The use of the diagenetic equations to predict impact on sediment due to discharges of drill cuttings and mud.

by

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1. Summary

When drilling operations are carried out offshore, debris from the drilling process is discharged to the sea. Parts of the discharge (particle matter and chemicals that are attached to the particles) will end up on the sea floor and thus impact on the sediment. A numerical model has been developed that is able to describe the environmental impact caused by the debris on the sea floor.

A bottom sediment module has been developed as a part of a more comprehensive model that is able to simulate the fate and associated environmental risks caused by the discharge of drill cuttings and mud both for the water column and the sediment. The deposit may cause different types of impact: The coverage of the debris on the sea floor may cause *burial* effects. 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 depositing particles (cuttings, barite, ..) may cause *oxygen depletion* in the sediment layer.

The sediment impact model developed is able to describe the features listed above. The paper explains the method applied to describe the impact (by use of "diagenetic equations" for the sediment) and the associated environmental risks. An example calculation is also included.

The method presented in this paper is developed as a part of the ERMS (= *Environmental Risk Management System*) project. This project is aimed at developing tools for reducing environmental impacts caused by discharges to sea from offshore activities in a cost effective manner. Details of the model presented here are extracted from the ERMS project report No. 18 on the model documentation (SINTEF 2006a).

2. Introduction

The offshore operators request numerical models for predicting environmental impacts in the sediment caused by drilling discharges. Numerical models to describe the fate of chemicals and particles discharged to the sea during drilling operations offshore have been developed and applied earlier. Recent model developments have focused on the calculations of the actual deposits, without considering the actual processes taking place in the sediment layer. Examples of such models are the OOC (= *Offshore Operators Committee*) model (Brandsma and Smith 1999, Brandsma 2001) and the *ParTrack* model (Rye et. al., 1998, 2004 and 2006).

A more recent model development has attempted to simulate the actual processes in the sediment caused by drilling discharges, namely the *BMT* (= *British Maritime Technology*) model developed as a part of the *UKOOA (= United Kingdom Offshore Operators Association)* Drill Cuttings Initiative (Sabeur et al., 2002). They tried to model processes in the sediment by means of the "diagenetic equations". The model was able to calculate the concentration of a contaminant (oil) within a pile, rate of losses of oil from the pile and effects caused by re-suspension (or removal) of matter from the pile caused by wave and current action. The model also includes an eco-toxicological risk assessment approach applied to the presence of oil (concentrations) in the cuttings pile. The model was applied to study the evolution of cuttings piles, both natural and man-made disturbances (that is, alternatives for remediation) for some of the cuttings piles in the North Sea.

In the present model development, a numerical model called DREAM (= *Dose related Risk and Effect Assessment Model*) was used as a starting point. The model concept applied in DREAM is a "particle" (or Lagrangian) approach. The model generates particles at the discharge point, which are 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. The formulas applied for spreading in the water column are given in Reed and Hetland (2002).

The ocean current field applied in the DREAM model is usually imported from outputs generated from three-dimensional (3D) and time variable hydrodynamic models. It is also possible to apply observed ocean current profiles generated from measurements at the drilling location.

The numerical model DREAM has been developed further to include impacts on sediment layer caused by discharges of drill cuttings and mud. The modeling of the discharges comprises the fates of the cuttings, particles in mud (barite, bentonite, other..) and non-particulate chemicals in the mud.

Both Water Based mud (WBM), Synthetic Based Mud (SBM) and Oil Based Mud (OBM) can be included. The DREAM model calculates fully three-dimensional and time variable concentration in the recipient caused by the discharges. The model calculates for all compounds that are assumed to represent a potential for harmful impact on the biota. It calculates the fate in the recipient of each compound considered under the influence of currents (tidal, residual, meteorological forcing),

turbulent mixing (horizontal and vertical), evaporation at the sea surface and reduction of concentration due to biodegradation

The DREAM model was also extended to include a near field plume for the discharge. Discharges of drill cuttings and mud have densities that are significantly heavier than the ambient water. The discharge will therefore sink down. 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. The near field plume model developed is a multi-purpose near field model, covering produced water discharges (including gas bubbles in the discharge), discharges of drill cuttings and mud (including mineral particles in the discharge) and also discharges caused by underwater blowouts (including gas bubbles and oil droplets). The principal features of the near field plume model are given in Johansen (2000), while the more specific features related to discharges of drill cuttings and mud discharges are given in Johansen (2006).

Figure 2.1 shows a vertical cross section of an underwater plume on the downstream side of the release calculated with the revised DREAM model. The discharge point is located to the left upper corner in the figure. The "depth of trapping" in the case shown in Figure 2.1 indicates that this appears at about 20 m depth (discharge depth is about 5 m). At this depth, the discharge separates into two parts:

- One part appears to spread horizontally at the depth of trapping. This part consists of dissolved compounds (not sinking) and of solid particles 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).
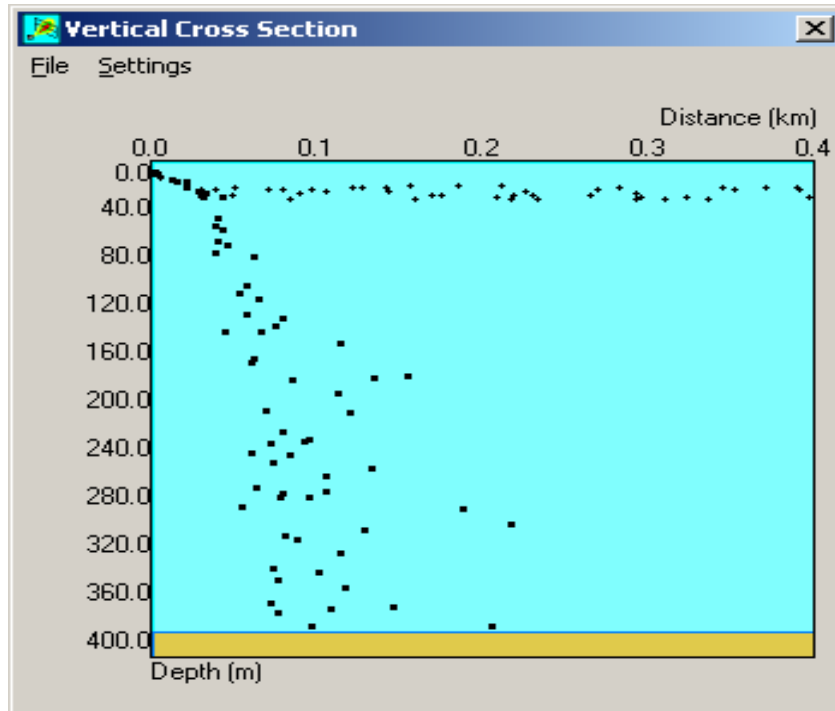
Figure 2.1. Vertical cross section of the near field plume and the deposition of particles on the sea floor. Example calculation. Discharge point to the upper left corner of the figure. Sea floor close to 400 m depth.

The model includes particles that 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). The inclusion of a three-dimensional (3D) and time variable ocean current field will cause a spread of the discharge in the water column. This spread is resulting into a deposition that is varying with the horizontal co-ordinates x and y. The DREAM model generates a grid on the sea floor, with a water depth associated with each cell. Each of the grid cells distributed on the sea floor then contains the amount of drill cuttings and mud (particles, chemicals) deposited on the sea floor within that cell.

Figure 2.2 shows one example of deposition particles and chemicals on the sea floor, calculated with the DREAM model. This deposition is the starting point for the calculation of the impact on the sediment caused by the discharges.

Four "stressors" have been defined for the impact on the sediment layer (TNO, 2006):

- *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 (averaged over the upper 3 cm of the sediment layer). These chemicals may however bioturbate into the original sediment layer, causing a mixing between the new and the old sediment.

- *The free oxygen depletion* is determined from simulating the vertical profile of the free pore water oxygen, both before and after the discharge has taken place. The actual reduction (depletion) of the free oxygen content in the pore water is calculated by taking the difference between the new oxygen content in the pore water after discharge and the oxygen content before discharge.

- *The change of grain size* (introduction of "exotic" sediment). 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 time varying distribution of the median grain size in the vertical within the sediment.
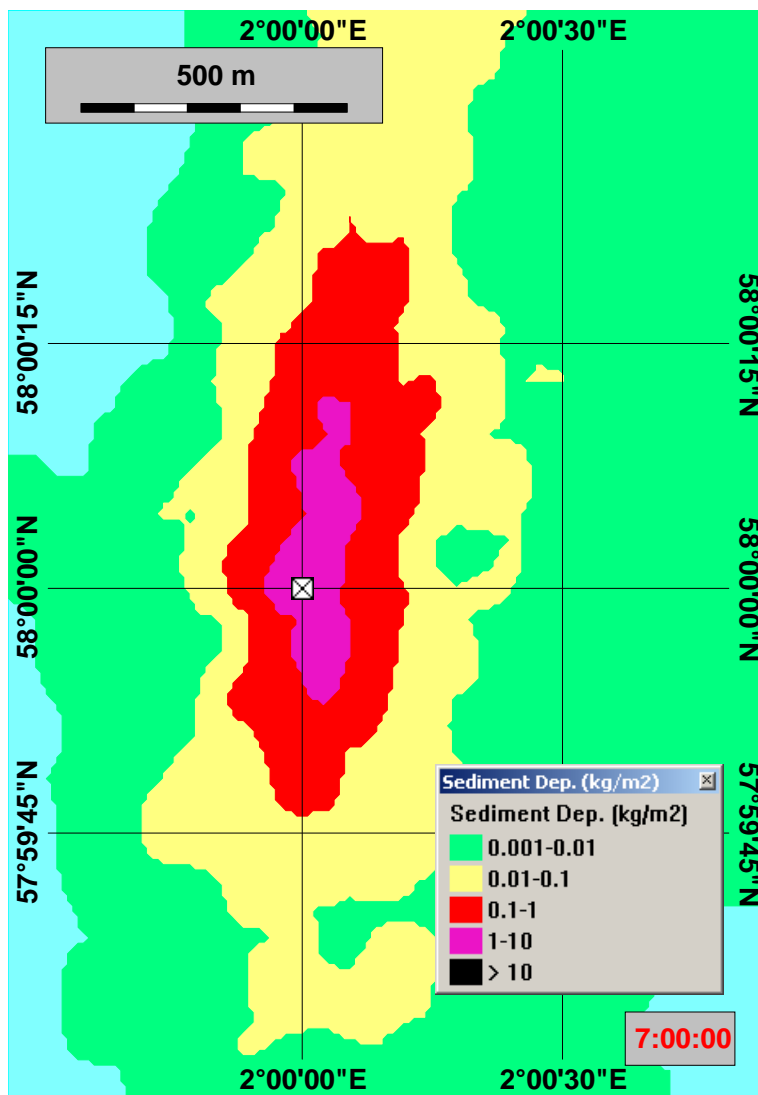

Figure 2.2. Example calculation of the deposition on the sea floor, caused by a discharge of drill cuttings and mud from a drilling rig.

For modeling the processes in the sediment, an Eulerian (non-particle) approach was chosen. That is, once the particles and chemicals are deposited on the sea floor, the fates of deposited matter are modeled in a vertical grid (with the use of the "diagenetic equations"). These equations make it possible to describe the fates of the depositions in the sediment (oxygen and chemical concentrations as well as median grain size) in the vertical (z- direction) for each grid cell defined on the sea floor (x- and y- directions). Thus, a three-dimensional and time variable description of the fates of the discharges in the sediment can be modeled.

3. Natural bottom sediment characterization before discharge

One of the stressors defined involves the *change* of oxygen content in the sediment layer due to the discharge. The content of the oxygen in the sediment layer both before and after the discharge needs therefore to be calculated.

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).

The natural 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 (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):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(D \ \frac{\partial C}{\partial z}\right) - K_C \ C + Q_C \qquad\qquad (3.1)$$

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 cell in the x- and y- directions.

These types of equations have been used to calculate the oxygen balance in the sediment layer before the discharge. The actual equations used are:

$$\frac{\partial O_2}{\partial t} = \frac{D_0}{\theta^2}\frac{\partial^2 O_2}{\partial z^2} - \frac{1-\varphi}{\varphi}[\gamma_1 k_1 C_1]\frac{O_2}{K_{O2}+O_2} \qquad (3.2)$$

for the free oxygen O_2 in the pore water, and

$$\frac{\partial C_1}{\partial t} = \frac{\partial}{\partial z}\left(D_B\frac{\partial C_1}{\partial z} - wC_1\right) - [k_1 C_1]\frac{O_2}{K_{O2}+O_2} \qquad (3.3)$$

for the biodegradable natural organic matter C_1 in the sediment.

The symbols are:

∂ = the partial derivative symbol
t = time dimension
z = the vertical dimension
O_2 (z, t) = the free oxygen pore water concentration
C_1 (z,) = concentration of biodegradable organic matter in the sediment
D_0 = diffusion coefficient for oxygen in pore water
θ = tortuosity of the sediment
D_B (z, t) = bioturbation coefficient
φ = porosity of the sediment
w = burial velocity from natural sediment deposition
γ_1 = Redfield number, combined with mol weights of C_1 and O_2
k_1 = biodegradation (respiration) rate of natural organic matter
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 ($\partial/\partial t = 0$). This is obtained by equating both left-hand sides of the equations to 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 φ 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 (3.3) 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 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 θ^2. The tortuosity is often related to the porosity φ by means of an empirical relationship. Boudreau (1997, chapter 4.2.5) reviews these, and recommends the following relationship:

$$\theta^2 = 1 - \ln(\varphi^2) \hspace{4cm} (3.4)$$

This relationship has been used in the present model. This also means that if constant porosity is assumed, constant tortuosity results as well. As an example, for a porosity φ chosen equal to 0.6, tortuosity squared θ^2 will be calculated by relation (3.4) to be close to 2.

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

$$D_0 = (0.2604 + 0.006383*(T/\mu))*10^{-5} \hspace{2cm} (3.5)$$

where T is the absolute temperature in the pore water and μ is the dynamic viscosity of water given in centipoise. D_0 is given here in $cm^2\ s^{-1}$. μ is approximated by

$$\mu = 1.7910 - 0.06144*temp + 0.001451*temp^2 \hspace{2cm} (3.6)$$

where "temp" is the temperature in ^oC in the pore water and μ is given in centipoise ($10^{-2}\ g\ cm^{-1}\ s^{-1}$). 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 at the sea floor.

The natural burial velocity w

The natural burial velocity *w* 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 following relations are used (Akvaplan-niva, 2005):

$$w = 3.5/H; \qquad H > 35 \text{ m depth} \qquad\qquad (3.7)$$

$$w = 0.1 \text{ cm/year}; \qquad H < 35 \text{ m depth} \qquad\qquad (3.8)$$

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 bioturbation coefficient D_B

The bioturbation coefficient D_B 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 for the sediment depth dependency (Boudreau, 1998):

$$D_B(z) = 3 D_{Bave} \left(1 - \frac{z}{L} \right)^2 \qquad\qquad (3.9)$$

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. 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).

The average bioturbation coefficient D_{Bave} has been found by Boudreau (1997, chapter 4.2.7) to be related to the burial factor w:

$$D_{Bave} = 15.7 \, w^{0.6} \qquad\qquad (3.10)$$

where w is natural burial given in cm per year and D_{Bave} in cm^2 per year. Since the burial is water depth dependent (see the equations 3.7 and 3.8), the average bioturbation coefficient will generally decrease with the water depth.

γ_1 = Redfield number

This factor is to be included because 32 grams of O_2 reacts with 12 grams of C to form CO_2. 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 γ_1 factor to be equal to $(138/106)*(32/12) = 3.47$, approximately. The complete equation formulations (*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:

$$k_1 = 3.0w^{0.6} + 0.4w^{0.6} \tag{3.11}$$

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 (3.2 – 3.3) includes the oxygen concentration in both the nominator and in the denominator. Based on a recommendation by Prof. Bernard Boudreau (Boudreau, 2004), so-called *Monod kinetics* were adapted to deal with the biodegradation term in the organic matter formula (3.3).

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 in the simulations.

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

$$\left(\frac{\partial C}{\partial t}\right)_{reaction} = -kC\frac{O_2}{K_{O2}+O_2} \tag{3.12}$$

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 $O_2 \gg K_{O2}$, and it is first order in O_2 when $O_2 \ll K_{O2}$ (Boudreau 1997, chapter 4.4.2).

The value of the K_{O2} 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 equations to pass below zero oxygen content (Boudreau, 2004).

Boundary and initial conditions

The differential formulas 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 will be a representative value of the oxygen concentration just above the sea floor. At the lower end of the sediment modeled, an oxygen concentration close to zero can be used.

4. The diagenetic equations for modeling the impacts caused by deposition of the discharge on the sea floor.

The DREAM model calculates the deposition on the sea floor as a function of time and the horizontal coordinates x and y, as explained in Chapter 2. A layer on the sea floor is then established, containing particles (cuttings, weighting material like barite etc.) and chemicals attached to the particles (like OBM or SBM). Also, metals in barite may be included.

The deposition on the sea floor requires a new setup of the diagenetic equations in order to describe the impacts from the discharges. The diagenetic equations to be used during and after the discharge will therefore be different from the ones used to simulate the present state of the sediment before the discharge (see equations 3.2 and 3.3). 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). See illustration in Figure 2.3.

- 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 sediment layer after the added deposition. 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.

The equations are written as:

$$\frac{\partial O_2}{\partial t} = \frac{D_0}{\theta^2}\frac{\partial^2 O_2}{\partial z^2} \;-\; \frac{1-\varphi}{\varphi}\,[\gamma_1 k_1 C_1 + \gamma_2 k_2 C_2]\frac{O_2}{K_{O2} + O_2} \qquad (4.1)$$

for the free pore water oxygen content O_2, and

$$\frac{\partial C_1}{\partial t} = \frac{\partial}{\partial z}\left(D_B\frac{\partial C_1}{\partial z} - wC_1\right) - \left[k_1 C_1\right]\frac{O_2}{K_{O2} + O_2} \qquad (4.2)$$

for the biodegradable natural organic matter C_1 in the sediment, and

$$\frac{\partial C_2}{\partial t} = \frac{\partial}{\partial z}\left(D_B\frac{\partial C_2}{\partial z} - wC_2\right) - \left[k_2 C_2\right]\frac{O_2}{K_{O2} + O_2} \qquad (4.3)$$

for the biodegradable added organic matter C_2 to the sediment, and finally

$$\frac{\partial R_{ave}}{\partial t} = \frac{\partial}{\partial z}\left(D_B\frac{\partial R_{ave}}{\partial z} - wR_{ave}\right) \qquad (4.4)$$

for the median grain size R_{ave} of the new mixed sediment.

The symbols used are the same as for the formulas (3.2) – (3.3) in Chapter 3. The additional symbols are:

C_2 (z, t) = added biodegradable organic matter in the sediment, kg/m^3
γ_2 = Redfield number for added organic matter – O_2 reaction
k_2 = biodegradation (respiration) rate of added organic matter
R_{ave} (z, t)= median grain size of the impacted sediment

The first three formulas 4.1 – 4.3 are coupled, and must be solved simultaneously. The free oxygen concentrations in the pore water are involved in three of the equations (4.1 – 4.3), 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 (4.1 – 4.4).

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 (4.3) 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 also form "agglomerated" particles in the discharge. 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 (4.3) for C_2.

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

$$C_2 = \sum_i C_i \qquad\qquad (4.5)$$

and the term in the bracket to the right in formula (4.3) is defined:

$$k_2 C_2 = \sum_i \left(k_i C_i \right) \qquad\qquad (4.6)$$

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

The average Redfield number for the added organic matter compounds is denoted γ_2 in the free pore water oxygen formula (4.1).

The formula (4.4) for the median diameter particle change:

This equation is new. It can be 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 (4.4) 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 (4.4) 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 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 (4.4) 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

$$\sum_i (Vol_i \, R_i) = R_{ave} \sum_i Vol_i \qquad\qquad (4.7)$$

where Vol_i is 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 (4.7) as well. However, for the natural sediment, only median particle size is used, which then has to be specified separately.

γ_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_1 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 γ_2 in the free oxygen formula (4.1) is assumed to be equal to γ_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 (4.3) 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) summarize 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 (2006b).

Boundary and initial conditions

Boundary conditions for the oxygen formula (4.1) 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 added carbon is expressed as adding new layers with discharged particles deposited and new carbon to the original sediment layer.

For initial conditions, the calculated distributions of $O_2(z)$ and $C_1(z)$ generated prior to the discharge are used for the formulas (4.1) and (4.2). 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. Numerical methods applied for solution of the differential equations

The system equations (Eq'ns 4.1 – 4.4 and also Eq'ns 3.2 – 3.3) cannot be solved analytically because they are non-linear with respect to the state variables (O_2, C_1, C_2, and R_{ave}) and the parameters (D_O, D_B, γ'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 this advection-diffusion problem must be solved by an approximate technique.

A finite difference method is used to discretize the system of equations. The method applied utilizes an implicit/central differencing. The problem domain $x = [0, L]$ is divided into N elements (N+1 points). A finite difference approximation of the system equations (Eq'ns 4.1 – 4.4 and also Eq'ns 3.2 – 3.3) are worked out based on an implicit/central difference scheme.

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 convergence of state variables.

6. An example calculation.

Input data for the simulations.

One example calculation has been carried out to illustrate the results that this sediment model is able to produce. 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 ½", 12 ¾" and 8 ½") are discharged from the drilling rig.

Grain size distributions for the cuttings and barite particles used in the calculations are shown in Tables 6.1 and 6.2. The fate of these particles are calculated by the DREAM model to essentially end up on the sea floor (particle size dependent). This distribution of deposited matter forms 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 assumed to be 0.03 mm.

Table 6.1. Grain size distributions of cuttings particles and their sinking velocities. The sinking velocity is determined from particle diameter and density. Based on Saga (1994).

DRILL CUTTINGS				
Diameter, mm	Weight, %	Density, Tonnes/m^3	Velocity, m/s	Velocity, 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 6.2.   Grain size distributions of barite particles and their sinking velocities. The sinking velocity is determined from particle diameter and density. Based on Saga (1994).

DRILLING BARITE				
Diameter, mm	Weight, %	Density, tonnes/m^3	Velocity, m/s	Velocity, 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

8 different discharges are defined for the exploration well. Each of these has its own composition of release and duration. The discharges comprise cuttings, barite and bentonite for the particle groups and lubrication for the drill string and the drilling chemical *Glydrill MC* for the chemicals. In addition, PLONOR (= *Pose Little Or NO Risk* to the environment) chemicals and water were present in the discharges. The lubrication chemicals were assumed to be "attached" to the cuttings particles. Therefore, they followed the cuttings particles down on the sea floor in the simulations. The discharge of the lubrication chemicals was estimated based on consumption of the chemicals per m well drilled, both for drill string lubrication and for casing lubrication.

The discharge period is lasting for about 10 days in this example simulation. This time span is generally shorter than the time used when drilling an exploration well. In the simulations, only "effective" drilling time is included, that is, when drilling is actually taking place. This drilling time is calculated from a drilling penetration rate downwards of order 10 – 25 m/hour for typical well sections. The penetration rate is somewhat dependent on the diameter of the well section drilled.

The sediment model is run for 10 years, because sediment processes are generally much slower than the time scale of the actual deposition on the sea floor.

Stresses calculated for the sediment.

The four stressors for the sediment layer listed in chapter 2 were calculated: Burial, toxicity, oxygen depletion and change of grain size. The results from the calculation of these are considered in the following.

The stresses in the sediment layer are calculated based on a PEC/PNEC approach. This is according to the principles outlined in the EU *Technical Guidance Document* (EU, 1996). The PEC is the *Predicted Environmental Concentration* (calculated with the DREAM model), while PNEC is the *Predicted No Effect Concentration* (or *Predicted No Effect Change*). The PNEC expresses the lower limit where effects on the marine biota in the sediment may be encountered. The PNEC level for toxic compounds is derived from laboratory testing of toxicity for each component (or chemical product) in question. The PNEC value is derived from EC50, LC50 or NOEC values from laboratory testing, where the EC50, LC50 or the NOEC value determined is divided by an "assessment factor" in order to arrive at the PNEC to be used. The PNEC values for the sediment are also dependent on the partitioning of the chemical between the pore water and the sediment. Concentrations are averaged over the upper 3 cm of the sediment layer. Details can be found in SINTEF (2006a).

The PNEC's for the non-toxic stressors in the sediment are:

- *Burial*: 0.65 cm added thickness
- *Oxygen depletion*: 20 % reduction of the free oxygen content in the pore water
- *Grain size change*: 0.0527 mm median diameter change within the upper 3 cm

Stress caused by burial. Figure 6.1 shows the deposit (in mm thickness) on the sea floor after the completion of all the 8 releases from the various drilling sections.

Figure 6.2 shows the grids that are exceeded by the PNEC limit of 0.65 cm added thickness. It will only be the grid points with the red color (closest to the discharge point) that will be impacted by burial stress.
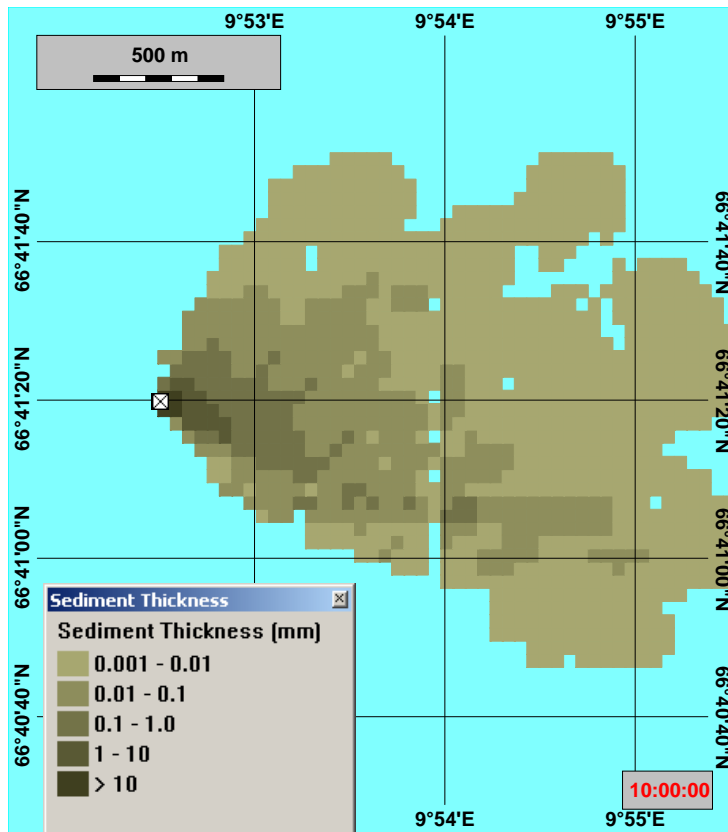
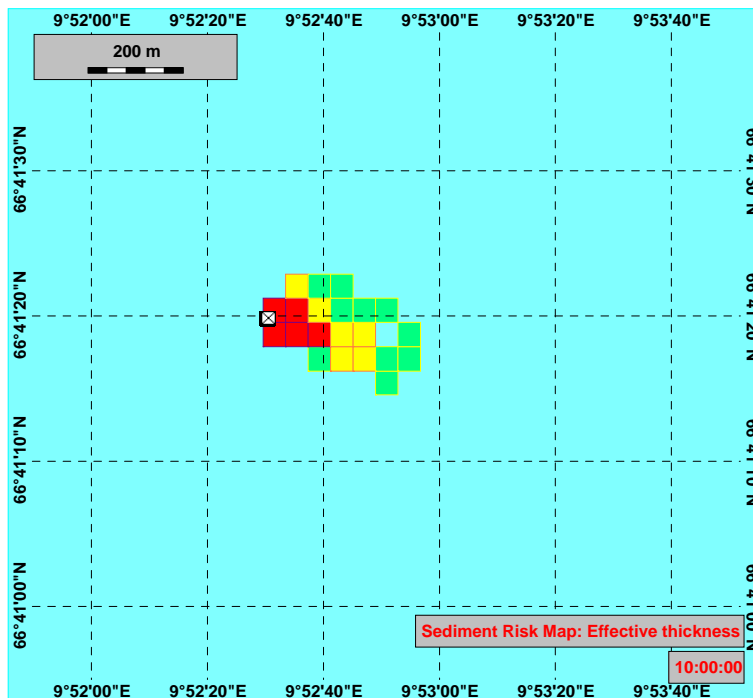*Figure 6.1. Deposition of discharge (layer thickness) at the end of the discharge period (after 10 days).*

Figure 6.2. Grids that are exceeding the PNEC level for burial at the end of the discharge period (red color). Grid points are approx. 50 x 50 m.

Stress caused by toxicity in the sediment. The chemicals that are brought down into the sediment layer are two "dope" chemicals used for lubrication. However, the concentration of these chemicals in the sediment is rather low (average over the upper 3 cm of the sediment layer). They are both well within the toxicity limits (PNEC's) for these chemicals in the sediment layer. Figure 6.3 shows the concentration of the sum of these two chemicals at the end of the discharge period.

Both lubrication chemicals that are used are however biodegradable, so the concentration of these chemicals reduces fast with time. Figure 6.4 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.
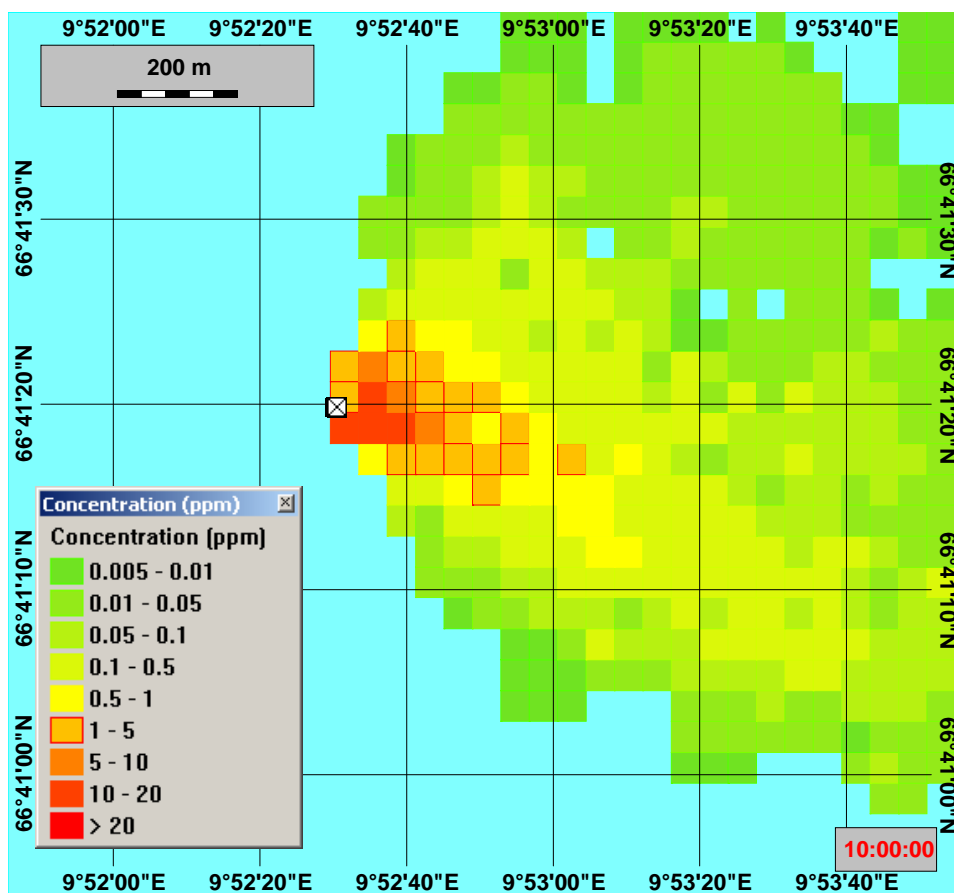
Figure 6.3. Concentration of the "dope" chemicals in the sediment layer at the end of the discharge period (10 days). Max concentration of the "dope" is about 16 ppm (mg/kg sediment)
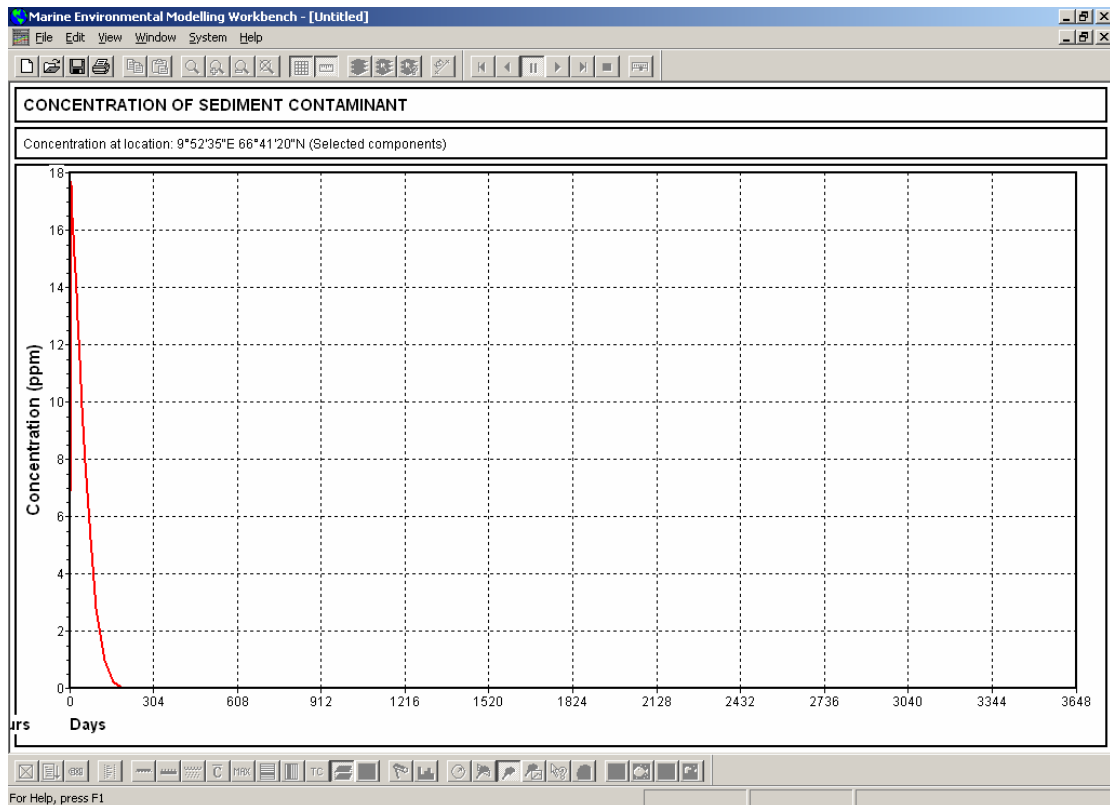
Figure 6.4. The time development of the "dope" concentration in the sediment layer for the grid with maximum concentration. Horizontal time scale in days. The concentration is biodegraded down to zero within about 6 - 8 months.

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 pore water oxygen 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 6.5 shows the reduction of the oxygen content in the sediment layer after about 20 days.

Figure 6.6 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 has ended. After the chemicals have biodegraded, the oxygen level returns to more normal levels.
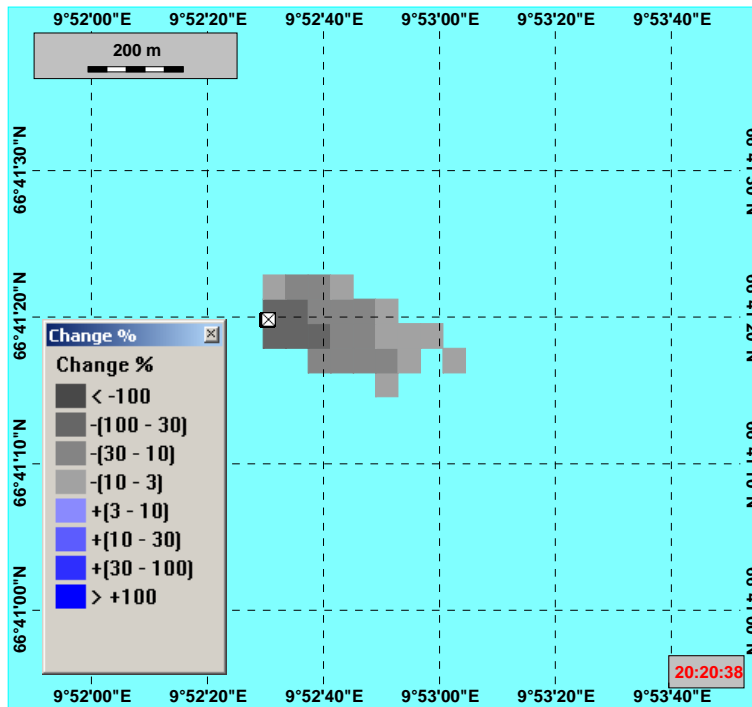
Figure 6.5. The oxygen depletion in the sediment layer after about 20 days of simulation time, caused by the degradation of the lubrication chemicals.
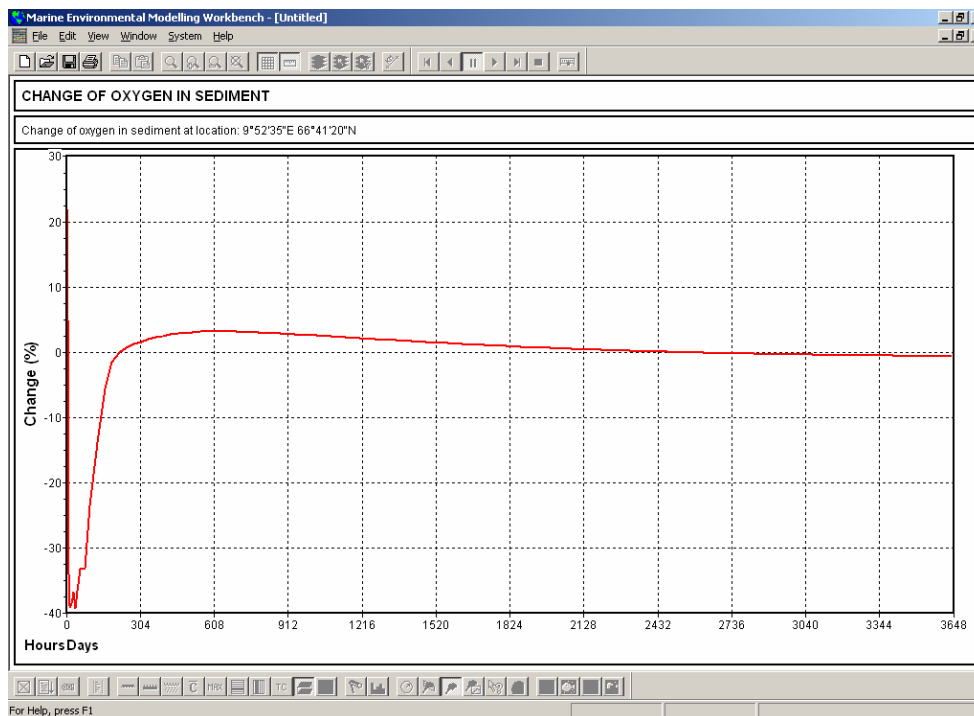

Figure 6.6. Oxygen depletion calculated as a function of time for the grid point with the largest concentration of the lubrication chemicals. Horizontal scale in days. The PNEC level of 20 % reduction of the oxygen content in the sediment layer is surpassed in a short time period (some months) in the beginning of the sediment impact simulation period.

Sediment stress caused by changes in median grain size. Natural sediment on the actual location has been specified to be about 0.03 mm diameter median grain size. The cuttings in particular have larger grain sizes (See Table 6.1) than the natural sediment on this site. Therefore, the median grain size for some grids will change due to the deposition of the cuttings particles. Figure 6.7 shows the change of grain size in the sediment at the end of the discharge period (after 10 days).

Figure 6.8 shows one example (one grid point) of the time development of the grain size change for the upper 3 cm of the sediment layer. 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. The reason for this is the effects of the bioturbation, bringing the original sediment back to the sea floor.
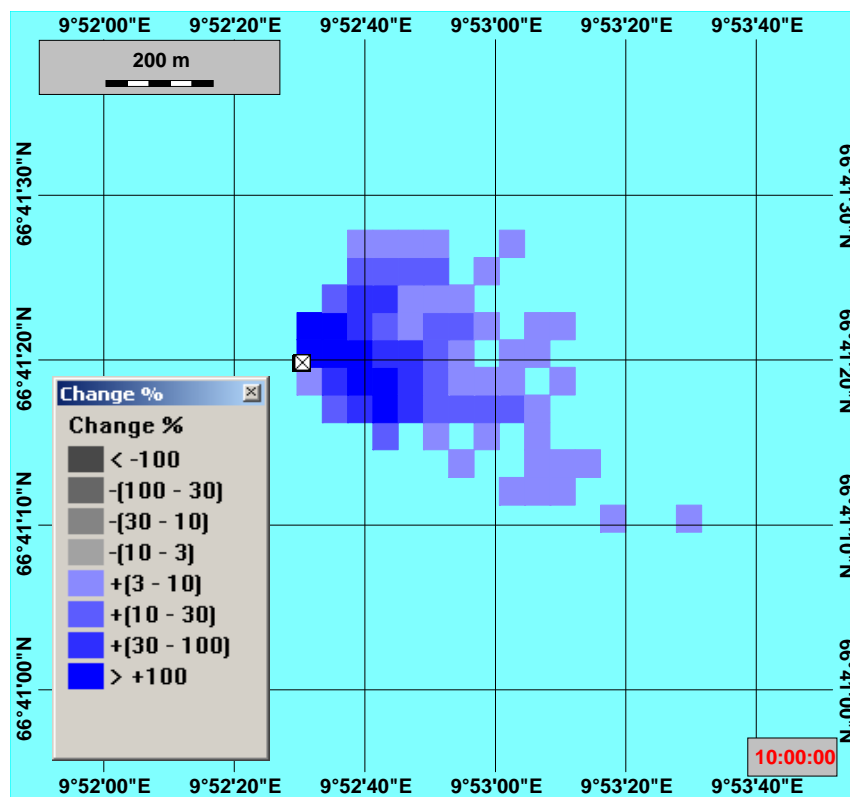

Figure 6.7. Change of grain size in the sediment at the end of the discharge period. The median grain size is averaged over the upper 3 cm of the sediment layer.
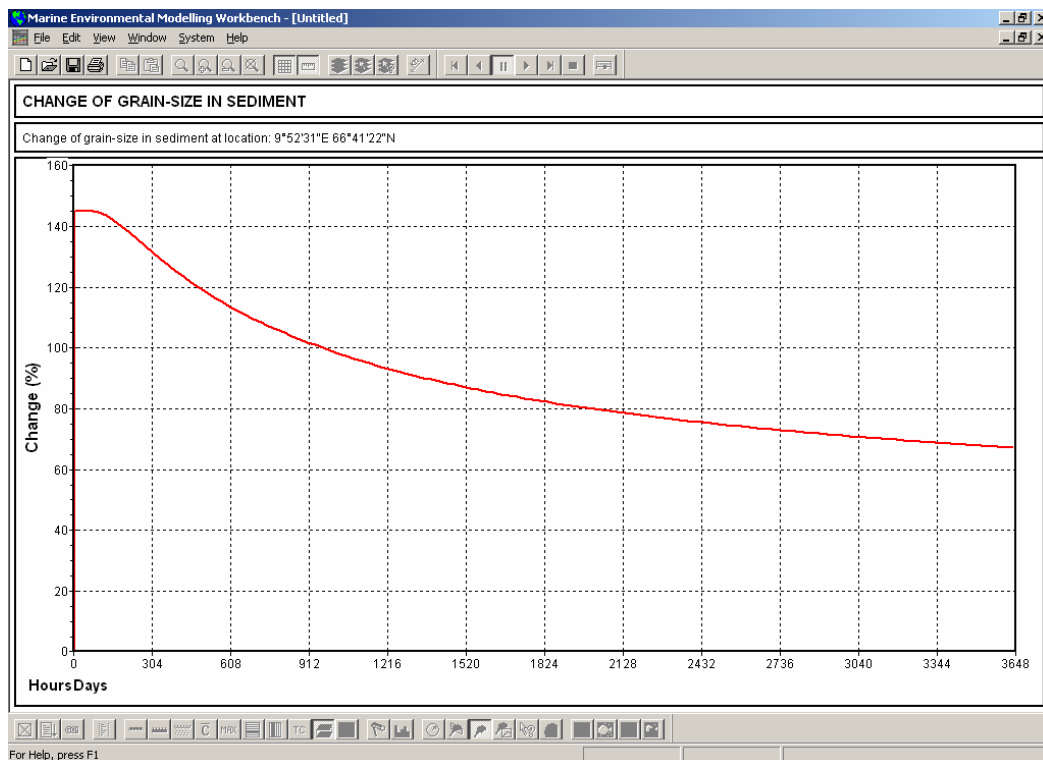
Figure 6.8.   *Time series for change of grain size for one selected grid point. The reduction of the grain size change with time is due to effects from bioturbation, spreading the added particles downwards while the original particles are spreading towards the sediment surface.*

7. Conclusion

Environmental risk assessment of drilling discharges is complex in the way different environmental compartments (water column and sediment) are influenced with different types of stress (toxic and non-toxic). As the existing fate models and risk assessment protocols were not covering this complexity, the need for the development of a new model describing the fate of drilling discharges to the sediment in particular was identified. Moreover the oil industry is presently working towards a "zero harmful discharge" goal for their discharges. Tools for approaching this goal in a quantitative and a cost effective manner are therefore required.

The use of the "diagenetic equations" for describing impacts on sediment caused by drilling discharges has been demonstrated to be able to quantify potential impacts on the sediment layer. The method is able to describe both the geographical area impacted as well as the time development of the impact. The latter may form a basis to estimate the restitution time of the impacted sediment as well.

Combined with PNEC's for the different impact stressors on the sediment, it is possible to calculate potential environmental risks associated with the various types of impacts in the sediment. This has only been shown for one of the stressors in the present paper, namely for the burial (see the Figures 6.1 and 6.2). Risk calculations for all four stressors in the sediment have been implemented in the DREAM model. The model development presented in this paper has thus resulted in a tool suitable to calculate environmental fates or several stressors resulting from the discharge of drill cuttings and mud.

The present paper describes the development of fate calculations in the sediment in particular. This sediment model has been implemented into the DREAM model to be used for a more complete risk calculation of drilling discharges to the sea in general. The revised DREAM model involves also the specification of the discharge (rates, amounts, composition), configuration of the discharge arrangement, plume mixing and descent of the near field plume, the role of the oceanic conditions (stratification, currents), the fates of the discharge in the water column (dissolution of the chemicals, transport and deposition of particles, biodegradation, attachment of chemicals to particles and eventually formation of "agglomerated" particles) and the fates of the discharge compounds in the sediment (like deposition, concentrations and biodegradation, bioturbation and the equilibrium partitioning for organic chemicals and heavy metals). The present DREAM model should therefore represent a first step towards a more comprehensive description of the essential factors involved when the exposures and stressors are to be calculated for drill cuttings and mud discharged to the sea.

8. Acknowledgement

9. Abbreviations

BMT	British Maritime Technology
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
NCS	Norwegian Continental Shelf
NOEC	No Observed Effect Concentration
OBM	Oil Based Mud
OOC	Offshore Operators Committee
PEC	Predicted Environmental Concentration/Change
PNEC	Predicted No Effect Concentration/Change
PLONOR	Pose Little or No Risk to the environment
SBM	Synthethic Based Mud
TGD	Technical Guideline Document (EC 1996)
THC	Total HydroCarbons in sediment
UKOOA	United Kingdom Offshore Operators Association
WBM	Water Based Mud

10 References

Akvaplan-niva (2005): "Sediment characterization and parameter estimation". ERMS report No. 12. Report APN-411.3119. Written by H.C. Trannum (NIVA) and F. Brakstad (MUST AS). Dated 5. April 2005.

Berner, Robert A. (1980): "Early Diagenesis. A Theoretical Approach". Princeton University Press.

Boudreau, Bernard P. (1997): "Diagenetic Models and Their Implementation. Modelling Transports and Reactions in Aquatic Sediments". Springer-Verlag Berlin Heidelberg.

Boudreau, Bernard P. (1998): "Mean mixed depth of sediments: The wherefore and why". Limnol. Oceanogr., 43(3), pp 524 – 526.

Boudreau, Bernard P. (2004): Communication with Prof. Boudreau during the execution of the ERMS project. Bernard P. Boudreau, Associate Professor, Dept. of Oceanography, Dalhousie University, Halifax, NS B3H 4J1, Canada.

Brandsma, M.G. and J.P. Smith (1999): "Offshore Operators Committee mud and produced water model – report and user guide". Report EPR.29PR.99. Production Operations Division. Exxon Production Research Company (later ExxonMobil Upstream Research Company). Houston, Texas.

Brandsma, M.G., 2001: "Visualization of Offshore Discharges". Proceedings, 5th Int. Marine Environmental Modelling Seminar, New Orleans, USA, October 9 – 11, 2001. pp. 703 – 713.

EU TGD 1996. Technical Guidance Document (TGD) in support of commission directive 93/67/EEC on risk assessment for new notified substances and commission regulation (EC) No. 1488/94 on risk assessment for existing substances. Part i to IV, Office for official publications of the European Communities. ISBN 92-827-8011-2.

Johansen, Ø. (2000): "DeepBlow – a Lagrangian Plume Model for Deep Water Blowouts". Spill Science & Technology Bulletin, Vol. 6, No. 2, pp 103 – 111.

Johansen, Ø. (2006): "Implementation of the near-field module in the ERMS project", ERMS report No. 23. Report from the ERMS project.

NIVA, 2005: "Remediation of sediments contaminated with drill cuttings. A review of field monitoring and experimental data for validation of the ERMS sediment module". ERMS report No. 22. Draft report by Morten Schaanning and Torgeir Bakke, NIVA, dated 30 June, 2005.

Reed, M. and B. Hetland, 2002: " DREAM: a Dose-Related Exposure Assessment Model. Technical Description of Physical-Chemical Fates Components". SPE paper No. 73856 presented at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production held in Kuala Lumpur, Malaysia, 20–22 March 2002.

Rye, H., M. Reed and N. Ekrol, 1998: "The *ParTrack* model for calculation of the spreading and deposition of drilling mud, chemicals and drill cuttings" *Environmental Modelling and Software*, Volume 13, No. 5-6, pp431-443, 1998. Elsevier.

Rye, H., M. Reed, T.K. Frost and T.I.R. Utvik, 2004: "Comparison of the *ParTrack* mud/cuttings release model with field data". *Environmental Modelling and Software*, Volume 19, No. 7 - 8, pp701-717, 2004. Elsevier.

Rye, H., M. Reed, T.K. Frost and T.I.R. Utvik, 2006: "Comparison of the *ParTrack* mud/cuttings release model with field data base on use of synthetic based drilling fluids". *Environmental Modelling and Software*, Volume 21, No. 2, February 2006. Elsevier.

Sabeur, Z., A. Tyler, I. Laiz and R. Barker (2002): "Adaption and Evaluation of Mathematical Model" UKOOA Drill Cuttings Initiative Phase II, Report from BMT Marine Information Systems Ltd. Report No. 14900/00 dated 01/02/2002.

Saga, 1994: "Miljøprogram i forbindelse med brønn 7219/8-1s i Barentshavet". Report prepared by Saga Petroleum a.s., Divisjon for Teknologi og utbygging dated 10. March 1994. Saga report R-TIY-0003. Written in Norwegian.

Shimmield, G. B. et. al. (2000): "Contaminant Leaching from Drill Cuttings Piles of the Northern and Central North Sea: Field results from the Beryl cuttings pile". Scottish Association for Marine Life, Centre for Coastal and marine Sciences.

SINTEF, 2006a: ERMS report No.18. Documentation report for the revised DREAM model. Final version, August 2006. SINTEF, 31 August 2006.

SINTEF, 2006b: "ERMS report No. 21. Restitution of an impacted sediment". Final report dated 31 August 2006.

TNO (2006): THE CONCEPT REPORT: Smit, M.G.D., Jak, R.G. & H. Rye: Framework for the Environmental Impact factor for Drilling discharges. TNO-report. R2006-DH-R0045. ERMS report no. 3