Flyer DREAM drilling

The numerical model approach to model regular discharges from drilling discharges is a combination of the DREAM model, as it has been developed or and applied to produced water risk assessment (Johnsen et al. 2000)and the numerical model ParTrack for calculation of dispersion and deposition of drill cuttings and mud (Rye et al. 1998, 2004; 2006).

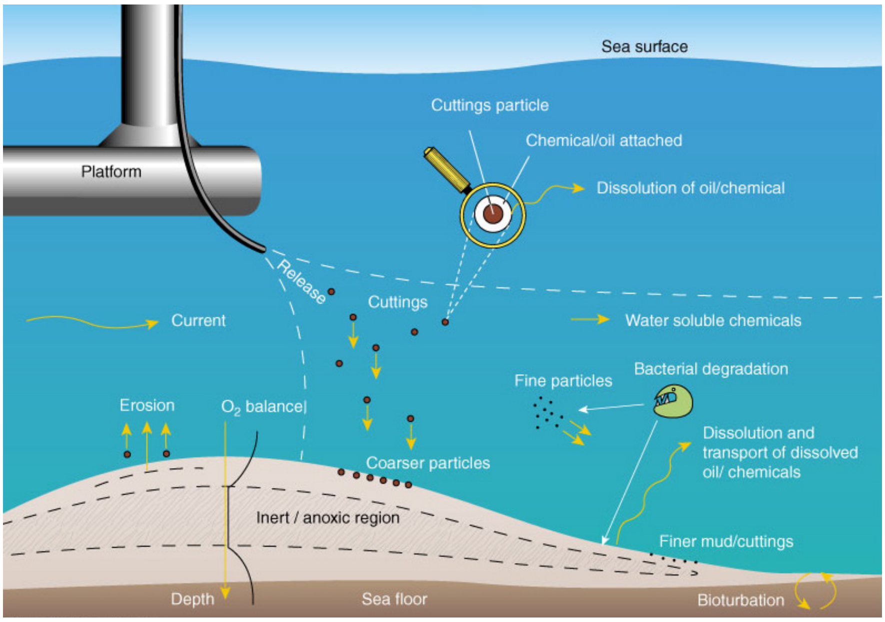

Figure 1: Schematic view of a drilling discharge and relevant processes.

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 states or phases, such as bubbles, droplets, dissolved matter 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 to the sea floor. Figure 2.1 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.

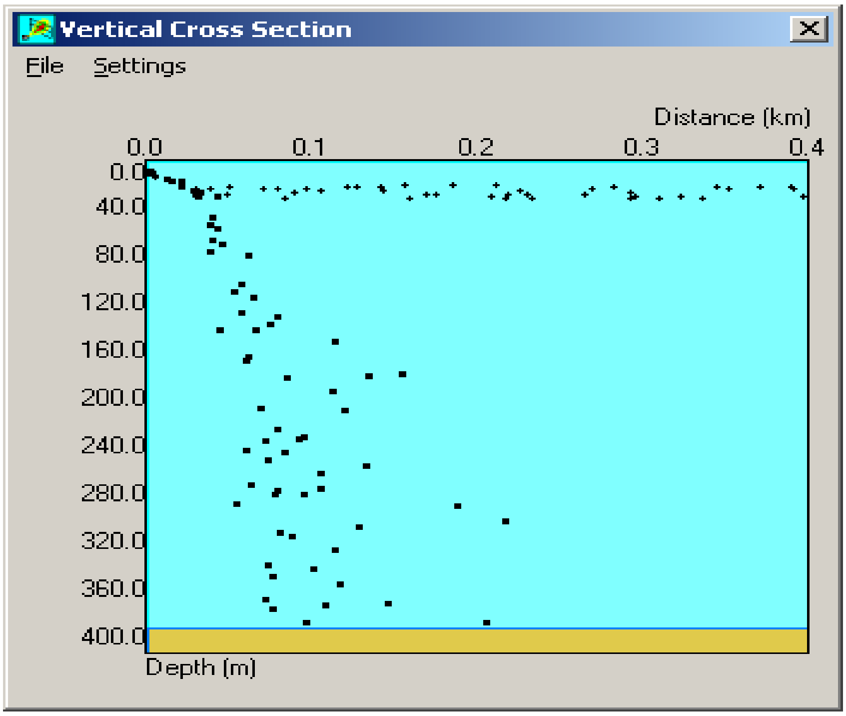

Figure 2.2 An example illustrating the vertical cross section of the near field plume and the deposition of particles on the sea floor. Discharge point to the upper left corner of the figure. Sea floor at about 400 m depth.

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:

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

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

The second 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:

$$W_2 = \sqrt{\frac{4}{3}\frac{d\,g'}{C_D}} \tag{2}$$

The drag coefficient C_D in this equation is a function of the Reynolds number ($\mathrm{Re} = W_2\, d / \nu$). On this basis, two asymptotic regimes are identified, the *Stokes* regime and the *Constant drag* regime (Equation 3):

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

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 the 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 Coastal Engineering Manual (2007) and the Equation 3 above. This equation takes into account that grains are usually non-spherical 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 2.2. For low diameter particles (diameters lower than 2 x 10^{-4} m), the equation corresponds well with the Stokes sinking velocity (Equation 1). For larger particle diameters (diameters larger than 2 x 10^{-3} m), the equation corresponds well with the friction dominated velocity (Equation 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 WBM (Water based Mud), most of the added chemicals are mainly assumed to dissolve in the water column. For other types of mud (e.g. OBM and SBM, Oil Based Mud and Synthetic Based Mud), 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.

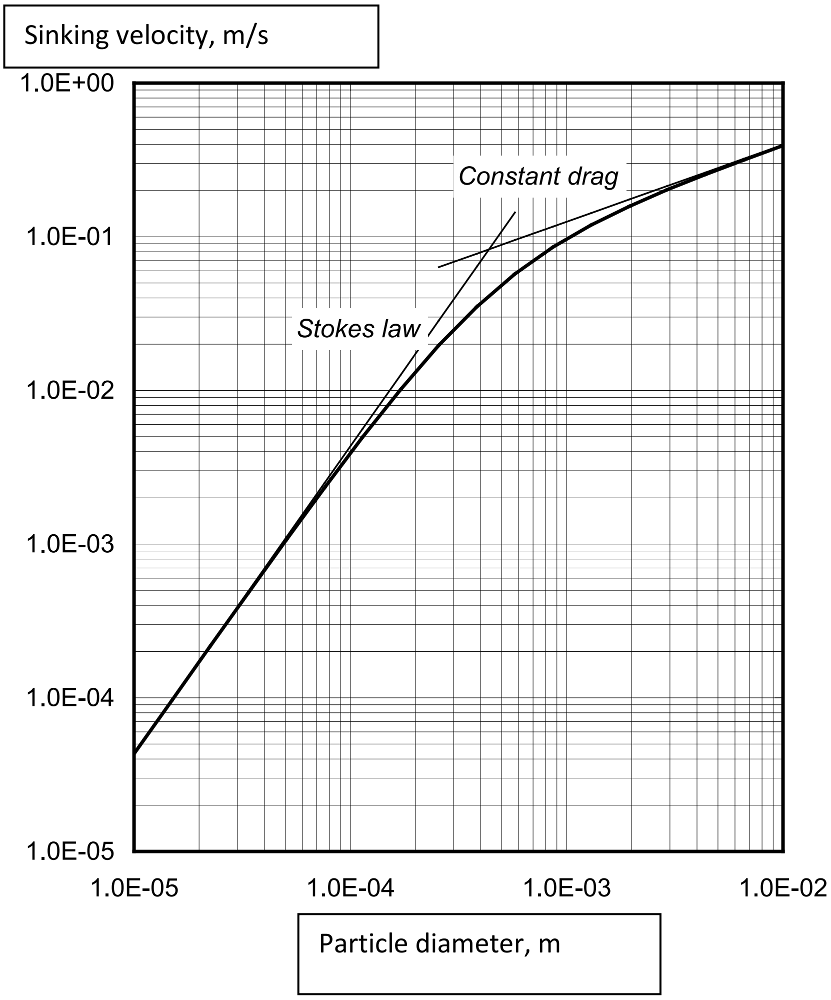

Figure 2.3 Particle size dependent variation in fall velocity of mineral particles in seawater. Solid density 2500 kg/m^3, resembling cuttings particles. Thin lines: Stokes law and constant drag law. Thick line: Interpolation formula.

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 logK_{oc} or logK_{ow} of ≥ 3 (or ≥ 1000 L/kg) can be used as a trigger value for sediment effects assessment”.

In accordance to the TGD the chemicals with low K_{ow} or K_{oc} values (< 1,000 L/kg) are assumed to dissolve (completely) in the water column. For large K_{ow} or K_{oc} values ($\geq$ 1,000 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}.

Figure 2.3 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).

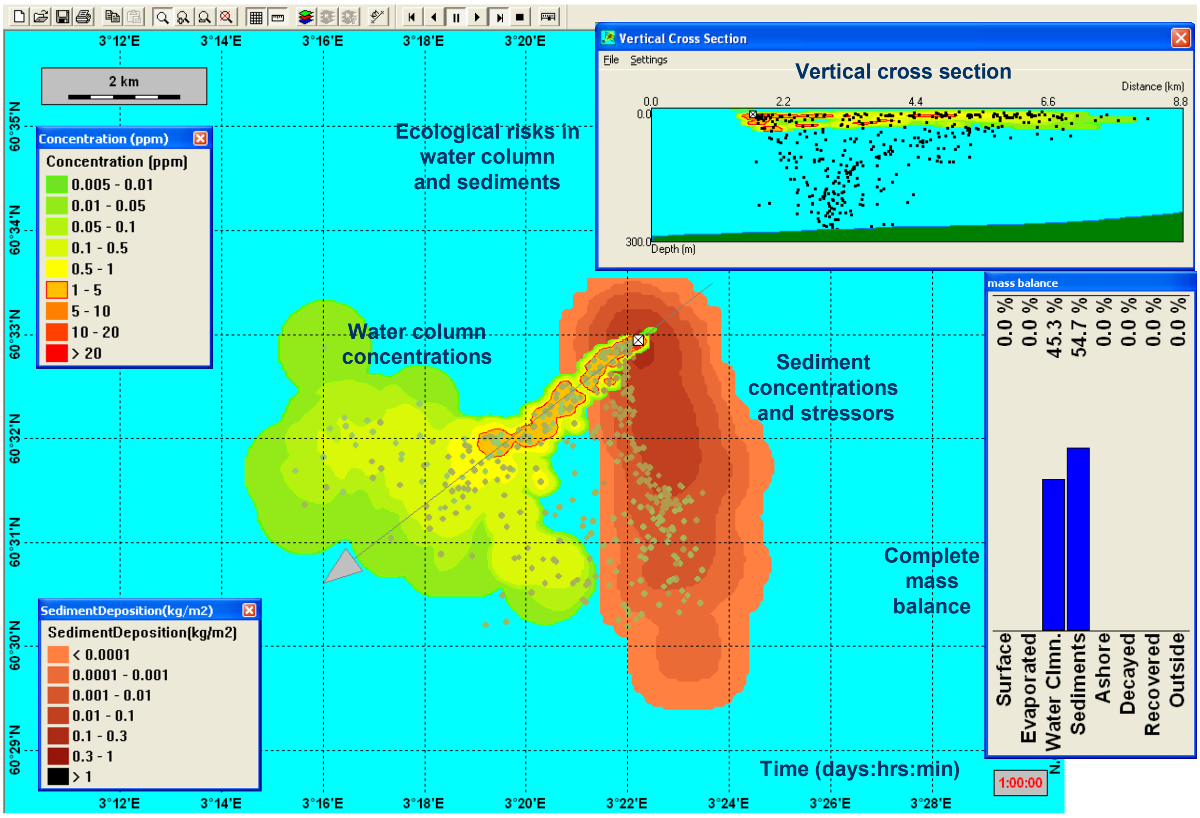

Figure 2.4 Visualization of the fate of drilling discharges. The figure demonstrates the following:

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/m2 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.

Flyer DREAM EIF Produced Water

Introduction

The operators on the Norwegian Continental Shelf (NCS) have agreed with the Norwegian Authorities to work towards a reduction of the environmental impacts from produced water releases (and from drill cuttings and mud releases as well) down to a level of "zero harmful effects". To more clearly define this goal, the EIF (Environmental Impact Factor) has been developed as an indicator of the potential impacts from produced water releases. The EIF is used as a measure of the environmental benefit achieved when alternate measures are considered for reducing environmental impacts.

The method has the advantage that it gives a quantitative measure of the environmental risks involved when produced water is released into the sea, and is thus able to form a basis for reduction of impacts in a systematic and a quantitative manner.

This method is based on the calculation of the EIF using the numerical model DREAM (*Dose related Risk and Effect Assessment Model*) developed by SINTEF, with financial support from Statoil, Norsk Hydro, ENI, Total, ExxonMobil, Petrobras, ConocoPhillips, and Shell.

General description of the method.

The EIF method is based on a PEC/PNEC approach, in which the concentration for each compound discharged into the recipient is compared to a concentration threshold for that compound. When the predicted (modeled) environmental concentration (PEC) is larger than the predicted no-effect concentration (PNEC), there may be a risk for ecological injury. When the PEC is lower than the PNEC threshold, the risk for injury is considered to be "acceptable".

An outline of the EIF method is given in Johnsen et. al., 2000.

The PEC

The PEC (Predicted Environmental Concentration) is the three-dimensional and time variable concentration in the recipient caused by the discharge of the produced water. The PEC is calculated for all compounds that are assumed to represent a potential for harmful impact on the biota. The calculations are using the numerical DREAM model. This model is fully three-dimensional and time variable. 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
- reduction of concentration due to biodegradation

Figure A.1 shows an example of a concentration field calculated with the DREAM model. The ocean current field used in the calculations is based on a hydrodynamic model operated by the Norwegian Meteorological Institute in Oslo. The output from the hydrodynamic model is used as input to the DREAM model. Further details on the model DREAM are presented in (Reed et. al., 2001).

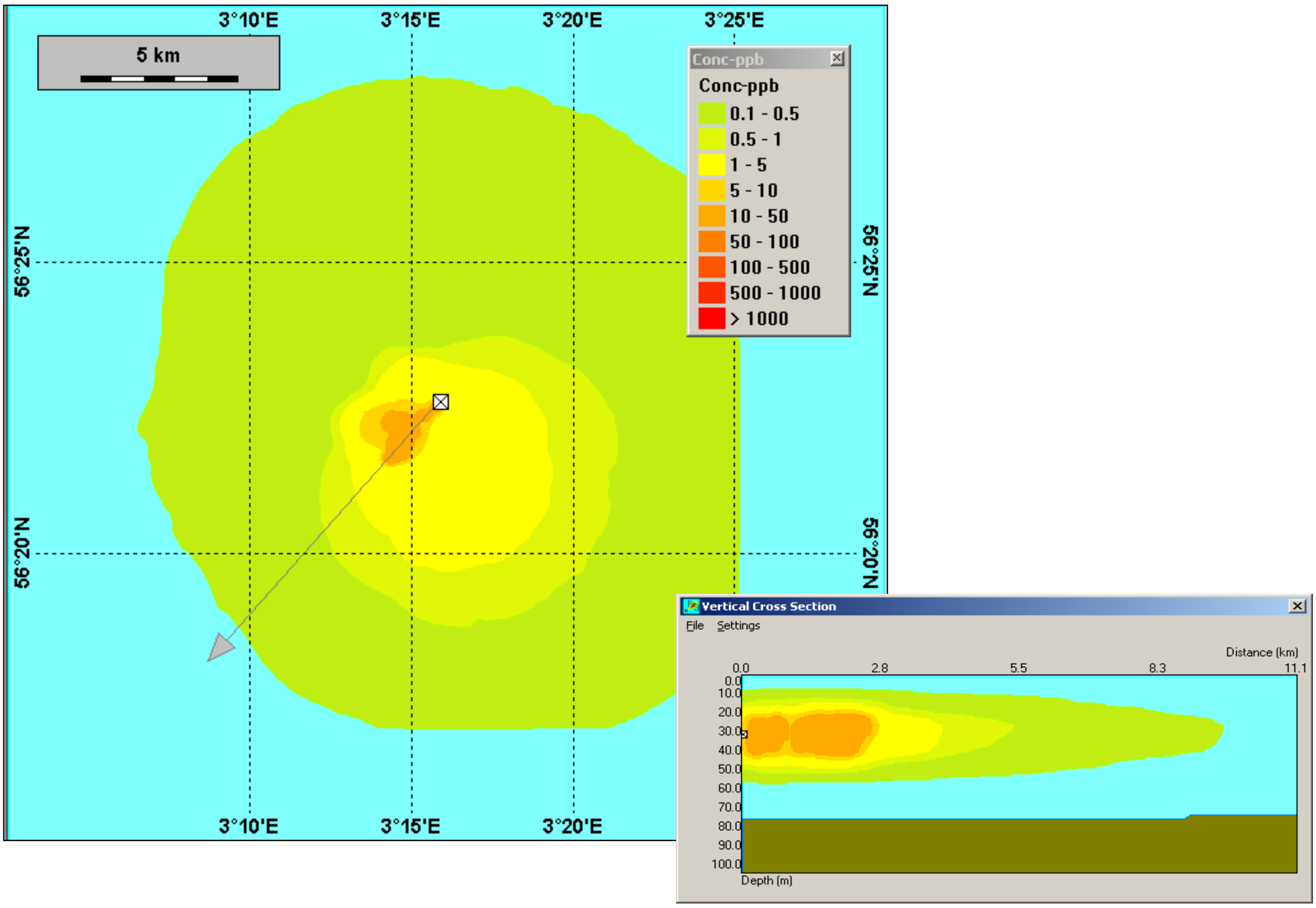

Figure A.1 Example concentration field for discharge. The concentration field shown is the total concentration including all substances in the release. Snapshot of the concentration field after 15 days of discharge.

The PNEC

The PNEC (Predicted No Effect Concentration) is the estimated lower limit for effects on the biota in the recipient for a single chemical component or component group. A PNEC level is given for each component in the produced water. It 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 some assessment factor in order to arrive at the expected PNEC.

A major data collection work has been performed in order to obtain data of sufficient reliability to be selected for determination of PNEC values. Different procedures have been selected for determination of the PNEC values for natural constituents in produced water and for added chemicals. Table A.1 shows the actual PNEC values used for natural compounds (or component groups) in produced water. For added chemicals, the PNEC values are usually based on the information found in the HOCNF (*Harmonized Offshore Chemical Notification Format*) scheme. Further details can be found in Johnsen et. al., 2000.

Table A.1 *PNEC values for natural constituents in produced water applied for the EIF calculations. Also, the table shows the list of natural constituents in the produced water presently applied in the DREAM EIF simulations for produced water.*

Natural compounds	**PNEC ppb**
Dispersed oil	40.4
BTEX mono-aromatics	17
Naphthalenes	2.1
PAH 2-3 ring (excl. naphthalenes)	0.15
PAH 4 - 6 ring	0.05
Phenols C0 - C3	10
Phenols C4 - C5	0.36
Phenols C6 +	0.04
Zinc (Zn)	0.46
Copper (Cu)	0.02
Nickel (Ni)	1.22
Cadmium (Cd)	0.028
Lead (Pb)	0.182
Mercury (Hg)	0.008

Environmental risk and the EIF.

The EIF for a single component or component group is related to the recipient water volume where the ratio PEC/PNEC exceeds unity. The ratio PEC/PNEC is related to the probability of biological injury according to a method developed by Karman et. al., 1994 (and also published in Karman and Reerink, 1997). When PEC/PNEC = 1, this corresponds to a level at which there exists a possibility of injury to the 5% most sensitive species. Figure A.2 shows the relation between the PEC/PNEC ratio and the probability of injury.

The EIF method has the advantage over other risk assessment methods in that it can calculate risk contributions from a sum of chemicals and/or natural compounds in the recipient. For the total risk from a sum of compounds, the total risk is calculated formulas for the sum of independent probabilities:

$$P(A+B) = P(A) + P(B) - P(A) * P(B) \qquad \text{(A.1)}$$

where P(A) is the probability of environmental risk for compound A and P(B) is the probability of risk for compound B. For small risks (that is, P(A) and P(B) are both small), or risks from chemicals which are toxicologically similar in their activity, the risks can be considered to be linearly additive, approximately. The method does not account for interactions among chemicals.

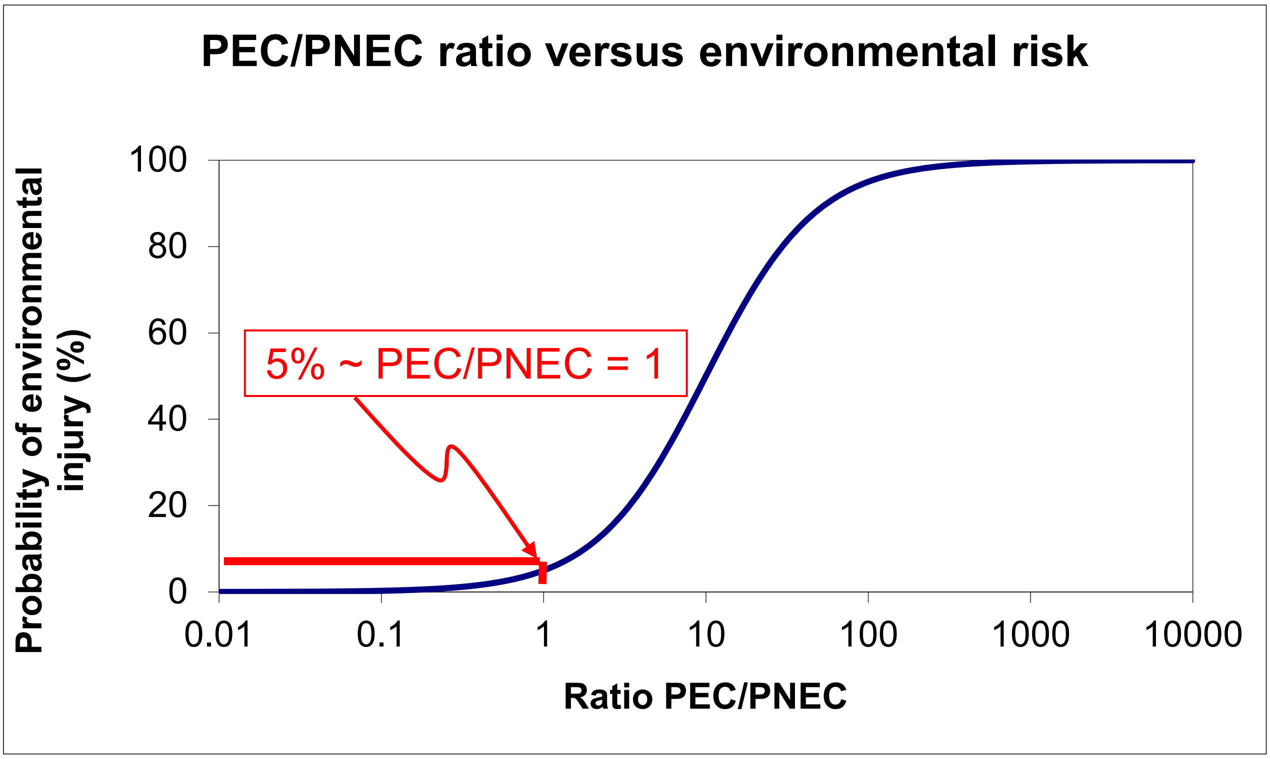

Figure A.2 Relation between the PEC/PNEC level and the risk level (in %) for injury to biota. Based on Karman et. al., 1994. PEC/PNEC = 1 corresponds to a level at which there exists a possibility of injury to the 5% most sensitive species

The total risk resulting from all components in a release is calculated by the DREAM model in space and time within the model domain. The sum of risks (for every point in space and for each time) is then summarized and converted back to a nominal PEC/PNEC value with the aid of the function in Figure A.2. The results are then presented as shown in Figure A.3 (snapshot in time). Results can also be presented as risk in percent. The water volume indicated by red then indicates the water volume where the nominal PEC/PNEC is larger than one. Note that the PEC/PNEC ratios for all individual components in the release may be less than unity, but the cumulative risk from all components may exceed 5%, such that the nominal PEC/PNEC ratio produced by the procedure described above, and representing a conglomerate value for the release, exceeds unity.

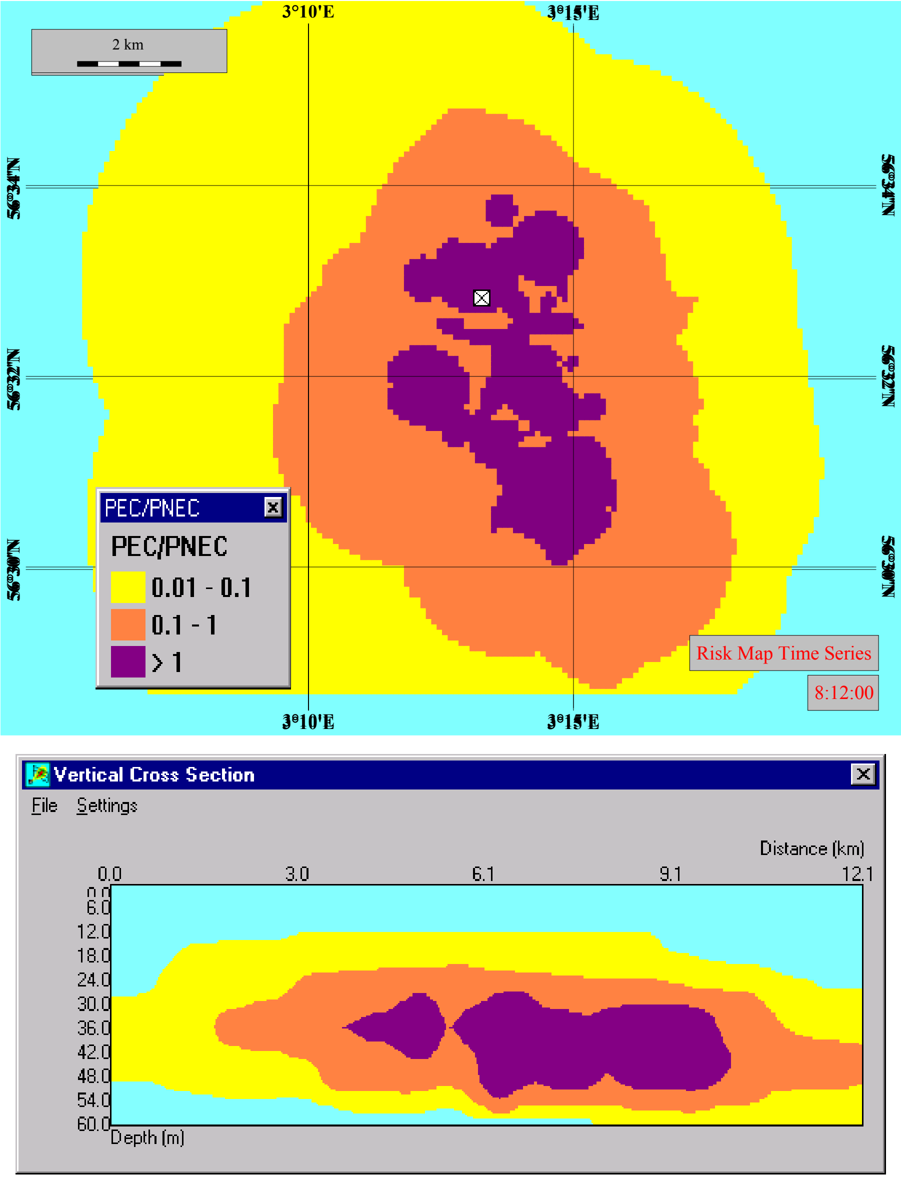

Figure A.3 Calculation of PEC/PNEC for the sum of various compounds in a discharge. Snapshot in time. Horizontal extent (upper figure) and vertical extent (lower figure) are both shown.

An EIF of unity is defined as a water volume 100 m x 100 m x 10 m (10^5 m^3) in which there is a risk of injury to the 5% most sensitive species. For a single component, this corresponds to a PEC/PNEC ratio exceeding unity. In addition, the EIF water volume is adjusted upwards by a factor of two for those compounds that have a small biodegradation factor combined with a large bioaccumulation factor. Details are given in Johnsen at. al., 2000.

An attractive feature of the EIF approach is that the method is able to discriminate among the various contributors to environmental risk. An example of the distribution of contribution to risk among components in a release is shown in Figure A.4. This capability provides useful information when comparing alternative proposed methodologies for reducing environmental risks associated with a discharge.

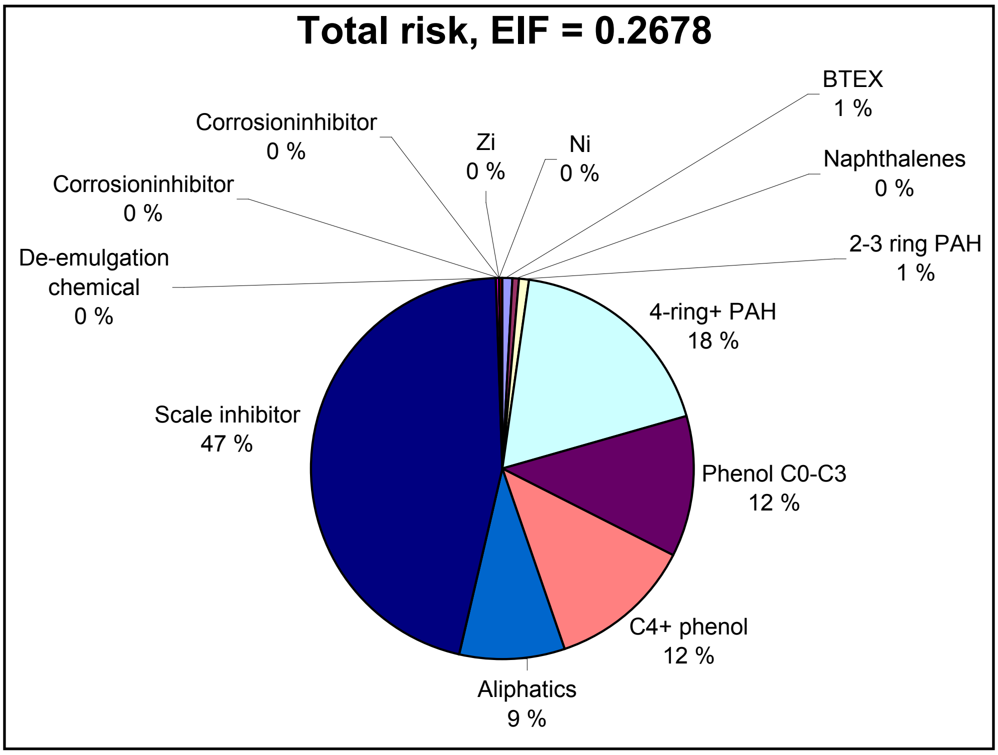

Figure A.4 Distribution of contribution to risk for an EIF calculation. Here the scale inhibitor contributes 47 % of the total risk.

Thus it is possible to separate a chemical product into its constituents and calculate the EIF contribution from each of them. The results of the calculations can then be used to improve the product in terms of replacing the constituents in the product with the largest contribution to the EIF.

As a “standard” for calculation of the EIF for the North Sea area, an ocean current field data base for the North Sea is applied (The OLF ocean current data base). This current data base comprises 5 years with data for the North Sea area (1990 – 1994). Time resolution is 2 hours and grid size is 20 km in the horizontal. A number of layers are included in order to account for vertical variations in the currents. The month of May 1990 is used as a “standard” for the EIF calculations for the North Sea area.

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