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Development of a Numerical Model for Calculating Exposure to Toxic and Nontoxic Stressors in the Water Column and Sediment from Drilling Discharges

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Special Section

EDITOR'S NOTE:

This is 1 of 5 papers reporting on the results of a 4-year project to develop an environmental risk-based decision support tool, to assist the oil industry in establishing cost-effective measures for reducing risk to the marine environment from drilling discharges.

ABSTRACT

Drilling discharges are complex mixtures of chemical components and particles which might lead to toxic and nontoxic stress in the environment. In order to be able to evaluate the potential environmental consequences of such discharges in the water column and in sediments, a numerical model was developed. The model includes water column stratification, ocean currents and turbulence, natural burial, bioturbation, and biodegradation of organic matter in the sediment. Accounting for these processes, the fate of the discharge is modeled for the water column, including near-field mixing and plume motion, far-field mixing, and transport. The fate of the discharge is also modeled for the sediment, including sea floor deposition, and mixing due to bioturbation. Formulas are provided for the calculation of suspended matter and chemical concentrations in the water column, and burial, change in grain size, oxygen depletion, and chemical concentrations in the sediment. The model is fully 3-dimensional and time dependent. It uses a Lagrangian approach for the water column based on moving particles that represent the properties of the release and an Eulerian approach for the sediment based on calculation of the properties of matter in a grid. The model will be used to calculate the environmental risk, both in the water column and in sediments, from drilling discharges. It can serve as a tool to define risk mitigating measures, and as such it provides guidance towards the "zero harm" goal.

Keywords: ERMS Drilling discharges Environmental fate Sediments

INTRODUCTION

Activities associated with offshore drilling operations lead to a variety of discharges with different durations and behavior in the recipient. Examples of the types of drilling muds used include water-based mud, synthetic-based mud (SBM), and oil-based mud. The discharges can take place from the drilling rig (when drilling deeper well sections) or directly to the sea floor (when drilling top well sections). Some constituents of the discharge are water-soluble chemical additives which dissolve into the water column while others are particulates (cuttings and weight material like barite) or highly lipophilic chemicals with a large octanol–water partition coefficient (log K_{ow}). Chemicals with sufficiently large K_{ow} values, may attach to particulate matter in the discharge. Heavy metals in barite may also cause environmental impacts in the sediment. Due to their particle content, the discharges will have a tendency to sink, and mineral particles typically separate from the discharge plume and sink to the sea floor. Therefore, the drilling discharges may cause impacts both in the water column and in the sediment. Sediment impacts can extend over long time scales (years) after the discharge period has ceased (UKOOA 2003), whereas the potentially harmful effects in the water column fade rather quickly after the end of the discharge period due to the dilution with the ambient water.

Numerical models describing the fate of chemicals and particles discharged to the sea during drilling have been developed and applied previously. However, these models are of different types and complexities. Some models incorporate environmental risks caused by the discharges, while some are limited to calculating the fate of the discharge (compounds) only. Other models focus on the actual deposits on the sea floor, without considering the actual processes within the sediment layer. Examples of models that do not include risks or processes in the sediment are described in Brandsma and Smith (1999), Brandsma (1996), Rye et al. (1998, 2004), and Rye, Reed, Frost, et al. (2006). Other models have attempted to include the actual time development of the environmental risk for the sediment caused by drilling discharges (Sabeur et al. 2002). However, as highlighted in a review article by Khondaker (2000), a comprehensive model that incorporates all of these essential processes and their resulting environmental risks in both the water column and sediments is lacking. The model presented in this paper attempts to meet this requirement by incorporating all essential stressors that can have potential impacts on biota in both the water column and in the sediments, from drilling discharges.

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Meinhold (1998) identifies the various impacts caused by drilling discharges that will be encountered in the sediment. Organic enrichment and toxicity both contribute to oxygen depletion (anoxia) within sediments. These stressors have also been incorporated in the development of the present model. In addition, Meinhold (1998) discusses the physical effects of the material deposited. This includes burial effects and changes of grain size caused by deposition of particles with diameters differing from the natural grain size at the drilling site. These effects have also been included in the development of the present model. Whilst Meinhold (1998) states that the effects for the water column are minimal, the model developed herein also includes the water column toxicity of the chemicals discharged as well as particle effects on filtering organisms. The latter effects are according to Cranford and Gordon (1999), who showed effects on filtering organisms from exposure to barite in the water column at concentrations below 1 ppm.

This paper describes the development of a model which can be used for risk management of drilling discharges. The guidelines for environmental risk assessment as described in the European Technical Guidance Document (TGD; EC 2003) are used as a basis. The TGD provides recommendations on prediction of environmental concentrations (PEC) of single substances both for the water column and the sediments. However, the complex nature of the drilling discharges concerning the complexity and nature of the stressors are not fully dealt with in the TGD. For instance, highly adsorptive or insoluble, solid substances may not be considered by the approach described in the TGD, as they are not in equilibrium between water and ambient suspended matter. This is due to their strong affinity to suspended matter. However, they may be desorbed or dissolved after ingestion by benthic organisms. Also particles are not covered by the TGD.

According to the TGD the sediment may be contaminated when the discharge plume is in contact with the sediment. However, experience has shown that even at high water depth the sediment may be impacted by discharges of drill cuttings and mud, even though the plume are not in contact with the sea floor at all. Therefore, the need for the development of algorithms which describe this process was evident. The mechanisms bringing the discharges down to the sea floor are sinking particles and/or chemicals attached to the particles (or chemicals that agglomerate to form new particles). Chemicals that are able to attach (or "adhere") to particles are generally those with large log K_{ow}. These are typically muds like SBM and/or oil-based mud that tend to adhere to cuttings and/or other particle matter in the discharge. The mineral particles may then be coated with the mud that, in turn, may give rise to the formation of "agglomerated particles" consisting of mud and mineral particles, forming new and larger particles that deposit quickly on the sea floor (Delvigne 1996; CAPP 2001). The model presented includes all these processes.

The present model calculates the (time and space variable) PEC in the recipient caused by drilling discharges. The model developed uses the Dose-Related Risk and Effect Assessment Model (DREAM model; Reed and Hetland 2002), which was originally developed for produced water discharges originating from oil and gas fields under production. The DREAM model was developed to quantify the environmental risks from disposal of produced water to the marine environment based on toxicity in the water column as the stressor (Johnsen et al. 2000). The revised DREAM also addresses contributions from additional stressors typically related to drilling discharges. These include suspended matter concentrations in the water column, burial, change of sediment texture (alterations of median grain size), and oxygen depletion in the sediment. The model also incorporates the calculation of environmental risk of drilling discharges, expressed as the PEC/(predicted no effect concentration [PNEC]) ratio. The PNEC is the concentration of the chemical in the environment below which it is unlikely that adverse effects on the biota will be observed. This risk assessment procedure is in accordance with the recommendations in the TGD (EC 2003) for toxicity issues. The ratio of the PEC to the PNEC indicates the likelihood of the occurrence of adverse effects on the biota.

Some dispersion/dilution models also include elements of risk calculations. Sadiq and collaborators (Sadiq 2001; Sadiq, Husain, Bose, et al. 2003; Sadiq, Husain, Veitch, et al. 2003) model exposure concentrations adjusting for the probability of the exposure. Moreover, the method is such that a single predicted concentration is arrived at, averaged over time, and given sediment area or given water volume. The model presented in this paper differs in the way that the environmental concentrations are calculated as a function of space and time. In addition, the environmental concentration is calculated as a deterministic function based on causality.

The US Environmental Protection Agency (USEPA; USEPA 1999a, 1999b) considered the use of SBM and the resulting impact on sediments. Use of SBM may cause benthic smothering, and because some of the SBMs are highly biodegradable, they may lead to hypoxia in the sediment. Due to the high biodegradation rate, the period of hypoxia in the sediment may be relatively short, and the recovery time of the sediment will generally be much shorter than experienced with the use of oil-based mud. Sadiq, Husain, Veitch, et al. (2003) used a multicriteria decision-making method to arrive at the recommendation that a 4 w% SBM attached to cuttings in the discharge may represent the best compromise between costs and environmental impacts.

The present paper focuses on the part of DREAM that calculates the exposure. The full environmental risk approach is outlined in a series of papers that all are published in the current journal (see Altin et al. 2008; Neff 2008; Singsaas et al 2008; Smit, Rye, et al. 2008). The exposure model developed is comprehensive and is described more extensively by Rye et al. (2006b) and Rye, Johansen, et al. (2006).

MATERIALS AND METHODS

The model approach

The numerical model approach is based on the DREAM model, as it has been applied to produced water risk assessments (Johnsen et al. 2000). In addition, some modules of the numerical model ParTrack for calculation of dispersion and deposition of drill cuttings and mud (Rye et al. 1998, 2004; Rye, Reed, Frost, et al. 2006) were implemented. The model concept applied 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, such as the mass of various compounds, densities, and sinking velocities, are associated with each particle. Model particles can also represent different state variables, such as gas bubbles, droplets, dissolved matter,

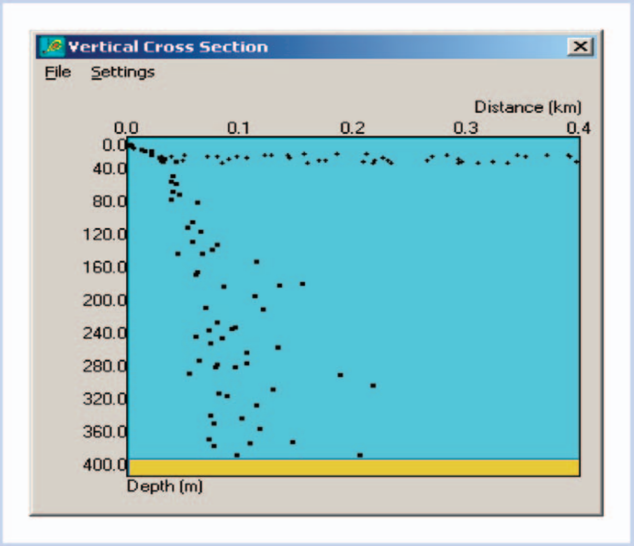

Figure 1. An example illustrating the vertical cross section of the near-field plume and the deposition of particles on the sea floor. Discharge point to the upper left corner of the figure. Sea floor at about 400 m depth.

and solid matter. For discharges of drill cuttings and mud, solid particles, organic matter, metals attached to solid particles, and dissolved matter will be of particular interest. 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 3-dimensional and time-variable hydrodynamic models. It is also possible to apply observed ocean current profiles generated from measurements at a specific location.

Generic features for the calculation of deposition

A more reliable description of the behavior of drilling discharges has been undertaken by incorporation of additional modules into the model system. These include a near-field plume, sinking velocities of particles depositing on the sea floor, and particle size distributions specified for each particle group (cuttings, barite).

Near-field plume—Discharges of drill cuttings and mud have densities that are significantly higher 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 when the density of the descending plume equals 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 to the sea floor and level out there. 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. The principal features of the near-field plume model are given in Johansen (2000, 2006).

Descent of particles on the sea floor—Figure 1 shows a vertical cross section of an underwater plume on the downstream side of the release site calculated with the 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). At this depth, the underwater plume separates into 2 parts: 1) 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 diameter that sinking velocities are negligible. 2) The other part of the discharge appears to sink down to the sea floor. This part may consist of coarser particles (like cuttings particles with relatively large diameters) with some chemicals attached to them.

The sinking velocities of the particles can be divided into 2 regimes, the Stokes regime and the constant drag regime. The sinking velocities within the Stokes regime for smaller particles are given by Equation 1:

$$W_1 = \frac{d^2 g'}{18\nu} \tag{1}$$

where W_1 is laminar Stokes sinking velocity of a particle, d is the particle diameter, g' is the reduced gravity $= g(\rho_{\text{particle}} - \rho_{\text{water}})/\rho_{\text{water}}$, g is the standard gravity, ρ is the density of particle or seawater, and υ = kinematic viscosity = 1.358×10^{-6} m^2/s at 10 °C for seawater.

The 2nd contribution to the sinking of the particles is the friction-dominated constant drag regime for larger particles. A general expression for this sinking velocity can be derived from the balance between buoyancy forces and drag forces acting on the particle (Hu and Kintner 1955) calculated by Equation 2.

$$W_2 = \sqrt{\frac{4dg'}{3C_D}} \tag{2}$$

The drag coefficient C_D in this equation is a function of the Reynolds number ($Re = W_2 d/\upsilon$). On this basis, 2 asymptotic regimes are identified, the Stokes regime and the constant drag regime (Eqn. 3):

$$\begin{aligned} &1)\quad \text{Stokes regime } (Re < 1),\ W_1 = \frac{d^2 g'}{18\nu} \\ &2)\quad \text{Constant drag regime } (Re > 1000),\ W_2 = K\sqrt{dg'} \end{aligned} \tag{3}$$

where K is an empirical dimensionless constant. For intermediate values of the Reynolds number ($1 < Re < 1000$), an interpolation equation for the total sinking velocity W of the particle may be used, expressed by Equation 4.

$$W = \frac{1}{\left(\frac{1}{W_1} + \frac{1}{W_2}\right)} \tag{4}$$

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 (2007) and Equation 3 above. This equation takes into account that grains are usually nonspherical and have therefore generally lower sinking velocities than grains with spherical shapes.

A graphical presentation of the curve shape given by Equation 4 is shown in Figure 2. For low diameter particles (diameters lower than 2×10^{-4} m), the equation corresponds well with the Stokes sinking velocity (Eqn. 1). For larger particle diameters (diameters larger than 2×10^{-3} m), the equation corresponds well with the friction dominated velocity (Eqn. 2). In the diameter range in between, the sinking velocities are influenced by contributions from both regimes.

Deposition of chemicals on the sea floor—In water-based mud, most of the added chemicals are mainly assumed to dissolve in the water column. For other types of mud (e.g., oil-based mud

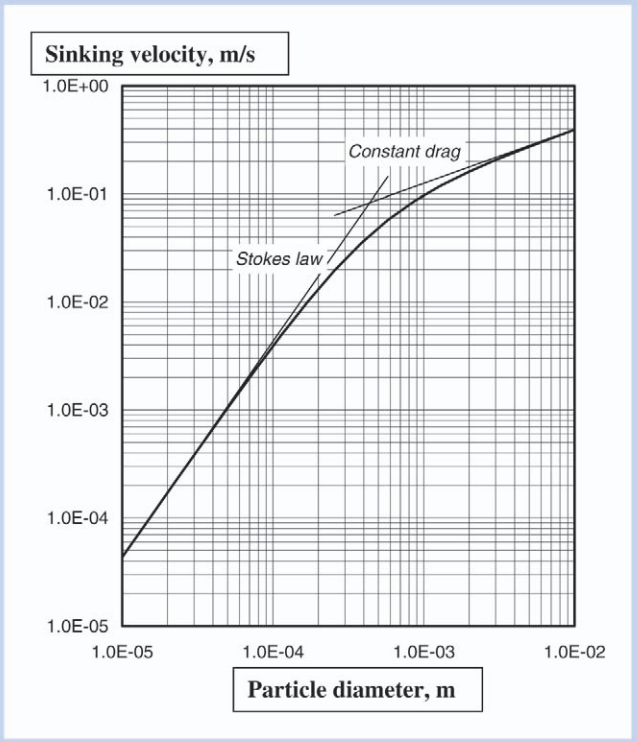

Figure 2. Particle size dependent variation in fall velocity of mineral particles in seawater. Solid density 2500 kg/m^3. Thin lines: Stokes law and constant drag law according to Equation 3. Thick line: Interpolation formula (Eqn. 4).

and SBM), dissolution of the chemicals in the water column may be slow. These chemicals (typically exhibiting large octanol–water partition coefficient, K_{ow}) may also have a high capacity for adsorption to organic matter present in the sediment or water column.

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

In accordance with the TGD the chemicals with low K_{ow} or K_{oc} values (<1000 L/kg) are assumed to dissolve (completely) in the water column. For large K_{ow} or K_{oc} values (≥ 1000 L/kg), the chemicals are assumed to adsorb (or "attach") to particles and eventually deposit on the sea floor. This process may take place either through "agglomeration" (in which new particles are formed) or by attachment, where chemicals are thought to attach to individual mineral particles in the discharge. The K_{ow} and K_{oc} are partition coefficients, the K_{ow} is the octanol–water partition coefficient, and the K_{oc} is the particle organic carbon partition coefficient. The relationship between K_{oc} and K_{ow} has been studied by Di Toro et al. (1991). It was found that K_{oc} and K_{ow} are closely related. The TGD (EC 2003) does not differentiate between use of K_{ow} or K_{oc}. Therefore, it is recommended to use K_{ow} if no K_{oc} value is available for organic substances. The octanol–water partition coefficient denoted P_{ow} is assumed equal to K_{ow}.

It has been highlighted that various processes in the sea may alter the grain size distribution of the released particulate matter. An example of these processes includes flocculation of particles. Seaconsult Marine Research Limited (2000) used a particle tracking technique to determine the fate of SBM discharged to sea. They suggest that particles smaller than 0.1 mm will form flocs due to the presence of phytoplankton and other organic substances in the ambient water. The flocs were then assumed to settle with a velocity of 100 m/d. This would represent an increase of the sinking velocities for the smallest particles, because very small particles may sink considerably slower than 100 m/d. An alternative formulation of enhanced sinking velocities may be based on the experiments by Delvigne (1996). The laboratory study focused on the formation of agglomerated particles resulting from discharges of oil-based mud and cuttings. This process of agglomeration is also likely to enhance the descent of the particles to the sea floor, as the newly formed particles were found to be significantly larger. Therefore, in the present PEC model Equation 4 was used for calculating the sinking velocities of agglomerated particles as well.

The formation of mineral particle flocs may also enhance the vertical descent of mineral particles. One attempt to approach the flocculation process in a systematic manner has been made by Huang (1992). Two opposing processes act upon the floc formation process. First, increased concentration of the particulate matter will stimulate the flocculation process. Second, the presence of shear currents in the ambient water (like for the presence of turbulence for a boundary layer flow or for an underwater plume) will typically break the bonds between the particles in the floc. It is difficult to determine which of the processes will dominate the floc formation (or disintegration) process without making attempts to quantify these processes. The floc formation could therefore both hamper and accelerate the descent of the barite particles in the water-based mud. If the flocs formed have a large surface area compared to their weight, the sinking of the barite could be slowed down due to friction (drag) forces. However, if the flocs formed have a more dense structure, the descent of the barite can be accelerated.

Huang (1992) conducted laboratory experiments on the settling speeds and flocculation properties of drilling muds (water-based mud) and river sediments. He was able to simulate in the laboratory both the driving force of the flocculation process (the concentration of the solids) and the disintegration of the flocs by means of the fluid shear (by using what he denotes as a "Couette flocculator").

Huang was also able to formulate a nondimensional number (the "flocculation number") which expresses the relative importance of these 2 forces. All of the results reported by Huang (1992) were then expressed in terms of this nondimensional flocculation number. In addition, he expressed the floc diameter, the floc sinking velocity, and the time taken to reach to the "equilibrium" state (i.e., the balance between the floc forming and dispersing processes) in terms of this nondimensional flocculation number.

However, by inserting typical numbers for the floc diameter, the floc sinking velocity, and the time taken to reach to the equilibrium state based on actual data for plume dilutions and far-field concentrations for actual drilling discharges, the parameter range in the field seems to be out of range compared to the laboratory findings of Huang (1992). If the results from the study by Huang (1992) are still assumed to be valid for an underwater plume generated by a discharge of drill cuttings and mud (during drilling), they indicate that floc formation probably does take place, but that the increase in the sinking velocity will only be slight. The

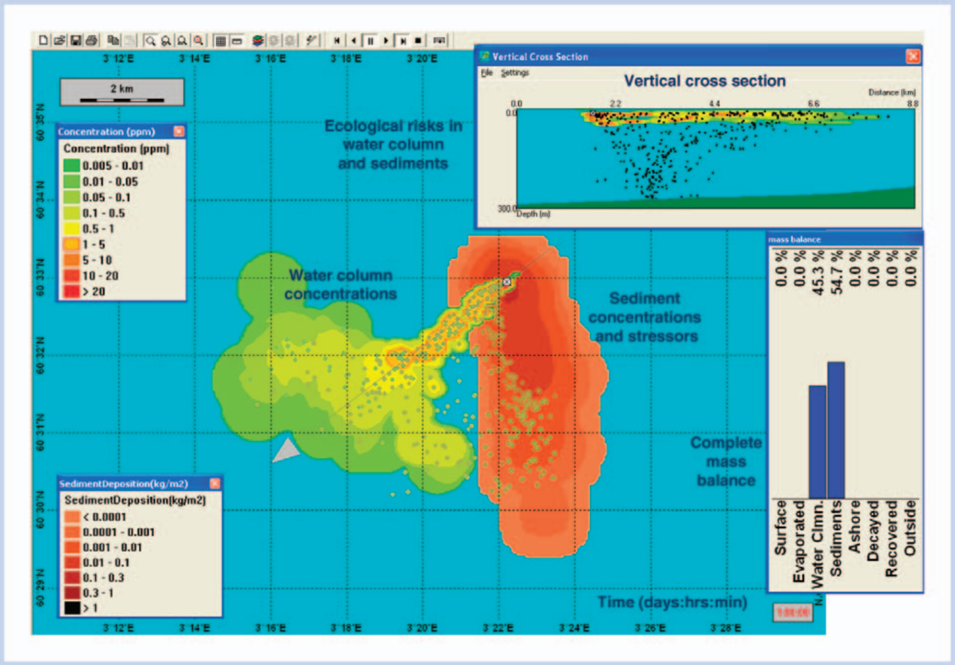

Figure 3. Visualization of the fate of drilling discharges. The figure demonstrates the following: 1). Concentrations of dissolved compounds (and/or particle matter) calculated for the water column, concentrations shown in ppm (mg/L). 2). Deposition of the particle matter on the sea floor (along with chemicals attached to the particles), deposition in kg/m^2 sediment surface. 3). A mass balance histogram that shows the amounts that are depositing on the sea floor, and the amounts that remain in the water column. 4). A vertical cross section that shows the plume in the water column (close to sea surface) and the deposition of particles falling out below the plume. The actual cross section chosen is shown by an arrow on the main figure.

equilibrium state predicted by Huang (1992) will in practice never be reached. The practical implication of these results is therefore the questionable benefit of including flocculation processes in the simulations. The sinking velocity of the flocks will be more or less similar to the sinking velocities of the particles, assuming that no flocculation processes are taking place. Further details on the implementation of Huang's results for an underwater plume generated by a drilling discharge are given in Rye (2005). Therefore, in the present implementation of the DREAM model, flocculation processes are not included, except the contribution from formulation of agglomerated particles.

Figure 3 shows the basic features of the developed model for calculating the fate of drilling discharges. Concentrations in the water column and depositions on the sea floor are illustrated. The particles in the model have been spread in the recipient due to ocean currents and turbulence (after the termination of the near-field plume phase).

CALCULATION RULES FOR EXPOSURE

Exposure in the water column

The model calculates the exposure concentrations as a 3-dimensional and time variable concentration in the water column. The concentrations of each compound are calculated under the influence of near-field mixing, subsidence of plume, currents, turbulent mixing, and reduction of concentration levels due to biodegradation. Formulas for the actual concentration calculated for the water column are according to the principles outlined in TGD (EC 2003), except that 100% solubility of the substances in the water is assumed (worst case scenario) and the recipient background values are neglected.

Chemicals—For chemicals in the drilling discharges the model calculates the concentration in the water column as a function of time and space. The TGD approach is followed, except that adsorption to ambient suspended matter and background concentrations are not taken into account. The effect of degradation is included. As discussed in the previous section, chemicals with $K_{ow} \geq 1000$ L/kg are assumed to be attached to particles in the discharge or to form agglomerated particles, and will to a large extent descend down to the sea floor. The formal equation for concentrations of chemicals in the water column can be expressed as

$$\mathrm{PEC}_{\mathrm{seawater}} = \mathrm{C}_{\mathrm{discharge}} \times \exp(-kt)/\mathrm{DILUTION} \qquad (5)$$

in which

$\mathrm{PEC}_{\mathrm{seawater}}$ = local concentration in seawater during emission episode [mg/L]
$\mathrm{C}_{\mathrm{discharge}}$ = concentration of the substance in the discharge [mg/L]
k = biodegradation factor (1/d)
t = time (d)
DILUTION = dilution factor

The DILUTION factor includes the effects from near-field mixing, currents, and ambient turbulence. Equation 5 thus expresses the effects from the natural processes acting on the discharge when released into the sea, including reduction of the concentrations due to biodegradation.

Particulate matter—The fate of particulate matter discharged into the water column (including barite particles) is calculated similarly to the chemicals in the water column, except that biodegradation is omitted. Moreover, the fall-out of particles (due to the sinking of particles with a high density) represents an extra "dilution" of the discharge because this process reduces the particulate matter content in the discharge plume. Formally, the PEC for the particulate matter in the water column can be expressed by Equation 6.

$$\mathrm{PEC_{seawater}} = \mathrm{C_{discharge}}/\mathrm{DILUTION} \qquad (6)$$

in which

$\mathrm{PEC_{seawater}}$ = local concentration of discharged particles in seawater during emission episode [mg/L]
$\mathrm{C_{discharge}}$ = concentration of the substance or particles in the discharge [mg/L]
DILUTION = dilution factor

Heavy metals in particulate matter—The exposure concentration of dissolved metals in the water column, which originate from particulate matter in the discharge (e.g., barite), can be estimated based on equilibrium partitioning between the metals in the particulate matter (barite) and the ambient seawater. The exposure concentration of metals of concern in water column originating from barite particles can be estimated by Equation 7.

$$\mathrm{PEC_{seawater}} = (\mathrm{C_{discharge}}/\mathrm{DILUTION}) \times (\mathrm{FRACTION}/Kp_{\mathrm{barite/seawater}}) \qquad (7)$$

in which

$\mathrm{PEC_{seawater}}$ = local concentration in seawater of dissolved metal [mg/L]
$\mathrm{C_{discharge}}$ = concentration of barite particles in the discharge [mg/L]
DILUTION = dilution factor for dilution of the discharge in recipient water
FRACTION = fraction of the metal in barite (kg metal/kg barite)
$K_{\mathrm{p_{barite/seawater}}}$ = partition coefficient of the metal between the barite particle and seawater

The $K_{\mathrm{p_{barite/seawater}}}$ is given by

$$K_{\mathrm{p_{barite/seawater}}} = \mathrm{C_{sol}}/\mathrm{C_{aqu}} \qquad (8)$$

in which

$\mathrm{C_{sol}}$ = total available barite metal concentration in the solid phase [mg/kg]
$\mathrm{C_{aqu}}$ = available dissolved barite metal concentration in the aqueous phase [mg/kg]

The metal concentrations in the water column are dependent of the concentration of barite particles in the drilling discharge and their dilution in the receiving environment. The dissolved metal concentrations of concern originating from barite particles are additionally influenced by 2 other factors: 1) The fraction of each metal in barite and 2) the dissolution potential of the metals in barite particles into the water phase (denoted by the $K_{\mathrm{p_{barite/seawater}}}$).

At present, 6 metals originating from barite are included: Cd, Cr, Cu, Hg, Pb, and Zn. Cuttings (and other particulate matter) may contain heavy metals as well, but the weighting agent barite is currently considered as the most significant contributor to the risk from heavy metals in drilling discharges. Values for $K_{\mathrm{p_{barite/seawater}}}$ for the selected metals applied to calculation of metals concentrations in the water column are given in Neff (2008). Further details on the selection criteria and PNEC derivation for the metals selected are described in Altin et al. (2008).

Exposure in the sediment

Initial conditions—Four stressors related to the deposition of drilling discharges are identified for the sediment compartment, including both toxic and nontoxic stressors (Smit, Rye, et al. 2008). The deposits, defined as the thickness of the layer deposited, may cause burial effects by covering existing biota on the sea floor. The grain size of the deposit may cause a change in characteristic of the sediment expressed as change in (median) grain size of the sediment that may favor other species on that location at the expense of the natural habitat (effects of adding "exotic sediment"). The grain size change is defined as change in median grain size within the upper 3 cm of the sediment layer. Chemical concentrations, defined as the concentration in the sediment layer averaged over the upper 3 cm of the sediment, may result in toxic effects on the biota on the sea floor. Only the fraction of the chemical or the metal that is dissolved into the porewater is considered bioavailable (and hence toxic). Biodegradation of the chemicals attached to the particulates that have deposited on the sea floor may cause oxygen depletion in the sediment layer. The oxygen depletion stressor is defined as a change in the content of the free porewater oxygen in the sediment (unit mg $\mathrm{O_2/m^2}$ sediment surface) compared to the content of oxygen in the sediment before discharge. The content of free porewater oxygen in the sediment is integrated vertically over the upper sediment layer (for each cell defined).

Depositions on the sea floor are calculated, varying with the geographical location. Amounts deposited are calculated within each grid cell, which then forms the basis for calculating the impact in the sediment and its geographical variation. For the sediment, an Eulerian approach was chosen, which means the exposures from the various stressors are calculated (within each cell defined for the sea floor) in a vertical grid directed downwards into the sediment.

Time development of stressors in the sediment—Two of the nontoxic stressors (the grain size change and the oxygen depletion) are defined such that the vertical variation of these parameters for the sediment must be known through the sediment layer. These are the oxygen change and the change of median grain size stressors. These are both related to the state of the sediment prior to the discharge (natural grain size and natural content of oxygen in the porewater). Therefore vertical distributions of these stressors must be known in order to calculate their magnitude.

These vertical distributions are calculated by solving a set of "diagenetic equations." These are differential equations which have to be solved numerically. One example of such an equation can be written as (simplified version):

$$\frac{\partial \mathrm{C}}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial \mathrm{C}}{\partial z}\right) - K_{\mathrm{C}}\mathrm{C} + \mathrm{Q_C} \qquad (9)$$

where ∂ is the partial derivative symbol, t is the time dimension, z is the vertical dimension, $\mathrm{C}(z,t)$ is the concentration of matter in the sediment, D is the diffusion coefficient or bioturbation coefficient, K_{C} is the biodegradation rate of matter C, and $\mathrm{Q_C}$ is the sink or source term for matter C.

The 2 last terms on the right-hand side are reaction or sink (or source) terms. The 1st term on the right-hand side is a diffusion term (which 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).

Four equations of this kind are used to simulate the fate of the deposits on the sea floor (1 equation each for oxygen, natural carbon, added biodegradable matter caused by the discharge, and the grain size change). The equations are solved in 1-dimensional form (vertical coordinate z is included only, along with the time variation), but has then to be solved for each horizontal grid in the horizontal (x and y). The matter deposited within each cell on the sea floor is then the starting point for the exposure calculations in the sediment. Details of the technique used for calculating concentrations and changes in the sediment (the PECs) due to depositions of chemicals (attached or agglomerated to particles), cuttings, and barite (and heavy metals in barite) are comprehensive and not described in detail in the present paper. A more detailed description of the use of the diagenetic equations is given in a separate publication (Rye et al. 2006a).

Organic substances in the sediment—The added chemicals and organic substances (with $K_{\mathrm{ow}} \geq 1000$ L/kg) and particulate matter are brought down to the sea floor as described in the *Materials and Methods* section. The diagenetic equations are then activated in order to redistribute the chemicals in the sediment (bioturbation effect). The exposure then becomes time variable. Once the matter is deposited on the sea floor, the exposure (or PECs in the sediment) of potential toxic chemicals in sediments are formally calculated according to the following equation.

$$\mathrm{PEC}_{\mathrm{sediment}} = \mathrm{PEC}(t=0)_{\mathrm{sediment}} \times \exp(-kt)/\mathrm{BIOTURB} \tag{10}$$

in which

$\mathrm{PEC}_{\mathrm{sediment}}$ = concentration of substances in the sediment [mg/kg]
$\mathrm{PEC}\ (t=0)_{\mathrm{sediment}}$ = same as above for the initial time step $t=0$
k = biodegradation factor for substances in the sediment [1/d]
t = time [d]
BIOTURB = dilution factor in the sediment due to effects from bioturbation

The PEC $(t=0)_{\mathrm{sediment}}$ for organic matter represents the initial concentration of the organic substances in the sediment at the time of the discharge. This factor varies with the distance and the direction from the discharge point. The deposition calculated is dependent on the actual ambient currents and the sinking velocities of the particles (and the chemicals attached) that are depositing, as explained in the *Materials and Methods* section. The k factor is a biodegradation factor which is specified as a constant, but may be reduced considerably during the computation, in situations where the oxygen in the porewater is consumed. This factor will therefore vary with the availability of free oxygen in the porewater. If the free oxygen is reduced to zero, the k factor will reduced to zero also. The factor BIOTURB is a dilution factor representing spreading of the organic matter below a sediment depth of 3 cm due to the effects of bioturbation. These effects are included in the model simulations through the use of diagenetic equations (Rye et al. 2006a).

In order to compare the PEC to an environmental tolerance level (PNEC) based on porewater concentrations following the equilibrium partitioning approach (Altin et al. 2008), the sediment concentration of organic substances must be expressed as the porewater concentration as well. The porewater concentrations of organic chemicals in the sediment are based on equilibrium partitioning expressed in Equation 11.

$$\mathrm{PEC}_{\mathrm{porewater}} = \mathrm{PEC}_{\mathrm{sediment}}/K_{\mathrm{p}_{\mathrm{sediment}}} \tag{11}$$

in which

$\mathrm{PEC}_{\mathrm{porewater}}$ = concentration of dissolved organic substances in the porewater [mg/L]
$\mathrm{PEC}_{\mathrm{sediment}}$ = concentration of organic substances in the sediment [mg/kg]
$K_{\mathrm{p}_{\mathrm{sediment}}}$ = partitioning coefficient between organic substances in sediment and porewater [L/kg]

The K_{p} for nonionic organic substances in the sediment is given in Equation 12.

$$K_{\mathrm{p}_{\mathrm{sediment}}} = F_{\mathrm{oc}} \times K_{\mathrm{oc}} \tag{12}$$

in which

K_{oc} = partition coefficient organic carbon–water [L/kg]
$K_{\mathrm{p}_{\mathrm{sediment}}}$ = partition coefficient between organic substances in sediment and porewater [L/kg]
F_{oc} = weight fraction of organic carbon in the sediment [kg/kg]

Equations 10 and 11 outline the calculation formulas implemented in the DREAM model for determination of the concentration of organic chemicals in the sediment. The following comments can be made regarding the various factors determining the PECs of organic chemicals in the sediment.

K_{oc} is assumed to correspond to the K_{ow} coefficient. The F_{oc} factor is assumed to be 0.01 (i.e. the natural total organic carbon in the sediment is assumed to be 1 w% of the total sediment). The choice of 1 w% for F_{oc} may seem to be toward the low end of the range when the natural content of total organic matter is typically between 1 w% and 10 w%. However, the content of the total organic carbon is typically only a fraction of the total organic matter, therefore use of 1 w% for the determination of F_{oc} is found reasonable; numbers for total organic matter for the Norwegian Continental Shelf (NCS) are given in Trannum et al. (2006).

Heavy metals in barite deposited on the sea floor—Heavy metals attached to the barite may enter the sediment layer along with the barite particles. In the model, the bioavailable proportion of the metals is determined through equilibrium partitioning. The formula for calculation of the total metal barite concentration in the sediment is given by Equation 13.

$$\mathrm{PEC}_{\mathrm{sediment}} = \mathrm{PEC}(t=0)_{\mathrm{sediment}} \times \mathrm{FRACTION}/\mathrm{DILUTION} \tag{13}$$

in which

$\mathrm{PEC}_{\mathrm{sediment}}$ = concentration of total barite metal in the sediment [mg/kg]
$\mathrm{PEC}\ (t=0)_{\mathrm{sediment}}$ = concentration of deposited barite in the sediment at $t=0$ [mg/kg]
FRACTION = content of the metal in barite [kg metal/kg barite]
BIOTURB = dilution factor in the sediment due to effects from bioturbation

The PEC $(t=0)_{\mathrm{sediment}}$ is the initial concentration of the barite in the sediment similar to the initial concentration of the organic chemicals in the sediment given by Equation 10. The FRACTION parameter in Equation 13 is the fraction of the metal in barite. The BIOTURB factor is calculated by the model, and represents the downward mixing of the metal in the sediment caused by the movement of organisms in the sediment (bioturbation effect).

As for nonionic substances, the PEC of metals in the sediment must be transferred to the porewater concentration in order for it to be comparable to the defined environmental tolerance level of the metal of concern (Altin et al. 2008). The porewater concentrations of the metals in the sediment are based on equilibrium partitioning and can be calculated similarly to Equation 11 applied for organic substances. However, for metals the partition coefficient is not related to the content of carbon in the sediment, as expressed in Equation 12. For metals the partition coefficients should be based on measured values rather than estimated partitioning values. The partitioning coefficients used in PEC estimations of metals in water column and sediments are derived from laboratory experiments simulating realistic conditions. The partitioning coefficients ($K_{\mathrm{p}_{\mathrm{barite/porewater}}}$) for different metals between barite and porewater in the sediment are given by Neff (2008) and are different from the $K_{\mathrm{p}_{\mathrm{barite/seawater}}}$ coefficients applied for the water column as given by Equation 8 (Neff 2008).

Nontoxic stressors—The time developments of the 2 nontoxic stressors grain size change and oxygen depletion are influenced by biodegradation of added chemicals (oxygen depletion only) and bioturbation. The bioturbation is expressed through mixing coefficients for the sediment. This mixing is caused by the motion of biota in the sediment. The oxygen depletion is determined by the biodegradation of the added chemicals in the sediment. The biodegradation process causes consumption of the free oxygen present in the porewater. This then has to be replenished through diffusion of new oxygen through the porewater from the free oxygen in the sea above the sediment layer. This diffusion process though the porewater is a relatively slow process. A balance is therefore established between the rate of biodegradation of organic matter in the sediment and the supply of new oxygen diffusing downwards into the sediment from above. All these processes are modeled with the DREAM model by use of the diagenetic equations (Rye et al. 2006a).

Restitution of the sediment

The model also calculates the time required to restitute the natural state of the environment when the discharge has ceased to occur. For the water column, this will happen shortly after the termination of the drilling period. However, for the sediment layer, the restitution time may extend over several years. UKOOA (2003) presented a review of the experiences on environmental recovery from a selection of cuttings piles in the North Sea area. They found that "rates of ecosystem recovery are variable depending on location, and nature and spread of contaminant inputs." Generally, the impacted areas are local to the discharge sites.

Recolonization—The DREAM model was developed in order to provide an estimate of the local area affected and the time necessary to restitute the sediment layer. For the biodegradable and potential toxic compounds, this will be dependent on the biodegradation of the chemicals. When biodegradation has taken place, the porewater free oxygen will then replenish the sediment and pave the way for a recolonization of the sediment. Estimated times for recolonization vary in the literature. Based on judgment of the present literature data, a recolonization time of 5 y is used in the model until more information becomes available. A brief literature study on recolonization is reported in Rye, Johansen, et al. (2006).

Another case considered is for relatively large depositions where the thickness of the deposition exceeds the bioturbation depth. For such a case the grain size changes will be of a more permanent nature (neglecting effects from resuspension). Then a permanent change of community may occur due to the change of the substrate. In such a case, it is assumed that this new community is "accepted" after a time period of 5 y. It is therefore built into the model that the grain size stress is reduced gradually over a time period of 5 y, assuming that the toxic and/or oxygen consuming chemicals have biodegraded completely or to negligible levels. Details are given in Rye, Johansen, et al. (2006).

Resuspension—Particles deposited on the sea floor may redistribute due to the action of currents and waves. This redistribution can alter their potential impact on the sediment by moving the impacted area downstream. At the same time, the matter deposited will spread to larger areas. Resuspension and redistribution of particulate matter deposited on the sea floor is therefore a critical process for estimation of the time duration of the impacts. In areas with shallow water exposed to wave action, the particles on the sea floor may be spread out very efficiently. A simulation option is therefore included in the DREAM model for resuspension of added particulate matter, given the wave (wind), the current conditions, the grain sizes, and densities of the particles deposited (Rye, Johansen, et al. 2006). Only unconsolidated material and deposited matter were considered. Model predictions were compared to measurements of remnants of cuttings piles at the Frigg Field in the North Sea. The simulations show that the results are sensitive to the input grain size distribution. Due to lack of data on grain size distributions for the matter deposited, it proved difficult to verify the comparison between simulation results and the observed results. The resuspension model as such is implemented, but at present it is recommended that case-specific grain size distribution data for the discharge be used. The availability of field data will obviously increase the reliability of model applications. The theory of the actual model development is not given in the present paper, but is addressed in more detail in Rye, Johansen, et al. (2006).

Validation of the PEC model

A separate "validation" study was carried out aiming to compare model results with field measurements. Measurements were carried out in the field during a production drilling in the North Sea. In addition to monitoring the discharges and sediment, filtering organisms were deployed in cages in order to study potential impacts (biomarker responses) caused by drilling discharges from the drilling rig. The validation of the model was therefore aimed at comparing biomarker responses with the stresses/concentrations calculated with the model for the rig locations. In addition, the depth of entrapment for the underwater plume was observed with an ROV, as well as the sizes of the cuttings particles descending through the water column. A good correspondence was found between the calculated and observed depth of entrapment of the underwater plume (Berland et al. 2006).

DISCUSSION AND CONCLUSIONS

The work presented in this paper has resulted in a tool suitable for description of the fate and calculation of environmental concentrations and levels of toxic and nontoxic stressors from the discharge of drill cuttings and mud to the sea. The final model also includes a full environmental risk assessment module based on a comparison of environmental fate and environmental tolerance levels for the various stressors (Altin et al. 2008; Smit, Holthaus, et al. 2008; Smit, Rye, et al. 2008).

The present paper describes the development of fate and exposure calculations specifically designed for drilling discharges. It involves 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 (e.g., concentrations and biodegradation in the sediment, bioturbation, equilibrium partitioning for organic chemicals and heavy metals, oxygen content in the porewater, change of grain size, and burial). The model represents a 1st step towards a more comprehensive description of the essential factors involved in the calculation of exposures and stressors for drill cuttings and mud discharged to the sea. This developed model is therefore concurrent with the recommendation given by Khondaker (2000) who stressed the need for a more comprehensive model to predict potential impacts caused by drilling discharges.

The DREAM model generates valuable information of environmental fate of discharges from drilling activities, and a need for verification/validation of the results from the model simulations with actual measurements in the field is present.

Additionally, the model can be used for the prediction of environmental risk of future discharges and to be used as a management tool. In one example, Sadiq, Husain, Veitch, et al. (2003) found that an amount of 4 w% of SBM base fluid attached to the cuttings in the discharge represents the best "management option" in their study where both cost and technical feasibility were optimized. One of the reasons for using SBM is that the biodegradation rate is generally fast. The time of impact is therefore expected to be relatively short. The model presented here is able to calculate the time of impact on the sediment for a given discharge case with SBM attached to cuttings. It has been shown that the time of recovery for a sediment layer impacted by SBM may be large. Simulations carried out show that the results depend on how the SBM attached to the cuttings is distributed on the sea floor. If it is distributed over a larger area, the recovery time may be short (e.g., within a year). If the deposition is concentrated over a smaller area, the recovery time will be considerably longer (but the impacted area will also be smaller). The biodegradation of SBM in the sediment consumes the free oxygen in the porewater relatively rapidly, leading to hypoxia in the sediment. The amount of free oxygen in porewater is generally relatively small, of order 0.2 g/m^2 sediment surface for a sediment with oxygen diffusing down to approximately 3 to 4 cm below the sediment surface (porosity 0.6, oxygen level at the sea floor assumed to be 10 mg/L). This amount of oxygen is consumed by the biodegradation of the chemical by an equal quantity (or less, depending on the Redfield number for the oxygen consumption of the chemical during biodegradation). The oxygen in the porewater must then be replaced by diffusion of new free oxygen from the seawater above, which is a relatively slow process. The state of hypoxia may therefore persist over a long period of time, dependent on the amount of chemical deposited on the sea floor per square meter of the sediment surface. Under hypoxic conditions the biodegradation rate of the chemicals in the sediment will be slower than the biodegradation indicated by the Harmonized Offshore Chemicals Notification format testing of the chemicals (where oxygen is not considered to be a limiting factor). The biodegradation must take into account the availability of the free porewater oxygen in the sediment. This reduction of biodegradation rates (availability of oxygen in the sediment layer) is built into the present sediment model (by use of the diagenetic equations; Rye et al. 2006a). The model can therefore be used as a tool to assess the assumptions made when "best management options" are considered. Finally, the model is also considered useful for the planning of sampling stations to be used during surveillance of the sediments at a drill site.

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REFERENCES

Altin D, Frost TK, Nilssen I. 2008. Approaches for derivation of environmental quality criteria for substances applied in risk assessment of discharges from offshore drilling operations. *Integr Environ Assess Manag* 4:204–214.

Berland H, Rye H, Sanni S. 2006. ERMS- and PROOF programmes: Experimental validation of drilling effects in the field. ERMS report No. 20. Edited by Akvamiljø Report no. AM 2006/004. http://www.sintef.com/erms.

Brandsma MG. 1996. Computer simulations of oil-based mud cuttings discharges in the North Sea. The physical and biological effects of processed oily drill cuttings. Summary report. London, UK: E & P Forum. Report No. 2.61/202. pp 25–40.

Brandsma MG, Smith JP. 1999. Offshore Operators Committee mud and produced water model—Report and user guide. Houston (TX): Production Operations Division. Exxon Production Research Company (later ExxonMobil Upstream Research Company). Report EPR.29PR.99.

[CAPP] Canadian Association of Petroleum Producers. 2001. Offshore drilling waste management review. Calgary (AB): Canadian Association of Petroleum Producers. Report No. 2001–0007.

Cranford PJ, Gordon DC, Lee K, Armsworthy SL, Tremblay GH. 1999. Chronic toxicity and physical disturbance effects of water- and oil-based drilling fluids and some major constituents on adult sea scallops (*Placopecten magellanicus*). *Mar Environ Res* 48:225–256.

Delvigne GAL. 1996. The physical and biological effects of processed oily drill cuttings. Summary Report. London (UK): E & P Forum. Report 2.61/202. p 16–24.

Di Toro DM, Zarba CS, Hansen DJ, Berry WJ, Swartz RC, Cowan CE, Pavlou SP, Allen HE, Thomas NA, Paquin PR. 1991. Technical basis for establishing sediment quality criteria for nonionic organic chemicals using equilibrium partitioning. *Environ Toxicol Chem* 10:1541–1583.

[EC] European Commission. 2003. Technical guidance document on risk assessment in support of Commission Directive 93/67/EEC on risk assessment for new notified substances and Commission Regulation (EC) No 1488/94 on risk assessment for existing substances and Directive 98/8/EC of the European parliament and of the council concerning the placing of biocidal products on the market. Brussels (BE): EC.

Hu S, Kintner RC. 1955. The fall of single liquid drops through water. *AICE Journal March* 1955:42–48.

Huang H. 1992. Transport properties of drilling muds and Detroit river sediments [PhD thesis]. Santa Barbara (CA): University of California.

Johansen Ø. 2000. DeepBlow—A Lagrangian plume model for deep water blowouts. *Spill Sci Technol Bull* 6:103–111.

Johansen Ø. 2006. Implementation of the near-field module in the ERMS project. ERMS report no. 23. http://www.sintef.com/erms.

Johnsen S, Frost TK, Hjelsvold M, Utvik TR. 2000. The Environmental Impact Factor—A proposed tool for produced water impact reduction, management and regulation. SPE paper 61178. In: SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production; 26–28 June 2000; Stavanger, Norway. Richardson (TX): Society of Petroleum Engineers.

Khondaker AN. 2000. Modeling the fate of drilling waste in marine environment—An overview. *Computers and Geosciences* 26:531–540.

Meinhold AF. 1998. Framework for a comprehensive environmental assessment of drilling fluids. Tulsa (OK): National Petroleum Technology Office, Office of Fossil Energy, US Department of Energy. BNL-66108.

Neff JM. 2008. Estimation of bioavailability of metals from drilling mud barite. *Integr Environ Assess Manag* 4:184–193.

Reed M, Hetland B. 2002. DREAM: A dose-related exposure assessment model. Technical description of physical-chemical fates components. SPE paper No. 73856. In: SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production; 20–22 March 2002; Kuala Lumpur, Malaysia. Richardson (TX): Society of Petroleum Engineers.

Rye H. 2005. The influence of flocculation processes on the deposition of drill cuttings and mud on the sea floor. Paper presented at the 8th International Marine Environmental Modeling Seminar, 23–25 August 2005; Helsinki, Finland. http://www.sintef.com/erms.

Rye H, Johansen Ø, Durgut I, Reed M, Ditlevsen MK. 2006. Restitution of an impacted sediments. ERMS Report no. 21. SINTEF Report no. STF80MK A06226. http://www.sintef.com/erms.

Rye H, Reed M, Durgut I, Ditlevsen MK. 2006a. The use of the diagenetic equations to predict impact on sediment due to discharges of drill cuttings and mud. International Marine Environmental Modeling Seminar; 9–11 October 2006; Rio de Janeiro, Brazil. http://www.sintef.com/erms.

Rye H, Reed M, Durgut I, Ditlevsen MK. 2006b. Documentation report for the revised DREAM model. ERMS report No. 18. SINTEF Report no. STF80MK F06224. http://www.sintef.com/erms.

Rye H, Reed M, Ekrol N. 1998. The *ParTrack* model for calculation of the spreading and deposition of drilling mud, chemicals and drill cuttings. *Environmental Modelling and Software*. 13:431–443.

Rye H, Reed M, Frost TK, Utvik TIR. 2004. Comparison of the *ParTrack* mud/cuttings release model with field data. *Environmental Modelling and Software* 19:701–717.

Rye H, Reed M, Frost TK, Utvik TIR. 2006. Comparison of the *ParTrack* mud/cuttings release model with field data base on use of synthetic based drilling fluids". *Environmental Modelling and Software* 21:190–203.

Sabeur Z, Tyler A, Laiz I, Barker R. 2002. Adaption and evaluation of mathematical nodel. UKOOA drill cuttings initiative Phase II. Southampton (UK): BMT Marine Information Systems Ltd. Report No. 14900/00.

Sadiq R. 2001. Drilling waste discharges in the marine environment: a risk based decision methodology [PhD thesis]. St. John (NL): Memorial University of Newfoundland.

Sadiq R, Husain T, Bose N, Veitch B. 2003. Distribution of heavy metals in sediment pore water due to offshore discharges: An ecological risk assessment. *Environmental Modelling and Software* 18:451–461.

Sadiq R, Husain T, Veitch B, Bose N. 2003. Risk management of drilling waste disposal in the marine environment—A holistic approach. *Oceanic Engineering International* 7:1–22.

Seaconsult Marine Research Limited. 2000. Modelled predictions of well cuttings deposition and produced water dispersion of the proposed white rose development. Salt Spring Island (BC): Seaconsult Marine Research Limited.

Singsaas I, Rye H, Frost TK, Smit MGD, Garpestad E, Skare I, Bakke K, Veiga LF, Buffagni M, Follum O-A, Johnsen S, Moltu UE, Reed M. 2008. Development of a risk-based environmental management tool for drilling discharges. Summary of a four-year project. *Integr Environ Assess Manag* 4:171–176.

Smit MGD, Jak RG, Rye H, Frost TK, Singsaas I, Karman CC. 2008. Assessment of environmental risks from toxic and nontoxic stressors; a proposed concept for a risk-based management tool for offshore drilling discharges. *Integr Environ Assess Manag* 4:177–183.

Smit MGD, Holthaus KIE, Trannum H, Neff J, Kjeilen-Eilertsen G, Jak RG, Singsaas I, Huijbregts MAJ, Hendriks AJ. 2008. Species sensitivity distributions for suspended clays, sediment burial and grain size change in the marine environment. *Environ Toxicol Chem* 27:1006–1012.

Trannum HC, Brakstad F, Neff J. 2006. Sediment characterisation and parameter estimation. ERMS Report No. 12. Akvaplan-NIVA Report no. APN-411.3119. http://www.sintef.com/erms.

[UKOOA] UK Offshore Operations Association. 2003. Drill cuttings initiative. Food chain effects literature review. Aderdeen (UK): Prepared for UKOOA by Hartley Anderson Ltd., Battelle Memorial Institute, School of Ocean Sciences at the University of Wales Bangor and Continental Shelf Associates Inc.

US Army Corps of Engineers. 2007. Part 3, Chapter 1: Coastal sediment properties. In: Coastal Engineering Manual. http://users.coastal.ufl.edu/~sheppard/eoc6430/manual/Part-III-Chap-1,%20Coastal%20Sediment%20Properties.pdf.

[USEPA] US Environmental Protection Agency. 1999a. Development document for proposed effluent limitations guidelines and standards for synthetic-based drilling fluids and other non-aqueous drilling fluids in the oil and gas extraction point source category. Washington DC: USEPA. EPA-821-B-98–021.

[USEPA] US Environmental Protection Agency. 1999b. Environmental assessment of proposed effluent limitations guidelines and standards for synthetic-based drilling fluids and other non-aqueous drilling fluids in the oil and gas extraction point source category. Washington DC: USEPA. EPA-821-B-98–019.