediment layer due to burial at the end of the discharge period (10 days). Grid points are approx. 50 x 50 m.

Note that at the end of the simulation period for the sediment layer (10 years), the risks due to burial have been reduced somewhat. This is shown in Figure 7.3. The reason for this reduction is that bioturbation (that is, mixing of sediment due to the motion of biota in the sediment) will tend to bring the original sediment back to the surface and thus restoring the original sediment somewhat. This has been taken into account in the burial risk calculations.

Figure 7.4 shows the time development of burial risk in one single grid point during the time span of 10 years. Note that the 5 % risk level (corresponding to the PEC/PNEC = 1 level) is crossed during the simulation period, which means that the contribution to the EIF for this particular grid point is removed during the simulation period.





Figure 7.3. Risks for the sediment layer due to burial at the end of the simulation period for the sediment layer (10 years simulation time).



Figure 7.4. The time development of the risk due to burial at a grid point close to the discharge site. Note that the 5 % risk level (corresponds to a risk level equal to PEC/PNEC = 1) is passed after about 1300 days (about 3.5 years).

*Stress caused by toxicity in the sediment.* The chemicals that are brought down into the sediment layer are two "dope" chemicals used for lubrication. These have both logPow values high above



the threshold of value 3 (actual values are close to 6). However, the concentration of these chemicals in the sediment is rather low. They are both well within the toxicity limits (PNEC's) for these chemicals in the sediment layer. Figure 7.5 shows the concentration of the sum of these two chemicals at the end of the discharge period (10 days).



Figure 7.5. Concentration of the "dope" chemicals in the sediment layer at the end of the discharge period (10 days). Max concentration of the "dope" is about 16 ppm (mg/kg sediment)


Both dopes that are used are however biodegradable, so the concentration of these chemicals reduces fast. Figure 7.6 shows the concentration of the "dope" chemicals as a function of time for the grid point with the largest concentration. The chemicals are both biodegraded within one year simulation time.



Figure 7.6. The time development of the "dope" concentration in the sediment layer for the grid with maximum concentration. The concentration is biodegraded down to zero within about 6 - 8 months.



*Stress caused by oxygen depletion in the sediment.* Although the lubrication chemicals did not contribute to risk in terms of toxicity, the biodegradation consumes oxygen in the sediment layer. This consumption may cause a reduction of the oxygen content in the sediment.

The PNEC level for oxygen reduction in the sediment layer is set to 20 % reduction of the sediment content in the layer (in terms of mg  $O_2/m^2$  sediment surface). This level is surpassed in some of the grid points temporarily. Figure 7.7 shows the reduction of the oxygen content in the sediment layer after about 20 days.

Figure 7.8 shows the time development of the oxygen content in the grid point with the maximum concentrations of dope chemicals. The 20 % level of reduction of oxygen content (compared to the oxygen content before discharge) is surpassed in a relatively short time interval (some months) just after the discharge period. After the chemicals have biodegraded, the oxygen level returns to more normal levels.





*Figure 7.7. The oxygen depletion in the sediment layer after about 20 days of simulation time, caused by the degradation of the lubrication chemicals.* 



*Figure 7.8. Oxygen depletion calculated as a function of time for the grid point with the largest concentration of the lubrication chemicals.* 



Figure 7.9. The risks calculated for the oxygen depletion. Maximum risk occurs after about 36 days of simulation time.



Sediment stress caused by changes in median grain size. Natural sediment on the location has been specified to be about 0.03 mm diameter median grain size. The PNEC (= Predicted No Effect *Change* for grain size) is specified to be 0.0325 mm. This means that all sediments with median grain size after discharge larger than (0.0300 mm + 0.0325 mm =) 0.0625 mm will contribute to EIF due to change in grain size.

Figure 7.10 shows the change of grain size in the sediment at the end of the discharge period (after 10 days).

Figures 7.11 and 7.12 show the change of grain size (in terms of environmental risks) at the end of the discharge period (10 days) and at the end of the simulation period (10 years). Note that the risks are reduced somewhat at the end of the simulation period. The reason for this is the effects of the bioturbation, bringing the original sediment back to the sea floor. Thus, the median grain size stress is reduced somewhat towards the end of the simulation period (sediment layer tends to be re-colonized by the original habitat).



Figure 7.10. Change of grain size in the sediment at the end of the discharge period. The median grain size is averaged over the upper 3 cm of the sediment layer. The PNEC level for the grain size change is close to 100 % (that is, a doubling of the median grain size compared to the median diameter of the natural grain size).

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*Figure 7.11.* Environmental risk due to change in grain size at the end of the discharge period. The case is the same as shown in Figure 7.10.



*Figure 7.12.* Environmental risk due to change in grain size at the end of the simulation period (10 years). The risks are reduced somewhat due to the effects from bioturbation.



Figure 7.13 shows one example (one grid point) of the time development of the grain size change for the upper three cm of the sediment layer. As for burial, the risks due to the change of the median grain size for the upper 3 cm of the sediment layer is reduced somewhat over time due to the return of the original sediment present below 3 cm sediment depth. This return of the original sediment is caused by the bioturbation.



Figure 7.13. Time series for change of grain size for one selected grid point. The reduction of the grain size change is due to effects from bioturbation. The grid point chosen is one of the grids that changes from "red" in Figure 7.11 to "yellow" in Figure 7.12 during the simulation time (10 years). The PNEC level is located close to 100 % change for the present case.

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### 7.3 Risk calculations for the water column

The risk calculations for the example case in the water column are presented in this chapter.

Four figures are shown. These are

- Concentration field for the case with maximum EIF calculated
- Corresponding risk field for the maximum EIF case
- Time development of the EIF and the corresponding risk contributions
- Pie chart for the over-all EIF calculations.

The results are shown in the Figures 7.14 - 7.17 to follow.



*Figure7.14. Concentration field for the case with maximum EIF calculated in the water column. Vertical cross section is inserted.* 





Figure 7.15. Corresponding risk field for the maximum EIF case in the water column as shown in Figure 7.14. Vertical cross section is inserted.



#### Time development chart



Figure 7.16. Time development of the EIF and the corresponding risk contributions in the water column. Only barite (particle stress) and the drilling chemical (chemical stress) contribute to the risks.

Weighted contribution to risk, EIF = 20



Figure 7.17. Pie chart showing the contribution from the compounds to EIF in the water column. Release amounts and concentrations for the compounds for each drilling section are listed in Table 7.3.



### 7.4 Risk calculations for the sediment

The risk calculations for the example case in the sediment are presented in this chapter.

Four figures are shown. These are

- Deposition in the sediment for the discharge
- Risk field for the maximum EIF case
- Time development of the EIF and the corresponding risk contributions
- Pie chart for the over-all EIF calculations.

The results are shown in the Figures 7.18 - 7.21 to follow.



*Figure7.18. Deposited mass on the sea floor.* 





Figure 7.19. Risk field in the sediment for the maximum EIF case.



Figure 7.20. Time development of the EIF and the corresponding risk contributions for the sediment. Only change in grain size, oxygen depletion and burial (thickness) are contributing to the risk in the sediment layer.





Figure 7.21. Pie chart showing the contribution from the risk stressors to EIF in sediment. Release amounts and concentrations for the compounds for each drilling section are listed in Table 7.3

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