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# The derivation of a PNEC-water for weighting agents in drilling mud

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# The derivation of a $PNEC_{water}$ for weighting agents in drilling mud

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# Summary

Discharges of drilling muds and cuttings will result in increased concentrations of suspended particulate matter (SPM) in the water column, of which a substantial part will settle rapidly to the sediment surface. Smaller particles, however, may persist in the water column for longer time and may cause an impact on water column organisms, and organisms inhabiting the sediment but having contact with the overlying water. Particularly in water systems with relatively low suspended sediment concentrations (< 10 mg/l) an increase of the turbidity will lead to an increase of ecological effects (Van Dalfsen, 1999).

In order to assess the relevance and the potential impact of increased SPM concentrations due to the presence of weighting agents in Water Based Muds (WBM) discharges, a literature review is performed. The aim is to collect information that could contribute to establish a Predicted No Effect Concentration (PNEC) for weighting agents in analogy to the PNECs derived for toxic substances. These PNECs can then be used to derive the "Environmental Impact Factor (EIF) - water column" that will deal with the risk of effects of drilling discharges in the water column (Smit *et al*., 2006a).

The available information covers various taxonomic groups, enabling the use of assessment factors or Species Sensitivity Distributions (SSDs) to derive a PNEC. However, the quality of data is highly variable, because protocolised laboratory tests for suspended matter are lacking. The effect data on weighting agents include different types of particles (e.g. barite, bentonite, attapulgite and WBM) and several types of end-points (lethal and sub-lethal effects). In order to make use of the available acute data, application factors as described in the EU Technical Guidance Document, were applied to derive PNEC values for barite, bentonite, attapulgite and WBM (Note that no regulatory framework is available for the assessment of environmental effects of SPM). The calculated PNEC value for barite using marine assessment factors was 0.0032 mg/l. As the lowest observed (sub-lethal) effect level from a field realistic exposure was 0.5 mg/l (Cranford *et al*., 1999), this value for the PNEC seems to be very conservative. When PNECs are derived from SSDs, these values (0.2; 0.09; 1.8 and 0.8 mg/l for barite, bentonite, attapulgite and WBMs respectively) are less conservative and more in line with observed effect levels in the field and in field-relevant exposures. It is suggested to use these values in the calculation of the EIF for drilling discharges.

In order to gain more insight in the physical effects of SPM from WBM on marine organisms it is recommended to investigate the effects of barite/metals in WBM particles and to investigate the importance of these effects versus the toxicological effects of WBM chemicals. Furthermore, field studies with indicator organisms living in the Benthic Boundary Layer (BBL) for the North Sea and different types

of WBM with known compositions need to be performed in order to validate the model predictions.

Finally, there are ongoing long term studies (funded by the Norwegian oil industry and Norwegian Research Council) with fish (cod) and scallops/mussels exposed to water based mud (used) and barite/ilmenite particles. The results from the present study and the follow up-study (NRC) have to be taken into account in the future revision of the PNEC values for suspended particles.

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# 1. Introduction

## 1.1 Environmental Impact Factor for drilling discharges

The present study to derive threshold effect values for increased suspended matter (SPM) concentrations due to weighting agents in Water Based mud (WBM) is part of the ERMS (Environmental Risk Management System) project. The goal of the ERMS project is to develop an integrated model system to enable the offshore oil and gas E&P companies to perform risk analyses for different discharge scenarios (produced water and drilling operations). The work carried out within the scope of the ERMS project will build on the present Environmental Impact Factor (EIF) being used for produced water discharges aiming at the development of a similar factor for drilling discharges.

The Environmental Impact Factor (EIF) is developed as a management tool based on environmental risk and hazard assessment to identify the most potential environmentally harmful discharges (of produced water and drill cuttings/drilling muds) and to quantify the environmental benefit of different actions to reduce the hazard and risks. The basis for this approach is the comparison of the exposure and sensitivity for a range of disturbance levels i.e. burial (layer thickness on sediment), hypoxia (oxygen concentration in the sediment), particle densities in the water column and toxicity.

The EIF for drilling discharges will consist of two parts which will be developed separately (Smit *et al*., 2006a) and need to be integrated at a later stage of the ERMS project. The two parts concern:

1) An *EIF-water* for risk that may occur in the water column for the duration of drilling activities, resulting from the release of muds and cuttings. The disturbances included are:
    a) toxic substances;
    b) SPM.
2) An *EIF-sediment* that focuses on the risk for the benthic compartment as a result of drilling activities. The disturbances included are:
    a) toxic substances;
    b) change of grain size distribution;
    c) organic carbon enrichment;
    d) changes in the oxygen level.

In this report, an EIF will be developed for part 1b) of the ERMS project on drilling discharges. The current study focuses on the effects of drilling mud and cutting particles in the water column. The ecotoxicological effects and sediment disturbances caused by the settlement of particles will be discussed in different documents (Smit *et al*., 2006b).

## 1.2 Project description: The risk from SPM exposure as part of the EIF

To aid the offshore oil and gas industry in the development of the "zero harm" strategy and selection of cost-benefit based solutions, the EIF was developed as a part of DREAM (Dose-related Risk and Effect Assessment Model), based on major risk assessment principles, as defined by the European Union (EU). In this context DREAM is based on the traditional PEC (Predicted Environmental Concentration)/PNEC (Predicted No Effect Concentration) ratio approach, also termed Risk Characterization Ratio (RCR). The basis of this risk assessment is the comparison of the exposure (disturbance) of (a part of) the ecosystem to a chemical with the sensitivity of (the same part of) the ecosystem for this chemical (through this specific exposure-route). The PEC/PNEC approach is directly based on this comparison (see Figure 2 for a schematic overview). The principles of the method are described in the EU Technical Guidance Document (EU-TGD) (EEC, 2003) adopted by OSPAR (Agreement 2003-20). The application of Risk Assessment methodology with regard to Hazardous Substances by OSPAR is described in OSPAR ref. Nr. 2002-19.

In this report, a PEC/PNEC approach will be elaborated and applied to weighting agents in drilling muds, to be included in the acute EIF. The PNEC will be based on existing literature information to assess the potential physical effects of SPM from WBM in the water column. Thresholds for WBM will be derived based on the variation in species sensitivity and using safety factors following similar procedures as applied to toxic substances in the water column. Both approaches for the derivation of a PNEC are described in the EU-TGD (EEC, 2003).

The PEC/PNEC approach is especially developed for the evaluation of chemical substances and is included in several guidelines for risk assessment (e.g. CHARM and EU-TGD). In the current project the same approach is applied to a non-toxic stressor: suspended matter. A challenge in the application of the PEC/PNEC approach for SPM is the lack of a regulatory framework for this kind of exposure and the limited availability of specific information on the effects of particles that originate from drilling muds and cuttings.

The environmental concentrations of SPM originating from drilling operations in the marine environment will be based on representative field-verified model calculations for particles of drilling muds and cuttings[1]. For the derivation of the PNEC, data on physical effects of SPM from WBM on marine organisms is needed. The PNEC represents the sensitivity of the ecosystem, and is usually derived from protocolised toxicity tests. These tests are not available for SPM,

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1 Currently, the ParTrack model is used to assess the environmental fate of particles (from muds and cuttings). A field monitoring program is planned to verify the model predictions on particle distributions in the water column and the sediment (Rye, 2002).

however some specific experiments focussing on the effects of SPM have been carried out and reported. Since the nature of available data varies in quality and relevance for the study purpose, an evaluation similar to the expert judgement to evaluate the adequacy of toxicity data (EEC, 2003) is needed for effect data for SPM from WBM in order to allow the derivation of a PNEC.

For toxicity, the PNEC can be derived from chronic NOEC and/or acute $L(E)C_{50}$ data for trophic groups of marine organisms, by applying an assessment factor according to the EU-TGD (EEC, 2003). Increasingly, Species Sensitivity Distributions (SSDs) – logarithmic distributions of effect data for species – are used in ecological risk assessment to derive a PNEC. In the current report, it will be discussed whether a realistic PNEC can be calculated by using assessment factors or whether it should be derived from SSDs for SPM from WBM.

## 1.3 Activities

The literature study will focus on the physical effects of suspended particles from WBM and its clay particles in the water column. Quantitative data on different effect types and effect levels of WBM and clay particles were collected in a database for analysis. A challenge is the limited availability of specific information on the physical effects of these particles on marine organisms. Conform the approach for the effects of toxic substances from WBM in the water column, PNEC values will be derived in order to determine the variation in species sensitivity.

## 1.4 Scope of report

In chapter 2, a description of the physico-chemical characteristics and the environmental fate of WBM particles is given. The results of the literature survey on ecological effects of SPM are presented in chapter 3. The methodology to derive a PNEC from the quantitative data on physical effects from suspended particles of WBM on marine organisms is described in chapter 4, as well as the calculated PNEC values. Conclusions are drawn and discussed in chapter 5. Chapter 6 outlines the next steps to be taken for further research on the effects of SPM from WBM in the marine environment.

# 2. Physico-chemical characteristics of WBM

## 2.1 Drilling muds and cuttings

Drilling muds (fluids) used during offshore E&P drilling activities bring cuttings to the surface, control subsurface pressures, support the walls of the well hole, suspend the drill string and casing, prevent corrosion and cool and lubricate the bit. There is no standard prescription for the standard composition of drilling muds. The composition depends on the needs of the particular situations. These differ considerably in different regions and may even radically change during each drilling process. At present, three main types of drilling muds are used in offshore drilling. The Oil Based Muds (OBMs) are based on crude oil, oil products and other mixtures of organic substances (i.e. diesel, paraffin oils). The WBMs are based on water (freshwater or seawater with bentonite, barite and other components added). Drilling muds are usually not discharged overboard after a single application. Instead, they are regenerated and reintroduced in the circulation system. Synthetic Based Muds (SBMs) are based on products of chemical synthesis with ethers, esters, olefins and polyalphaolefins. Discharge of SBM is permitted in some marine areas on a limited basis, but is expected to be phased out soon.
During the last 10 years, preference is given to the use of the less-toxic WBM. However, in some cases, for example during drilling of deviated wells through hard rock, the use of OBM is still inevitable. Current legislation in the North Sea prevents discharge of cuttings containing more than 1% oil. Current platform based technologies cannot remove sufficient oil to meet this limit, so cuttings containing OBMs are either re-injected down the well or removed to shore for treatment.
Drill cuttings separated from drilling muds have a complex and extremely variable composition. This composition depends on the type of rock, drilling regime, formulation of the drilling fluid, technology to separate and clean cuttings and other factors (Patin, 1999).

## 2.2 Composition of mud

All WBM have at least one common ingredient: extremely hydrophilic clays. These clays are either added purposely (barite, bentonite-sodium montmorillonite or attapulgite) or occur naturally from drilled solids.
The two major functions of barite, bentonite or attapulgite in a drilling mud are; (i) increased viscosity (production of a collodial gel), and (ii) the formation of an impermeable filter cake (fluid loss control) on the bore wall (Khondaker, 2000).
Water-based drilling muds can be characterised as specially formulated mixtures of clays and/or polymers, weighting agents, lignosulfates and other materials suspended in water, with barium, chromium, lead and zinc often present at substantially higher levels than in natural marine sediments (Patin, 1999; Holdway, 2002) but lower than in clays (barite) used in the North Sea. Drilling mud additives

may be water-soluble, colloidal or particulate (Neff, 1987). For illustration the main components of two types of WBM are given in Table 1.

*Table 1 Representative composition of two types of WBM (Patin, 1999).*

| **Lignosulfonate WBM** | | **Polymer WBM** | |
|---|---|---|---|
| Component | Weight % | Component | Weight % |
| Seawater | 76 | Seawater | 80 |
| Barite | 15 | Barite | 17 |
| Bentonite | 7 | Bentonite | 2 |
| Lignosulfonate | 1 | Partially Hydrolysed Poly-Acrylamide (PHPA) | 0.2 |
| Lignite | 1 | Xanthan gum biopolymer | 0.2 |
| Starch | 0.2 | Starch | 0.6 |

## 2.3 Grain size of mud particles

Particle size analysis of the principal components of drilling mud, bentonite clay and barite, and of used WBM shows that they mainly consist of fine silt and clay particles. Particle size analysis of disaggregated inorganic drilling mud shows a very distinct size distribution with a modal diameter of < 1 µm (bentonite) (Cranford, 2001; Muschenheim & Milligan, 1996).
The environmental behavior of cuttings and barite will be strongly dependent on the sizes of the particles. Small-sized particles have a small ability to fall through the water column, and will thus be carried away with the currents.

## 2.4 Environmental fate

The primary concern with the discharge of WBMs and cuttings is their content of clays, which would be released in large quantities. In general, the larger particles will rapidly sink towards the seabed. The fine, mud-like particles have low sinking velocities and even weak currents may be enough to keep these particles in the water column and have them transported over long distances (Kenchington, 1997).

A number of fate models (Khondaker, 2000; Rye, 2002), based on field monitoring studies, has been developed to predict the deposition of the drill cuttings and mud on the sea floor as well as the concentrations of the drilling mud and chemicals in the free water masses. The Predicted Environmental Concentrations (PEC) of WBM and cutting particles in the water column in the current study will be based on the fate model *ParTrack* (Rye, 2002), which uses Norwegian field monitoring data on sediment build-up caused by drilling discharges (data available from the regular monitoring or surveillance of the sediments surrounding the discharge locations on the Norwegian Continental Shelf).

Drilling waste will undergo a number of physical-chemical processes upon discharge. The physico-chemical transport processes of drilling mud and cuttings discharges involve; (i) advection, (ii) dispersion, (iii) flocculation/aggregation, (iv) settling, (v) deposition, (vi) consolidation, (vii) erosion, (viii) re-suspension, (ix) re-entrainment, and (x) change in bed evaluation (Khondaker, 2000). The fate of the discharged drilling wastes (cuttings and fluids) will depend upon the local oceanographic conditions, quantities and conditions of discharge, amount, type of (and concentration of fluids on) muds and cuttings, and fall velocity of particles of muds and cuttings.

When drilling wastes are discharged into the marine environment, the dispersed solid phase mainly contains particles of clay minerals, barite and crushed rock. This solid phase differentiates and large and heavy particles are rapidly sedimented. Small (pellet) fractions gradually spread over large distances. Particles less than 0.01 mm in size can glide in the water column for weeks and months. As a result, large zones of increased turbidity are created around drilling platforms (Patin, 1999). Turbidity modifies the transmission of light through a column of the seawater; the total extinction varies proportionally to the concentration of suspended solid material, which causes the turbidity. Particle size determines the nature of the light scattering and subsequently the transparency. In the North Sea, water of low salinity usually has high turbidity values because of the inflow of freshwater from rivers (Kinne, 1971). Several field studies have shown that drilling fluids discharged to the ocean are diluted rapidly to very low concentrations, usually within 1000 to 2000 m down current from the discharge pipe and within 2 to 3 h after discharge. Quite frequently, dilutions of 1000-fold or more are encountered within 1 to 3 m of the discharge (Neff, 1987).
The environmental consequences of drilling wastes are often more similar to the situations emerging during bottom dredging and dumping operations or during some natural events (i.e. resuspension of bottom sediments as a result of storm and wave activities in shallow coastal waters) (Patin, 1999).

# 3. Environmental impact of WBM particles

## 3.1 Introduction

The replacement of OBM by WBM does not fully eliminate environmental hazards that were observed for discharged OBM. High mud concentrations can be found only in direct vicinity to the discharge point (within a radius of several meters). Comparative studies showed that marine organisms were more sensitive to the suspended particulate phase of drilling muds than to the liquid phase. This indicates that physical effects of suspended particles of WBM may contribute substantially to their effects (Patin, 1999).

Literature data on the physical effects of WBM particles on marine organisms are limited. As the properties of WBM particles and their inert constituents -clay particles- are considered to resemble those of SPM, the current chapter focuses on the physical effects of SPM on functional groups of marine organisms.

In estuaries and coastal areas, natural SPM concentrations are much higher (up to 400 mg/l) compared to the open North Sea (typically < 20mg/l). Particularly in water systems with relatively low suspended sediment concentrations (< 10mg/l) an increase of the turbidity will lead to an increase of ecological effects (Van Dalfsen, 1999). Plumes of SPM for offshore drilling activities can have an impact on fish, shellfish, algae and other marine organisms. The increased turbidity and sedimentation, which are normally considered as temporary impacts, can become chronic when large quantities are released (Dankers, 2002).

A distinction has to be made between turbidity in the water phase and subsequent sedimentation on and in the seabed (Figure 1). These different stages have their specific problems for different species. In the current study, the focus will be on the ecological effects of WBM particles in the water column and includes algae (phytoplankton), zooplankton, benthic filter feeders and predators, other invertebrates, fish and larger vertebrates (birds and mammals).

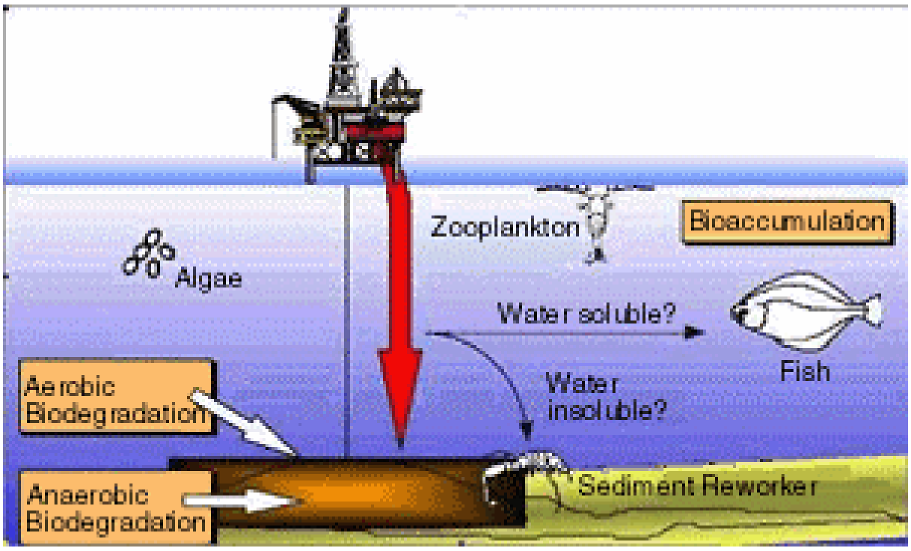


*Figure 1* *Impacts of discharged WBM on pelagic and benthic marine organisms, depending on the water solubility of the components.*

The two major ingredients in most WBMs, bentonite clay and barite, are practically toxicologically inert (Neff, 1987). Bentonite (sodium montmorillonite) is naturally occurring, insoluble clay that usually is considered non-toxic. It is added to drilling muds in quantities ranging from 30-140 kg/$m^3$ to provide viscosity to suspend barite and cuttings, as well as for filtration control.

Barite is a naturally occurring, highly dense, inorganic salt that is commonly used in water-based muds as a weighting agent. It is added as a fine powder in concentrations ranging up to 2,300 kg/$m^3$. Barite is insoluble, and when discharged at sea, will disperse over a wide area and settle to the sea floor (Bohem *et al.*, 2001).

Bentonite and barite may, however, cause physical damage through abrasion or clogging of gills, damage to the gastrointestinal tract or they may change the texture and grain size of sediments where they settle, rendering the substrate less suitable as habitat for some benthic species and more suitable for others. The acute toxicity of these natural mineral materials is usually greater than 7000 mg/l (96h $LC_{50}$) (Neff, 1987; Daugherty, 1951).

Benthic organisms are considered more sensitive to barite than pelagic species. For instance, suspended barite particles are most toxic to oysters with a 216 day $LC_{50}$ of 50-60 mg/l (Cabrera, 1971). Barite is also toxic to copepod *Acartia tonsa* and algae *Skeletonema costatum* with toxicity values at 590 and 385, 1650 mg/l respectively (EG&G, 1976; Hinwood *et al.*, 1994). Mysids, fish *Mollienisia latipinna*, and shrimp *Pandalus hypsonotus* are more tolerant to barite with $LC_{50}$s >100,000 mg/l (Dames & Moore, 1978; Grantham & Sloan, 1975; Leuterman *et al.*, 1989).

Bentonite is practically non-toxic in many 96-hr acute toxicity studies with $LC_{50}$s ranging from 22,000- >100,000 mg/l for various organisms. Studies show that bentonite is only toxic for the first few hours of exposure, while the solids were in suspension. Once the clay settled to the bottom, no further effects were observed (Carls & Rice, 1980).

Despite the relatively high values of $LC_{50}$ (usually $10^4$-$10^6$ mg/l) obtained in acute experiments for most drilling muds, they cannot be considered completely non-hazardous wastes. Under natural conditions and chronic impacts, these muds can cause effects that short-term testing is unable to predict (Patin, 1999).

Laboratory experiments have shown barium uptake, from WBM-contaminated sediments and foods, by both flounder and lobster juveniles. However, there does not seem to be any evidence for its biomagnification into the food chain. In the experimental setting, the contaminants suppressed growth of both species and enhanced lobster mortality at concentrations of 9 g/kg of sediment and a 98 or 99-day exposure – concentrations unlikely to be found offshore for such a prolonged period. The finer grain size of bentonite should ensure that it is at least as mobile as the barite and probably more so. Unfortunately, it might be environmentally damaging before reaching deep water (Kenchington, 1997).

In Russia, "Rules for water protection" (1991) do not allow increasing the SPM in fisheries water bodies over 0.25-0.75 mg/l above background natural levels. As direct observation in areas of exploratory drilling on the eastern shelf of Sakhalin showed, the persistent plumes of increased turbidity disturb the balance of production-destruction processes in the surface (photic) layer of seawater. It can also cause disturbances at the ecosystem level. Experimental evidence shows the negative effects of pellet suspension (particles with a size of 0.005-0.01 mm) on marine organisms. A short-term increase in concentration of such suspension above the level of 2-4 g/l caused quick adverse effects and death to fry of salmon, cod and littoral amphipods (Patin, 1999).

## 3.2 Ecological effects of WBM

In this chapter, an overview is given of the various effects of SPM published in the scientific literature. The effects are described for the organism groups as are commonly used in environmental risk assessments, to facilitate comparison. These groups are algae (phytoplankton), zooplankton, benthic filter feeders and predators, other invertebrates, fish and larger vertebrates (birds and mammals). Apart from the physical effects of inert WBM particles on organisms, it is possible that substances bound to these particles (i.e. metals) can be toxic to these organisms.

### 3.2.1 Phytoplankton

Decreased light penetration caused by higher turbidity can affect primary production and predators that feed on sight. Primary production is a source of food for marine organisms. It serves as the basis of the food chain. A change in primary production thus will have consequences for many organisms higher in the food web. In general, light is the most important limiting factor for primary production by phytoplankton. Furthermore, a decrease in light penetration can give rise to a shorter or shifted bloom period for algae or shifts in species composition of phytoplankton communities, or the introduction of deep-sea microbes to the surface zone (Dankers, 2002).

*Growth*
The preliminary results of a laboratory study on the effect of a mixture of kaolinite and montmorillonite of 30 mg/l on 10 algae species (size ranging from 4 to 70 µm) indicated that an increased turbidity of the water has negative effects on the growth and bloom of algae. At light limiting conditions this negative effect is increased. The effects of the clay particles are the largest for the smallest algae (Veldhuis *et al.*, 2002).

However, exposure of the small coastal diatom (*Thalassiosira pseudonana*) to WBM concentrations up to 50 mg/l for 10 days did not result in significant changes in algae biomass or physical condition (Cranford *et al.*, 1998). This suggests that not size, but rather adaptation to natural SPM conditions plays a major role.

Phytoplankton growth in the open North Sea is light-limited during winter, while phosphate and nitrogen are probably limiting in respectively spring and summer (Peeters *et al.*, 1993). In the latter period, light interception by suspended material will have only limited effects on phytoplankton growth, unless severe light limitation results in stronger growth reduction than nutrient limitation.

Microalgae, *Skeletonema costatum,* are affected by suspended bentonite at levels of 9600 mg/l. Again, this can be attributed to physical effects of bentonite, such as reduction of sunlight and reducing photosynthesis in the alga.

### 3.2.2 Zooplankton

Zooplankton is composed of small animal species with a pelagic mode of life. They may be herbivorous (feeding on the phytoplankton), or carnivorous (feeding on smaller zooplankton) or both. Most zooplankton species used in ecotoxicological testing and, therefore, in ecological risk assessment, are crustaceans. For this reason, zooplankton is treated here as a crustacean group. However, in fact the zooplankton comprises all small, pelagic biota, including crustaceans and other taxonomic groups.

*Shifts in community composition*
Mine tailings at concentrations of 40 and 300 mg/l increased total numbers of both larvaceans (appendicularians) and copepods over those in the control, possibly by both delaying and increasing primary productivity. On the other hand, dredged polluted sediments at concentrations of 11.2 and 112 mg/l appreciably depressed total numbers of copepods compared with controls, but did not produce a consistent pattern with respect to *Oikopleura* numbers (Lalli, 1992).

*Feeding behaviour*
High concentrations of SPM interfere with feeding of copepods. This may result in reduced growth and egg production, or in increased mortality due to starvation. Filter feeding species, such as *Pseudocalanus* sp. are more able to discriminate and select food particles among inedible particles than species that prefer larger prey, such as *Temora longicornis* (DeMott, 1988).

The food uptake of *Temora longicornis* and *Acartia clausi* was found to be reduced by about 15-25% in response to the addition of 10 mg clay to the natural phytoplankton community. The clay interfered with copepod feeding via the formation of aggregates, which fit into the food size spectra of marine copepods. As a consequence the daily carbon ration of various zooplankton species was reduced. This reduction was accompanied by a pronounced effect on the feeding selectivity of both species, which indicate that the flow of organic matter changes in the presence of clay (Dutz, 2002).

Paffenhöfer (1972) found a 5 to 8 times higher mortality of sub-adult stages of *Calanus helgolandicus*, as well as reduced growth and a changed swimming behaviour, due to exposure to 0.6 tot 6 mg/l red mud, which consists of very small anorganic particles. Four species of zooplankters reacted differently to suspensions of relatively large latex beads (45 µm diameter). The clearance of the ciliate *Favella ehrenbergii* and of the rotifer *Brachionus plicatilis* is almost unaffected by latex beads up to 38 mg/l. The gastropod veliger, *Philine aperta* showed significant grazing and behavioural responses to interference particles at natural concentrations of large particles. The copepodite stage of *Acartia tonsa* reacted to latex beads with a dramatic reduction in clearance presumably caused by an increase in jump frequency and interrupted swimming (Hansen *et al.*, 1991).

The filtration activity of the estuarine copepod *Eurytemora affinis* is affected by SPM concentrations of approximately 250 mg/l, whereas the filtration activity of *Acartia tonsa* is already reduced at a concentration of 100 mg/l (Sherk *et al.*, 1975). The latter species occurs seawards from *E. affinis*, where SPM concentrations are usually lower. In a field study, *A. tonsa* itself appeared to be less sensitive than *Centropages velificatus* and *Eucalanus pileatus*, which occur further offshore. *E. pileatus* was never found when SPM concentrations exceeded 42 mg/l, even though effects on food gathering efficiency were not observed at these concentrations (Tester & Turner, 1989). These results emphasize that species naturally occurring in high turbidity zones, are less sensitive to increased SPM concentrations than species in turbid conditions. Apparently adaptation to high SPM levels occurs.

*Reproduction and growth*
Barium concentrations of 5.8 mg/l have been observed to impair reproduction and growth in daphnids during 21-day tests (Biesinger *et al.*, 1986).

*Survival*
Uncontaminated suspended solids at a concentration of 500 mg/l caused no significant mortality of the freshwater water flea *Daphnia magna* within 48 h exposure (Weltens *et al.*, 2000).

### 3.2.3 Benthic filter feeders

Filter feeders, i.e. mussels, cockles and other shellfish mostly collect their food from suspension. They feed on bacteria, microzooplankton and phytoplankton. Grain size, organic fraction and the state of decomposal of the organic material are of high importance for filter feeders. Most filter feeders prefer small particles like silt and clay to distract their food from. A lot of them are even specialised in certain grain sizes. Higher SPM concentrations can cause obstruction and clogging of the filter apparatus. Furthermore, increasing turbidity causes limiting growth of phytobenthos (Dankers, 2002).

Specific data on effects of SPM on bivalve molluscs are only known for some intertidal species. It may be assumed that offshore species, adapted to lower natural levels of SPM, show a higher sensitivity, but also within species, populations from relatively 'clean' areas may be more susceptible than populations from areas with a higher natural turbidity. Little specific information is available on the effects of increased SPM concentrations on marine snails. Due to clogging of the gills, respiration may be affected, but probably to a lesser extent than in suspension-feeding bivalves (Loosanoff, 1962). The green-lipped mussel *Perna viridis* survived at test concentrations of 0-1200 mg/l SPM over a period of 96h. No significant changes in oxygen consumption and dry gonosomatic index were observed at concentrations of SPM of 0-600 mg/l at 14d exposure. However, under similar treatments in different concentrations of SPM and exposure time, gill damage was significantly greater in treatments (Shin *et al.*, 2002).
High SPM concentrations may interfere with olfaction, thereby hindering the ability of scavenging and predatory species to locate prey items (Loosanoff, 1962).

*Feeding behaviour*
Suspension feeding bivalve molluscs are sessile organisms and cannot move to another area to avoid high SPM concentrations. These organisms will, therefore, be strongly affected when the particles have a low food quality, since feeding may then become energetically ineffective (Barnes *et al.*, 1993). Consequently, suspension-feeding is most effective in relatively clean water (Loosanoff, 1962).

Some marine molluscs seem to be able to cope with elevated concentrations of suspended sediment by adjusting their feeding and digestion behaviour. Bricelj & Malouf (1984) suggested that a suspension-feeding bivalve's success in maximizing its energy gain in a turbid environment depends on the combination of two features: a high selection efficiency and a high rate of pseudofaeces production. It is proposed that species which regulate ingestion primarily by producing pseudofaeces are better adapted to cope with high suspended sediment loads than species such as *Mercenaria mercenaria*, which control ingestion mainly by reducing clearance rate.
It is known from the Blue mussel, *Mytilus edulis*, that they may adapt their feeding apparatus to the ambient suspended particulate material concentrations within a range of 0 to 50 mg/l. These adaptations are considered to be phenotypically and may be obtained within one growing season (Essink, 1993; Groenewold & Dankers, 2002). The clearance rate was increased at concentrations of 5 mg silt/l as compared to clearance in a pure algal suspension. Ingestion and growth rate were increased with algal concentration, and growth rate was further increased by the addition of 5 mg silt/l (Kiørboe *et al.*, 1981a).
At SPM concentrations of 100 to 200 mg/l, however, the filtration capacity is reduced, whereas it is completely inhibited above 250 mg/l (Widdows *et al.*, 1979). For small particles (< 2 µm) in the near field, movement of cirri of *Mytilus edulis* was essential for successful capture of particles either by direct contact or with water acting as a hydromechanical coupler (Silverman *et al.*, 1999). However, controversy still attends the question whether bivalves exercise selectivity over ingested material (Bernard, 1974).

Barium (as barium acetate) caused abnormal shell calcification and embryo morphology in California mussels *Mytilus californianus* at concentrations of 200-900 µg/L (Spangenberg & Cherr, 1996), well above the single-phase solubility of barium in seawater).

The soft shell clam, *Mya arenaria*, seems to be more sensitive than the Blue mussel. Already at SPM concentrations below 20 mg/l, its filtration rate decreases, while feeding stops at SPM concentrations of 100 to 200 mg/l (Grant & Thorpe, 1991).
Oysters, *Crassostrea virginica*, showed a marked decrease in pumping rates (~50%) at 100 mg/l (the lowest concentration tested) of silt, clay, or chalk. Prolonged exposure (48h) resulted in longer recovery periods, indicating serious injury to the ciliary system of gills and palps (Loosanoff, 1962). The species experienced more effects than controls in a 192-day study with $LC_{50}$s of 110-119 ppm (Cabrera, 1971). This is probably due to the effects of bentonite deposition on bottom sediments and burial, interfering with normal functions of the animals. Toxic responses that occur as a result of physical harm include abrasion, erosion, or clogging of respiratory surfaces (Sprague & Logan, 1979). Also the oyster species *Crassostrea gigas* is sensitive for high SPM concentrations. Smaller gills and larger labial palps were observed in specimens at a higher turbidity zone

compared to specimens from a low turbidity zone in the same bay (Barillé *et al.*, 2000).

The clearance rate of cockles (*Cerastoderma edule*) declined with increasing suspended bottom sediment concentrations, the regulation of ingestion rate at high particle load was mainly achieved by pseudofaeces production (Navarro *et al.*, 1992). Møhlenberg & Kiørboe (1981) have observed an increase of the growth rate of *Spisula subtruncata* with increased concentrations of suspended bottom material of 10 to 110 %. This positive effect of suspended bottom material on growth is due to a higher efficiency of assimilation of the ingested algae and/or to the utilization of organic matter in the suspended bottom material.
However, a treatment of *Spisula solidissima*, with 100 to 1000 mg/l attapulgite indicated that anthropogenic turbidity-producing discharges at levels as low as 100 mg/l may have adverse effects on the feeding and digestive efficiency of surf clam populations. The levels generally encountered in continental shelf bottom waters are generally lower (< 5 mg/l) than the concentrations of attapulgite tested (Robinson *et al.*, 1984).

In a test with daily doses of 1,2 and 3 mm depth equivalents barite showed to adversely affect the ctenidia of the suspension feeding bivalve, *Cerastoderma edule* and the deposit feeder, *Macoma balthica*. In some extreme cases the gill structure disintegrated. There was 100% mortality within 12 days (Barlow & Kingston, 2001).
In contrast to the general picture of limited effects of WBM discharges, Cranford & Gordon (1992) reported low tolerance of dilute bentonite clay suspensions in *Placopecten magellanicus*. Sea scallops fed natural seston without added bentonite displayed filtration rates twice as high as when 2 mg bentonite/l was added. When provided with a diet of *Tetraselmis*, a similar reduction in filtration rate required bentonite concentrations exceeding 6 mg/l, levels lower than 1 mg/l enhanced filtration rates (Cranford & Gordon, 1992).
The sensitivity of scallops seems to be based mainly on physical interference with feeding structures, caused by elevated amounts of fine material in suspension. At extremely high concentrations of SPM, irreversible physical damage to the gills may occur (Muschenheim & Milligan, 1996).

*Growth*
Concentrations, as low as 0.5 mg/l of barite, caused significant detrimental effects to adult scallop growth. Threshold drilling waste concentrations causing reductions in somatic and/or reproductive tissue growth are: > 10 mg/l for used WBM, 2 mg/l for bentonite and 0.5 mg/l for barite. Non-nutritious particles in the food supply and chemical toxicity affected the growth rate and survival of sea scallops by altering physical state (scope for growth) and nutritional condition (O:N ratio)(Cranford *et al.*, 1999). In a similar study with sea scallops, extensive chronic mortalities and significant impacts on somatic and reproductive tissue growth were inhibited at suspended bentonite concentrations of 10 mg/l (Cranford & Gordon,

1992). Sediment concentrations in the lowest levels of the benthic boundary layer of the water column (levels in which scallops live and from which they draw their food) can be 100 times higher than those only a few metres above the bottom. In one survey, around a site at which drilling had been proceeding for seven months, tidally-resuspended bentonite was found at detectable levels even at the most distant station sampled, 8 km from the platform, though the concentrations there seem to have been around 0.01 mg/l and so should not have been high enough to affect scallops. What significance these results may have for scallop growth and survival around platforms remains unclear. There is the potential of some suppression of production, through reduced growth and increased death rates, within a few kilometers of each platform while drilling is in progress (Kenchington, 1997).

Cranford *et al.* (1999) found that used WBM and its major constituents, bentonite and barite caused effects on the growth, reproductive success and survival of sea scallops, which were attributed to chronic toxicity and physical disturbance. It may be that *Placopecten* is especially sensitive to drill muds (or fine sediments in general) or that in the field, water based drilling discharges very rapidly disperse to below effective concentrations.
Similarly, suspension-feeders may be more impacted than deposit/sediment-feeders. Specific information is, however, scarce. Data were only found for the tunicates *Ciona* and *Ascidiella*. These are suspension-feeding animals that feed on very small particles (<2 µm), but lack specific mechanisms to separate these from inedible particles. At SPM (Fuller's earth; attapulgite) concentrations as low as 25 mg/l effects were observed, with growth being completely halted in *Ciona*. Mortality, however, only occurred after prolonged exposure (at least 5 days) to SPM concentrations of 600 mg/l (Robbins, 1985).

*Shifts in community composition*
Studies of the effects of WBM discharges from 3 production platforms in 130-210 m off California found significant reductions at some stations in the mean abundance of 4 of 22 hard bottom taxa investigated using photographic quadrats. It was concluded that these reductions reflected possible negative responses to drilling discharges, attributed to the physical effects of particulate loading, namely disruption of feeding or respiration, or the burial of settled larvae (Hyland *et al.,* 1994; DTI, 2002). The effect of suspended matter only cannot be obtained from this information.

### 3.2.4 Benthic deposit feeders

Compared to suspension feeders, less severe effects are expected for deposit-feeding species, since these species do not actively filter SPM, but use a water flow to suck up deposited material, which normally will contain a relatively high amount of inorganic particles. Rhoads & Young (1970) even postulated that active burying deposit-feeders could render an area unsuitable for suspension-feeders by bringing particles in suspension.

*Feeding behaviour*
The presence of inert clay materials from WBM might be advantageous for the feeding efficiency of deposit feeders. *Corophium volutator* can only utilize bacteria adsorbed to particles within the size range 4-63 µm (the presence of clay and silt particles in the sediment is necessary for efficient feeding of this amphipod). *C. volutator* can utilize bacteria suspended in the water pumped through its burrow for respiration if silt and clay particles are present in the sediment (Fenchel *et al.,* 1975). A feeding model for deposit feeders predicted that the smallest particles should always be ingested, while the selection of larger particles depends on several parameters, including gut passage time and assimilation efficiency of the deposit feeder (Taghon *et al.*, 1978).

### 3.2.5 Benthic predators

Not much is known about the sensitivity of larger crustaceans for suspended particles. High concentrations of suspended particles may result in clogging of the gills and interfere with foraging behaviour. Some mobile invertebrates (e.g. the swimming crab *Liocarcinus holsatus*) are known to avoid clouds of SPM (Groenewold & Dankers, 2002).

*Feeding behaviour*
Antennular and leg chemoreceptors are important in eliciting normal feeding behaviour in lobsters, Although behavioural assays have demonstrated that feeding behaviour is altered following exposure to drilling muds, there is no conclusive proof for a causal relationship between chemoreceptor interference and behavioral deficits (Derby & Atema, 1981).
Conklin & Rao (1984) found histological damage to the posterior gut epithelium in grass shrimp consuming pure particulate barite.

*Survival*
In several chronic studies with shrimp *Palaemonetes pugio* and substrates heavily contaminated with solid barite, there were elevated amounts of barium in the exoskeleton, hepatopancreas, and muscle tissue.
*Palaemonetes pugio* exposed to a substrate of particulate barite for up to 106 days, ingested the barite. Although this did not affect survival of the shrimp, several sub-lethal responses were observed. Barite ingestion caused damage to the epithelium of the posterior midgut, possibly in part by abrasion (Neff, 1987).
First stage lobster larvae (7-17 days old) exhibited a significant decrease in survivorship at 100 mg/l WBM, but the lower concentrations had no effect (Cranford *et al.,* 1998).

*Vertical movement and swimming*
Swimming activity in larvae of Dungeness crabs and dock shrimp was inhibited following exposure for 24 to 119 h to 400-4280 mg/l suspensions of barite or bentonite in seawater (Neff, 1987).

### 3.2.6 Other invertebrates

Generally, the susceptibility of other invertebrate taxa to increased SPM concentrations will follow the same patterns as is described above. Thus, estuarine and coastal species adapted to environments with a relatively high natural load of suspended material, are probably less sensitive compared to species having their optimum occurrence further offshore.

Red abalone (*Haliotis rufescens*) were used in a series of laboratory experiments with drilling muds from a platform off southern California to determine the effects of drilling muds on fertilization, early development, survivorship and settlement. Several exposures to drilling muds resulted in weak, but significant, positive effects of drilling muds on settlement of competent larvae. This suggests that drilling muds affect either the abalone's ability to detect natural settlement inducers, or they affect the inducer itself (Raimondi *et al.,* 1997).

### 3.2.7 Fish

Some fish and birds may be curtailed in their possibilities to catch food. Not only by the decrease in light intensity but also by the changes in the spectral composition and polarisation pattern of the light. Some fish and mobile invertebrates have shown to flee from clouds of SPM (Dankers, 2002). An increased suspended sediment concentration influences the food uptake of filter feeders, the oxygen uptake through gills of fish, fish larvae and invertebrates and the exchange of gasses by fish eggs. Sublethal effects are observed by concentrations of 100-300 mg/l (Baveco, 1988).

*Filtering activity and respiration*
Static bioassays conducted with fuller's earth (attapulgite) suspensions on white perch, spot, silversides, bay anchovies, mummichogs, striped killifish and menhaden showed that significant mortality in five of the seven species could be caused by concentrations of natural suspended solids typically found in estuarine systems during flooding, dredging and spoil disposal. Lethal concentrations ranged from as low of 580 mg/l fuller's earth (24 hr LC10) for silversides to 2450 mg/l fuller's earth (24 hr LC10) for mummichogs. Generally bottom-dwelling species were most tolerant to suspended solids; filter feeders were most sensitive. Early life stages were more sensitive to suspended solids than adults.
Exposure to sublethal fuller's earth concentrations significantly increased hematocrit value, hemoglobin concentration and erythrocyte numbers in the blood of white perch, hogchokers, and striped killifish but not of spot and striped bass. Evidence of $O_2$-$CO_2$ transfer interference during exposure to sub-lethal concentrations of fuller's earth was exhibited by the gills of white perch, which showed tissue disruption and increased mucus production (Sherk *et al.,* 1975).

The clay fraction of suspended solids may injure gills since these particles tend to remain in suspension and are hard and angular. The inert suspended clay kaolin was found intracellular in gills of rainbow trout, *Salmo gairdneri*, since the uptake of the clay is stimulated by phagocytosis (Goldes *et al.*, 1986). Study on fish with exposure to clay particles up to concentrations of 2000 mg/l during 144 h revealed no mortality. An increased respiration rate, morphological changes in gill tissue and decolouration of the skin in fish at chronic exposure to low concentrations (90 mg/l) of solids were also reported in literature (Weltens *et al.*, 2000).

*Growth*

Very few studies have looked at the effects of drilling fluids in the region within the first few meters of the seabed known as the Benthic Boundary Layer (BBL). This region has specific characteristics, which differ from the overlying water column and may result in particles settling from the overlying water column remaining suspended and concentrated within the BBL. Fine drilling wastes in the BBL can develop over periods that are ecologically significant and that they may remain suspended in the BBL and be detectable several kilometres from the discharge point.

*Feeding behaviour*

Larvae and eggs of fish are more sensitive for an increased concentration of suspended sediment than adult life stages. Concentrations above 100 mg/l can already result in an increased mortality (Van Dalfsen, 1999). It is suggested that concentrations of SPM in the region of 200 mg/l damages the gills of fish; higher concentrations are said to inhibit feeding activity of fish (Kinne, 1971).
Herring larvae fed at 20 mg dry sediment/l did consume significantly fewer *Artemia* nauplii than did the controls. Smaller larvae were found to be more affected by increased levels of suspended sediment than are larger larvae (Johnston & Wildish, 1982).

*Survival*

Survivorship of embryos and larvae was determined following 96-h acute exposures to 0, 1, 10, 50, and 100 mg/l WBM. Late-stage haddock embryos (8-12 days old) and yolk sac larvae (3-7 d post-hatch) showed a significant decrease in survivorship only at the highest WBM concentration tested. Early-stage embryos (1-4 days old) and feeding-stage larvae (13-17 days post hatch) showed no significant response to any of the WBM concentrations. Eggs of herring (*Clupea harengus*), exposed to constant concentrations of 5-300 mg/l or to a short-term high concentration of 500 mg/l silt, also showed no significant effects at different times during embryonic development. In this study, it was concluded that no harmful effects of dredging and similar operations to herring spawning grounds are likely to occur at the tested concentrations of silt (Kiørboe *et al.*, 1981b).

Concentrations of 1,000 mg/l of suspended sediments from Chesapeake Bay significantly reduced the hatching success of white perch and striped bass, but lower concentrations did not. Experiments with larvae indicated that concentrations of 500 mg/l significantly reduced the survival of striped bass and yellow perch larvae exposed for 48-96 h. Concentrations above 100 mg/l significantly reduced the survival of shad larvae continuously exposed for 96 h (Auld & Schubel, 1978).

*Sight*
Fish that are visual hunters are dependent on the amount and spectrum of light and the clarity of the water in order to locate and recognise prey. The sight of these fish species can be hindered by a high turbidity of the water column. The mackerel avoids a turbidity of more than 10 mg/l. When the turbidity lasts for a longer period, the mackerel might migrate to less turbid water.
Fish larvae use light to regulate their vertical migration. With increased turbidity the light penetration in the water column is limited, which misleads larvae to move to shallower and more unfavourable water (RIKZ, 1999).
Visual predators i.e. fish (herring, mackerel and turbot) and birds (cormorants, divers and sea ducks) are dependent on the amount of light and the clearness of the water to track and recognise prey species. Alteration of the turbidity influences the opportunity for a predator to capture a prey on one hand, while on the other hand the escape possibilities will be negatively influenced. From observations of herring and sprat it is known that they avoid turbid water. This can have severe consequences when the turbidity of the spawning area is increased (Van Dalfsen, 1999).

### 3.2.8 Effects on birds

Increased SPM concentrations can affect birds indirectly by changing the food web and food availability, and directly by reducing water transparency and detection of prey. Direct effects are especially relevant for plunge-diving species (e.g. terns, Gannet) that detect their prey when flying above the water surface. An increase of SPM in the top layer of the water column may drive away birds to other areas, change feeding technique, and lower the foraging success.

Little quantitative information is available. Marine tern species have a maximum diving depth of about 2 m, and it is suggested that foraging will only be affected in case transparency is reduced to less than 2m. Catching success is halved when transparency is reduced from 2 m to 50 cm (Stienen & Brenninkmeijer, 1994). Consequences for the fitness of individual birds, and consequences on the population level are unclear, but probably of little importance, since increased turbidity is limited to small (surface) areas. Species that feed underwater by way of pursuit diving (e.g. Guillemot, Cormorant) are thought to be less sensitive.

# 4. Risk assessment on SPM particles in drilling muds

## 4.1 Framework for risk assessment

### 4.1.1 Overview of guidelines

In order to evaluate the risk to the marine environment at an environmental concentration of substances, the European authorities have developed the well-known Predicted Environmental Concentration (PEC)/Predicted No Effect Concentration (PNEC)-ratio approach (EEC, 2003). The PEC is measured or estimated from different fate and exposure models while the PNEC is usually estimated by applying assessment factors, depending on the quantity and the quality of the available toxicity data, towards the most sensitive organism toxicity value (EEC, 1996; Garay *et al.*, 2000).

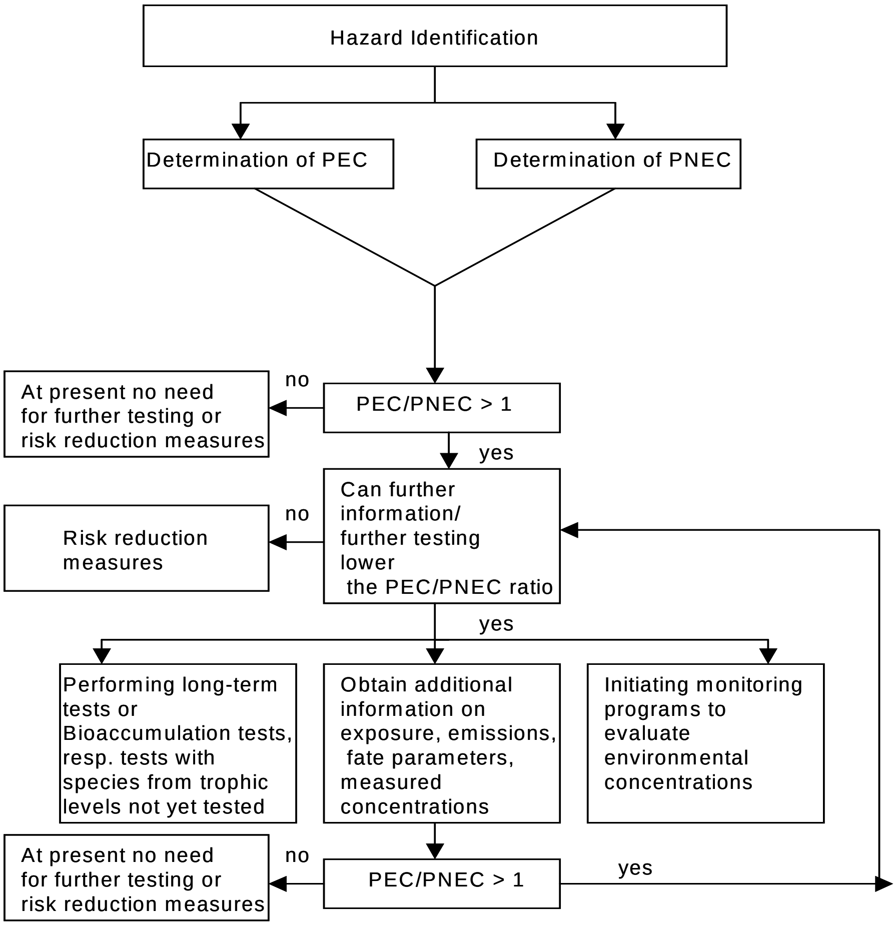


*Figure 2 General procedure for environmental risk assessment according to the EU-TGD (EEC, 1996).*

The ratio of PEC and PNEC (or the RCR) gives an indication of the likelihood of adverse effects to occur as a result of exposure to the specific chemical. It does, however, not provide a quantification of the environmental risk. The PEC/PNEC ratios can be translated into a probabilistic risk measure (i.e. the probability that an organism will be affected) on the basis of empirically estimated variation in sensitivity amongst marine biota derived from SSDs (Smit *et al*., 2005). As a cut-off criterion, the exposure of marine organisms to substances in their aquatic environment is considered acceptable if not more than 5% of the marine species is at risk at a PEC/PNEC ratio of 1 (EEC, 2003; Newman *et al.,* 2000; Van der Hoeven, 2001).

### 4.1.2 General determination of PNEC

Certain assumptions are made concerning the aquatic environment that allow an extrapolation to be made from single-species short-term toxicity data to ecosystem effects. It is assumed that:

– Ecosystem sensitivity depends on the most sensitive species, and;
– Protecting ecosystem structure protects community function.

These two assumptions have important consequences. By establishing which species is the most sensitive to the toxic effects of a chemical in the laboratory, extrapolation can subsequently be based on the data from that species. Furthermore, the functioning of any ecosystem in which that species exists is protected provided the structure is not sufficiently distorted as to cause an imbalance.

The definition of PNECs according to the EU-TGD (EEC, 2003) is:

*The concentration below which unacceptable effects on organisms will most likely not occur.*

### 4.1.3 Using assessment factors

It is generally accepted that protection of the most sensitive species should protect structure, and hence function. For most substances, the pool of data from which to predict ecosystem effects is very limited as, in general, only short-term toxicity data are available. In these circumstances, it is recognized that, while not having a strong scientific validity, empirically derived assessment factors (Table 2 and Table 5) must be used. Assessment factors have also been proposed by the US-EPA and OECD.
In applying such factors, the intention is to take into account the uncertainties in the information to predict a concentration below which an unacceptable effect will most likely not occur. It is not guaranteed to be a level below which the chemical is considered to be safe. However, it is likely that an unacceptable effect will not occur (EEC, 2003).

The PNEC can be derived from NOEC and/or $L(E)C_{50}$ data for three trophic groups of marine organisms, by applying an assessment factor. A lower assessment factor will be applied on the lowest NOEC derived in long-term tests with a relevant test organism (EEC, 2003). The assessment factors applicable on thropic groups of fresh water organisms (Table 5; EEC, 1996) are a factor 10 lower than the marine assessment factors (Table 4; EEC, 2003).

*Table 2 Assessment factors proposed for deriving $PNEC_{water}$ for saltwater for different data sets (EEC, 2003)*

| Data set | Assessment factor |
|---|---|
| Lowest short-term $L(E)C_{50}$ from freshwater or saltwater representatives of three taxonomic groups (algae, crustaceans and fish) of three trophic levels | 10000 |
| Lowest short-term $L(E)C_{50}$ from freshwater or saltwater representatives of three taxonomic groups (algae, crustaceans and fish) of three trophic levels, + two additional marine taxonomic groups (e.g. echinoderms, molluscs) | 1000 |
| One long-term NOEC (from freshwater or saltwater crustacean reproduction or fish growth studies) | 1000 |
| Two long-term NOECs from freshwater or saltwater species representing two trophic levels (algae and/or crustaceans and/or fish) | 500 |
| Lowest long-term NOECs from three freshwater or saltwater species (normally algae and/or crustaceans and/or fish) representing three trophic levels | 100 |
| Two long-term NOECs from freshwater or saltwater species representing two trophic levels (algae and/or crustaceans and/or fish) + one long-term NOEC from an additional marine taxonomic group (e.g. echinoderms, molluscs) | 50 |
| Lowest long-term NOECs from three freshwater or saltwater species (normally algae and/or crustaceans and/or fish) representing three trophic levels + two long-term NOECs from additional marine taxonomic groups (e.g. echinoderms, molluscs) | 10 |

*Table 3 Assessment factors proposed for deriving $PNEC_{water}$ for freshwater for different data sets (EEC, 1996)*

| Data set | Assessment factor |
|---|---|
| At least one short-term L(E)C50 from each of three trophic levels (algae, crustaceans and fish) | 1000 |
| Long-term NOEC from one trophic level (either fish or crustaceans) | 100 |
| Long-term NOEC from species representing two trophic levels (fish and/or crustaceans and/or algae) | 50 |
| Long-term NOEC from at least three trophic levels (fish, crustaceans and algae) | 10 |

### 4.1.4 Using Species Sensitivity Distributions

The Species Sensitivity Distributions (SSD), which can be visualised as frequency distributions (cumulative normal distribution curves) of L(E)C50 or NOEC values for marine organisms reflect the hazard of substances to marine organisms. The SSD can be translated into PNECs.

If a large data set of NOECs from long-term tests for different taxonomic groups is available, statistical extrapolation methods may directly be used to derive a PNEC. The main underlying assumptions of the statistical extrapolation methods are as follows:

- The SSD follows a theoretical distribution function;
- The group of species tested in the laboratory is a random sample of this distribution.

A confidence range can be associated with a PNEC derived by statistical extrapolation in case the database contains at least 10 chronic NOECs (preferably more than 15) for different species covering at least 8 taxonomic groups. For pragmatic reasons it has been decided that the concentration corresponding with the point in the SSD profile (based on NOECs) below which 5% of the species occur should be derived as an intermediate value in the determination of a PNEC. This 5% point in the SSD is also identified as a hazardous concentration (HC) at which a certain percentage (in this case 5%) of all species have risk to be affected (EU, 1992; Newman *et al.*, 2000; Van der Hoeven, 2001). A 50% confidence interval (c.i.) associated with this concentration should also be derived.

The PNEC is calculated as:

$$PNEC = \frac{5\%\ SSD\ (50\%\ c.i.)}{AF}$$

AF is an appropriate assessment factor between 5 and 1, reflecting the further uncertainties identified. Lowering the AF below 5 on the basis of increased confidence needs to be fully justified. The exact value of the AF must depend on an evaluation of the uncertainties around the derivation of the $5^{th}$ percentile (EEC, 2003).

In practice a large set of chronic NOEC values is often not available. However, a combination of the probabilistic approach and the assessment factor approach can be applied to acute data. In that case the variation in sensitivity of biota can still be assessed which enables the quantification of risk (Posthuma *et al*., 2002; Smit *et al*, 2005). In that case the PNEC cannot directly be assessed from the (acute) SSD. Additional assessment factors as described in the EU-TGD should be applied to the $HC_5$ of the distribution. These assessment factors include a factor of 10 to translate $EC_{50}$ level to NOEC level, a factor of 10 to translate laboratory data to field data and another factor of 10 to go from acute to chronic level. The marine TGD even promotes the use of another factor of 10 to account for high sensitive marine species. The combined methodology of assessments factors and SSDs is applied to weighting agents in drilling muds. The results will be discussed in chapter 4.3.

## 4.2 Overview of available effect data

The database analysed consists of data on (sub)lethal effects of suspended particulate matter - from attapulgite, barite, bentonite and various types of WBM- to aquatic organisms (see Appendix 3). Physical effect data were obtained from the TNO literature database TNOLIT, Current Contents, the Aquire database (US-EPA) and from Battelle (USA).

Most data were available for the functional and taxonomic groups phytoplankton, zooplankton, crustaceans, molluscs and fish for which effects on survival, feeding behaviour, growth, mobility, reproduction, oxygen consumption and effects on the gastrointestinal tract were observed. Figure 3 presents an overview of the reported effect concentrations for the different taxonomic groups.

When analysing the database it was noticed that the test conditions were mostly not reported (i.e. for hardness, oxygen concentration or pH) or incomplete and that the effect size was poorly quantified, as many effects were not expressed as $EC_{50}$, $LC_{50}$ or NOEC. This is the consequence of the absence of standardised laboratory test protocols for suspended solids. For none of the effect data, information was reported on the mortality of test species in the blancs, the way the concentration of the substance or mixture in the tested solution was determined, or on the scale of the experiment (laboratory or field). If the same quality criteria would have been applied as used for toxicity data, none of the effect data for suspended solids would have been accepted for derivation of a PNEC regarding the criteria listed in Appendix 2. Figure 4 presents the effect concentration ranges for taxonomic groups exposed to barite, bentonite, attapulgite, clay and WBMs.

Sufficient $EC_{50}$ and $LC_{50}$ data were available for the WBM clays attapulgite, bentonite and barite (bariumsulphate) and for (non-specified) clays. Furthermore, $EC_{50}$ and $LC_{50}$ values for supernatant and suspensions of used and new WBM/water-based fluids were analysed. Although none of the data or test conditions were completely reported, it was chosen to use these $EC_{50}$ data for analysis as it is the best available data.

Figure 3 and 5 show that the sensitivity of all aquatic organisms from the database to the different types of particles is comparable, even when effect concentrations are plotted for taxonomic groups and/or types of WBM clays. However, the sensitivity within types of WBM clays and/or taxonomic groups varies over 5 orders of magnitude. For barite, one particularly low effect concentration (0.5 mg/l for *Placopecten magellanicus*) was reported by Cranford (1999).

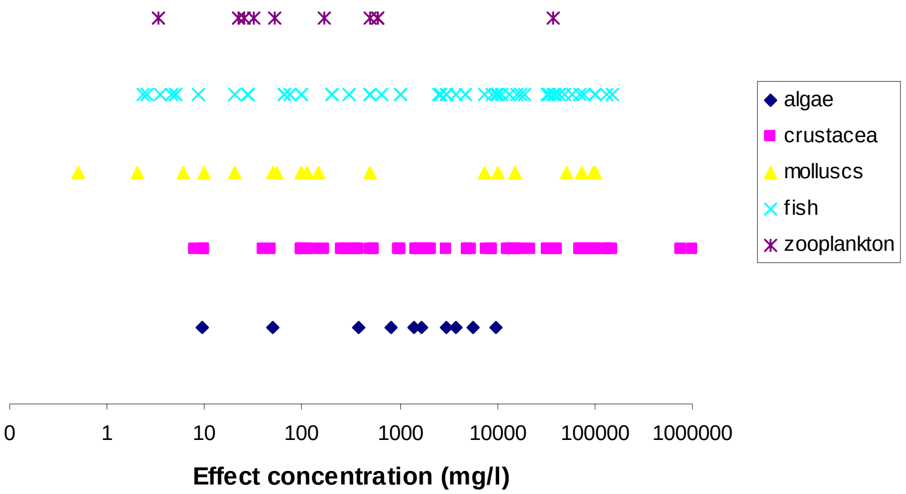


*Figure 3* *Effect concentration ranges for different taxonomic groups exposed to suspended solids from barite, bentonite, attapulgite and various types of WBM*

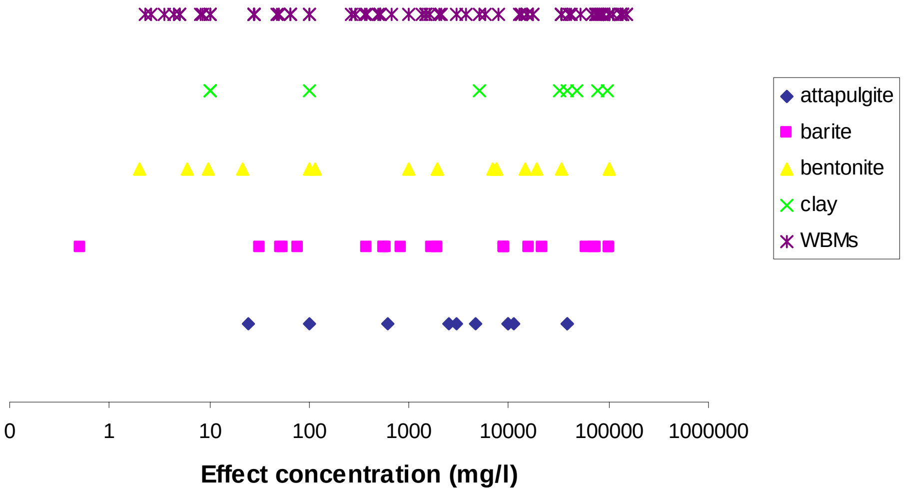


*Figure 4* *Effect concentration ranges for algae, zooplankton, molluscs, crustaceans and fish exposed to suspended solids from barite, bentonite, attapulgite, clay and WBMs*

## 4.3 A PNEC for weighting agents

### 4.3.1 Derivation of PNEC using assessment factors

Since the PNEC is supposed to represent the sensitivity of 'all' species, and physical effect data are only available for a few species and for limited effect endpoints, assessment factors can be applied as a precautionary measure in accordance with the EU-TGD.

The few NOEC data available were not appropriate for determining a PNEC as the information on the quality of the data was lacking. However, sufficient $L(E)C_{50}$ data were available for at least three taxonomic groups (algae, crustaceans and fish). The PNEC has therefore been based on acute effect data.

When only short-term toxicity data are available, an assessment factor of 10,000 (marine TGD) or 1000 (freshwater TGD) should be applied on the lowest $L(E)C_{50}$ of the relevant available toxicity data, irrespective of whether or not the species tested is a standard test organism (see paragraph 4.1.3). Table 4 provides an overview of the amount of data and the resulting PNEC applying the assessment factor approach.

*Table 4 Derivation of PNECs for barite, bentonite, attapulgite and WBMs based on acute toxicity data and by using assessment factors*

| Type of weighting material | barite | bentonite | attapulgite | WBMs |
|---|---|---|---|---|
| Number of effect data | 30 | 17 | 10 | 82 |
| Number of $L(E)C_{50}$ data | 15 | 12 | 7 | 63 |
| Number of tax. groups | 5 | 5 | 1 | 4 |
| Lowest effect value (mg/l) | 0.5 | 2.0 | 25 | 5 |
| Lowest $L(E)C_{50}$ (mg/l) | 32 | 9.6 | 2470 | 2.6 |
| PNEC (mg/l) using assessment factor of 1000 | 0.032 | 0.0096 | 2.5 | 0.0026 |

The assessment factor approach results in relatively low PNEC values. For barite the PNEC is a factor of 15 lower than the lowest effect level observed by Cranford *et al*., (1999), which can already be considered as an extreme low value.

### 4.3.2 Derivation of PNEC using Species Sensitivity Distributions

Species Sensitivity Distributions (SSDs) were based on $EC_{50}$ values for barite, bentonite, attapulgite and WBMs. (Figure 5). The mean (Xm) of the SSD curves represents the position of the distribution on the x-axis and the standard deviation (Sm) determines the slope of the curve. In terms of the sensitivity of species, the Xm gives an indication of the *mean concentration for the physical effects* of suspended mud particles to marine species. The Sm represents the *interspecies variation in sensitivity* of suspended WBM particles for marine species.

Table 5 provides an overview of the data used to construct the SSDs. For attapulgite only fish data was available. Therefore the SSD cannot be considered as representative for general marine biota.

*Table 5* *Overview of $EC_{50}$ data for attapulgite, barite, bentonite and WBMs to construct the Species Sensitivity Distributions (SSDs).Xm and Sm values for the SSD are presented together with the $HC_5$ value*

| Type of weighting material | barite | bentonite | attapulgite | WBMs |
|---|---|---|---|---|
| Number of $EC_{50}$ values | 20 | 12 | 8 | 63 |
| Number of species with 1 or more $EC_{50}$ values | 15 | 12 | 7 | 13 |
| Xm | 8.01 | 7.51 | 9.22 | 8.81 |
| Sm | 3.05 | 3.25 | 2.70 | 1.05 |
| $HC_5$ | 20.0 | 8.8 | 1800 | 79.8 |

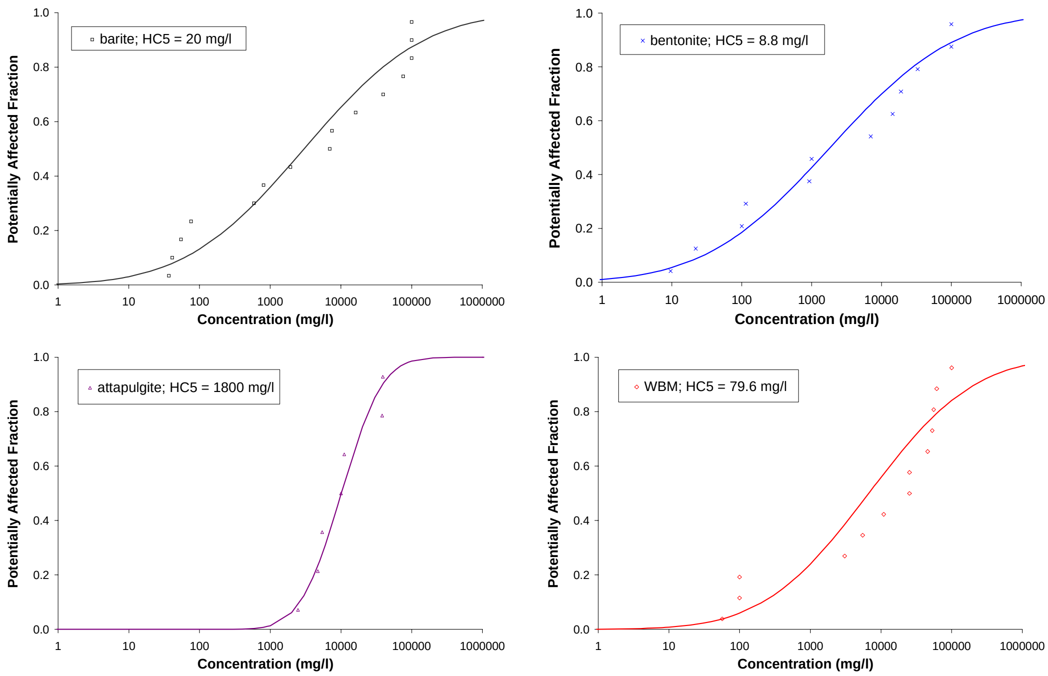


*Figure 5* *Effects related to risk distributions for barite, bentonite, attapulgite and WBMs at acute exposure (log-transformed).*

As the SSD for attapulgite is based on fish data only the $HC_5$ value is not representative for all marine biota. The SSDs of Figure 5 shows that based on the available data species are more sensitive for barite and bentonite than for WBM. However, when statistical analysis (ANOVA, significance level 5%) was performed on the effect concentrations of these WBM particles, no significant differences between effects could be determined.

In order to transform the $HC_5$ value based on acute effect data to a PNEC, assessment factors need to be applied (Posthuma *et al.*, 2002). A factor of 10 should be applied to account for the translation from $EC_{50}$ level to no-effect level. A second value of 10 should be applied to extrapolate from acute effects to chronic effects. It can be discussed whether this factor is necessary. It is unclear if chronic physical effects of WBM are likely to occur as the increased turbidity and sedimentation of SPM from discharged WBMs might only have a temporary impact on organisms. Another factor of 10 could be applied to translate laboratory effects to field effects. This factor is also under discussion while most of the data results from non standardised test carried out under semi-field conditions.

To the derived $HC_5$ levels one assessment factor is applied for the translation from $EC_{50}$ to NOEC level. Because the relevance of the acute to chronic translation and the lab to field translation can be questioned for this data, only one assessment factor of 10 is applied for these two translation steps. Because of the lack of data on more taxonomic groups an additional assessment factor of 10 is applied to the $HC_5$ for attapulgite. This results in PNEC levels for barite, bentonite, atapulgite and WBM of 0.2, 0.09, 1.8 and 0.8 respectively (Table 6).

The proposed PNECs for the weighting agents are all lower than the lowest observed effect levels as presented in table 4. For barite the PNEC is a factor of 2.5 lower than the 0.5 mg/l value determined by Cranford *et al*. (1999). The PNEC values for barite, bentonite and WBM derived from the $HC_5$ are higher than the levels determined with assessment factors. For attapulgite the values are comparable.

*Table 6 Overview of assessment factors applied to the $HC_5$ to derive the PNEC level*

| **Type of weighting material** | **barite** | **bentonite** | **attapulgite** | **WBMs** |
|---|---|---|---|---|
| $HC_5$ (mg/l) | 20.0 | 8.8 | 1800 | 79.6 |
| Proposed assessment factors | | | | |
| $EC_{50}$ to NOEC level | 10 | 10 | 10 | 10 |
| Lab to field & acute to chronic translation | 10 | 10 | 10 | 10 |
| Lack of data on different taxa | - | - | 10 | - |
| ***PNEC (mg/l)*** | ***0.20*** | ***0.088*** | ***1.8*** | ***0.8*** |

# 5. Conclusions and discussion

- Background concentrations of SPM in the open North Sea (< 20 mg/l) and in water systems with relatively low suspended sediment concentrations (< 10 mg/l) (Van Dalfsen, 1999) are over 5 orders of magnitude higher than the PNECs values derived for barite, bentonite, attapulgite and WBMs by using assessment factors. It is assumed that the mode of action for weighting agents in drilling discharges differs from natural SPM. As, low effect levels for barite, bentonite, attapulgite and WBMs have been observed.

- Organisms can respond differently to elevated concentrations of SPM in the water column as some functional groups of organisms are more adapted to deep water or coastal zones and thus to different naturally –occurring SPM concentrations. Mobile organisms i.e. fish have the ability to flee from clouds of SPM from WBM whilst sessile organisms i.e. benthic filter feeders are immobile are therefore more exposed.

- Very few studies have looked at the effects of drilling fluids in the region within the first few meters of the seabed known as the Benthic Boundary Layer (BBL). The BBL is a zone of intensive transport, both vertical and lateral, of solutes and (re) suspended particles and a zone of high chemical and biological reactivity. In recent laboratory studies of sea scallops *Placopecten magellanicus* from Georges Bank in the North Atlantic Ocean, simulation of the physical conditions which exist in the BBL in the presence of various components of drilling muds showed that adult scallops had very low tolerance to suspended clay (Holdway, 2002).

- The effect sizes were poorly quantified, many effects were not reported as $L(E)C_{50}$s or NOECs. Furthermore, test conditions (i.e. salinity, pH, grain size) were mostly incomplete or not reported at all. In case the ecotoxicity of WBM was reported, no information was given on its exact composition.

- The database analysed contains effect data for various types of weighting agents for freshwater species and species not inhabiting the North Sea. Few chronic effect values were reported in literature and it was not possible to base PNECs on chronic no-effect data.

- Barite contributes to a substantial part of the acute physical effects of WBM on aquatic organisms. However, when statistical analysis (ANOVA, significance level 5%) was performed on the effect concentrations of WBM particles, no differences between effects could be determined.

- The (marine) assessment factors in the EU-TGD are a factor 10 higher than the freshwater assessment factors when calculating a PNEC from acute effect data from three groups of aquatic organisms. The PNEC values calculated with the assessment factor approach are extremely low compared to the lowest observed effect levels.

- Statistical extrapolation can be used to derive PNEC values from Species Sensitivity Distributions. The $HC_5$ from the SSD can serve as an intermediate for the PNEC. As the SSD for weighting agents is based on $EC_{50}$ values, additional assessment factors to the $HC_5$ need to be applied.

- For barite, bentonite, and WBM two assessment factors are applied to the $HC_5$. One factor of 10 to account for $EC_{50}$ to NOEC translation and another factor of 10 to the combined translation of acute to chronic levels and lab to field data. Because the relevance of the acute to chronic translation and the lab to field translation can be questioned for this effect, only one assessment factor of 10 is applied for these two translation steps. For attapulgite an additional factor of is used to account for the lack of data on different taxa. This results in PNEC levels for barite, bentonite, atapulgite and WBM of 0.2, 0.09, 1.8 and 0.8 mg/l respectively. These values are a factor 2.5 to 25 lower than the lowest effect values observed. The PNECs derived from assessment factors only are probably too protective. The use of the PNECs derived from the combination of the assessment factor approach and the SSD approach is suggested. This approach resulted in realistic PNEC values below observed effect levels in sensitive (filter feeding organisms) at field-relevant exposures.

# 6. Recommendations

The following recommendations are made in order to gain more insight in the physical effects of SPM from WBM on marine organisms:

- To validate the model predictions, field studies with indicator organisms living in the Benthic Boundary Layer (BBL) for the North Sea and different types of WBM with known compositions should be performed.

- Investigate the effects of barite/metals in WBM particles.

- Investigate the importance of the physical effects of WBM particles versus the toxicological effects of WBM chemicals.

- The PNEC derived from Species Sensitivity Distributions for barite with a value of 0.2 mg/l can be used for calculation of the EIF for from drilling muds.

- There are ongoing long term studies (funded by the Norwegian oil industry and Norwegian Research Council) with fish (cod) and scallops/mussels exposed to water based mud (used) and barite/ilmenite particles. The results from the present study and the follow up-study (NRC) have to be taken into account in the future revision of the PNEC values for suspended particles.

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# 8. Authentication

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| R.G. Jak | Research scientist |

Names and establishments to which part of the research was put out to contract:

-

Date upon which, or period in which, the research took place:

July 2002 – March 2006

| Signature: | Approved by: |
|---|---|
| M.G.D. Smit | W. van der Galiën |
| Project leader | Teamleader a.i. |
| April 10, 2006 | April 10, 2006 |

# Appendix 1 The *ParTrack* model

*ParTrack* is a software tool for modelling and simulating the release of drilling muds, cuttings and chemicals from offshore platforms (Rye, 2002). The program *ParTrack* is used to predict the deposition of the drill cuttings and mud on the sea floor as well as the concentrations of the drilling mud and chemicals in the free water masses. The discharge comprises compounds of particle nature (cuttings and barite), chemical compounds that may be water-soluble or not (dependent of the mud type used) and seawater. The over-all density of the discharge is generally larger than the density of seawater (typically 1600 $kg/m^3$, dependent on the composition of the mud and the amount of water added to the discharge) and will thus sink down initially.

**Simulation steps**
Given model inputs such as ambient currents and densities, chemical and physical properties of the effluent, and details of the release scenario, *ParTrack* simulates the release and spreading of the effluent within a three-dimensional (3D) ocean grid. A *ParTrack* simulation consists of 2 sequential steps:

1. Convective descent in the near-field zone
2. Passive particle transport and spreading in the far-field zone

Step 1 lasts for a few minutes or so; they involve the creation of the "mud plume". The density difference between effluent and ambient leads to the initial convective descent of the plume. As the plume moves vertically, it entrains ambient water. This often enables the plume to attain a density equal to that of the ambient before the plume hits the ocean bottom. This neutral buoyancy signals the end of convective movement (for the most part) and the beginning of the spreading in the far field zone.
Particles are released from the plume in accordance with their sizes and densities (and hence sinking velocities). Particles are transported via ambient currents and diffusion. At each time step, *ParTrack* has an overview of all particle locations. From this data, it computes the mass distribution of the effluent along with its concentrations in both water and sediments. This data holds the most relevance for the typical environmental analyses performed by *ParTrack*.

Once released from the plume (or at the termination of the plume phase), the motion of particles becomes dependent upon ambient-current advection and diffusion. The advective motion is composed of a horizontal velocity component in two dimensions imported from an external database. For the vertical motion of the particle, the fall velocity of the particle is used, calculated as a function of diameter and particle density.
The concentrations in the water masses and on the bottom are then evaluated by averaging over the particle number located within one grid element, adding the mass associated to all particles within that element and then dividing with the

element volume (or area). The far-field spreading algorithm for a passive tracer has been verified against field measurements on the Oseberg field in the North Sea. Details can be found in Rye *et al.* (1996).

Particles on the sea floor accumulate over the simulation period. Concentrations of particles on the sea floor (deposition in kg/$m^3$ or thickness of layer) can be calculated for different particle classes. Both particle types and sizes can be varied. In the present *ParTrack* version, 24 particle classes are allowed. The model can thus distinguish between particles from cuttings and from barite, and also between different sizes from each.

Phenomena that are not included in the present version of the *ParTrack* model are as follows:

- Re-suspension of matter deposited on the sea floor
- Flocculation processes between particles in the water column
- Sediment processes taking place on the sea floor (degradation of non-particulate matter, effects from bioturbation, oxygen depletion, etc.)
- The fate of chemicals in the water column. All matter simulated is treated as a conservative agent, with no degradation, evaporation, dissolution etc.)

It is the purpose of the main project to include these processes in the *ParTrack* model. In addition, a field trial is planned to verify the relevance of the process descriptions developed for the model.

Typical particle size distributions and sinking velocities of drill cuttings and barite particles are defined for the ParTrack model and based on results of Saga (1994). For the sinking velocities of the size varying barite particles it is assumed that no flocculation processes are involved (Table 7 and Table 8).

*Table 7 Drill cuttings. Particle distribution, their density, sinking velocities and numbers. The parameters Re and Bi are given by equation 2.4. The sinking velocities of the particles are calculated by equations 2.5 – 2.7. Particle size distributions are according to Saga (1994). Amounts considered are 1 000 tons.*

**DRILL CUTTINGS**
**Amount kg: 1000000**

| Diameter | Weight | Density | Velocity | Velocity | Reynolds | Boyancy | Volume | Volume | No. part. | No. part. |
|---|---|---|---|---|---|---|---|---|---|---|
| mm | % | tonnes/m3 | m/s | m/day | Re | Bi | m3 | % | Ni | % |
| | | | | | | | | | | |
| 0,007 | 10 | 4,2 | 4,4E-05 | 3,8 | 0,0002 | 0,003 | 23,8 | 6,3 | 1,3E+17 | 86,1810215 |
| 0,015 | 10 | 4,2 | 2,0E-04 | 17,6 | 0,0016 | 0,030 | 23,8 | 6,3 | 1,3E+16 | 8,7585453 |
| 0,025 | 10 | 2,4 | 2,5E-04 | 21,2 | 0,0033 | 0,059 | 41,7 | 10,9 | 5,1E+15 | 3,3107301 |
| 0,035 | 10 | 2,4 | 4,8E-04 | 41,6 | 0,0091 | 0,163 | 41,7 | 10,9 | 1,9E+15 | 1,2065343 |
| 0,05 | 10 | 2,4 | 9,8E-04 | 84,9 | 0,0264 | 0,476 | 41,7 | 10,9 | 6,4E+14 | 0,4138413 |
| 0,075 | 10 | 2,4 | 2,2E-03 | 191,0 | 0,0892 | 1,606 | 41,7 | 10,9 | 1,9E+14 | 0,1226196 |
| 0,2 | 10 | 2,4 | 1,6E-02 | 1356,5 | 1,6900 | 30,448 | 41,7 | 10,9 | 9,9E+12 | 0,0064663 |
| 0,6 | 10 | 2,4 | 5,7E-02 | 4898,9 | 18,3100 | 822,092 | 41,7 | 10,9 | 3,7E+11 | 0,0002395 |
| 3 | 10 | 2,4 | 2,1E-01 | 17988,5 | 336,1680 | 102761,000 | 41,7 | 10,9 | 2,9E+09 | 0,0000019 |
| 7 | 10 | 2,4 | 3,2E-01 | 27483,8 | 1198,4400 | 1305451,000 | 41,7 | 10,9 | 2,3E+08 | 0,0000002 |
| | | | | | | | | | | |
| **SUM** | **100** | | | | | | **381,0** | **100** | **1,54E+17** | **100** |

*Table 8 Barite in drilling mud. Particle distribution, their density, sinking velocities and numbers. The parameters Re and Bi are given by equation 2.4. The sinking velocities of the particles are calculated by equations 2.5 – 2.7. Particle size distributions are according to Saga (1994). Amounts considered are 1 000 tons.*

**DRILLING MUD**
**Amount, kg: 1000000**

| Diameter mm | Weight, % | Density, tonnes/m3 | Velocity, m/s | Velocity, m/day | Reynolds Re | Boyancy Bi | Volume m3 | Volume % | No. part. Ni | No. part. % |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| 0,0007 | 10 | 4,2 | 4,4E-07 | 0,04 | 1,7E-07 | 3,0E-06 | 23,81 | 8,70 | 1,3E+20 | 71,3262 |
| 0,001 | 10 | 4,2 | 9,1E-07 | 0,08 | 4,9E-07 | 8,8E-06 | 23,81 | 8,70 | 4,5E+19 | 24,4649 |
| 0,002 | 10 | 4,2 | 3,6E-06 | 0,31 | 3,9E-06 | 7,0E-05 | 23,81 | 8,70 | 5,7E+18 | 3,0581 |
| 0,003 | 10 | 4,2 | 8,2E-06 | 0,71 | 1,3E-05 | 2,4E-04 | 23,81 | 8,70 | 1,7E+18 | 0,9061 |
| 0,005 | 10 | 4,2 | 2,3E-05 | 1,96 | 6,1E-05 | 1,1E-03 | 23,81 | 8,70 | 3,6E+17 | 0,1957 |
| 0,009 | 10 | 4,2 | 7,4E-05 | 6,35 | 3,6E-04 | 6,4E-03 | 23,81 | 8,70 | 6,2E+16 | 0,0336 |
| 0,014 | 10 | 4,2 | 1,8E-04 | 15,37 | 1,3E-03 | 2,4E-02 | 23,81 | 8,70 | 1,7E+16 | 0,0089 |
| 0,018 | 10 | 4,2 | 2,9E-04 | 25,41 | 2,8E-03 | 5,1E-02 | 23,81 | 8,70 | 7,8E+15 | 0,0042 |
| 0,028 | 10 | 2,4 | 3,1E-04 | 26,62 | 4,6E-03 | 8,4E-02 | 41,67 | 15,22 | 3,6E+15 | 0,0020 |
| 0,05 | 10 | 2,4 | 9,8E-04 | 84,88 | 2,6E-02 | 4,8E-01 | 41,67 | 15,22 | 6,4E+14 | 0,0003 |
| | | | | | | | | | | |
| **SUM** | **100** | | | | | | **273,81** | **100** | **1,9E+20** | **100** |

Note that the drill cuttings and barite distributions may be separated into a coarse and a fine part. For both cases, the coarse parts consist of the 5 classes with the coarsest (largest sized) particles. For the cuttings, these are the particles with sinking velocities larger than order 100 – 200 m per day. For the barite, these are the particles with sinking velocities larger than order 2 - 5 m per day. It is also evident that the sinking velocities for the different particle classes vary a lot, ranging over several orders of magnitude.

For the drilling mud, the particles are generally much finer. This also leads to lower sinking velocities. The barite will therefore generally tend to spread in the water column rather than sink to the bottom.

The amount of 1000 tons for both drilling mud and cuttings are assumed to represent order-of-magnitude sizes of the releases typically experienced during an exploratory or production drilling.

The *ParTrack* model is based on a Lagrangian “particle” approach, in the sense that particles are generated in the model to represent the properties of the discharge (particle sizes and densities and resulting sinking velocities). Particles are thus released from the (Eulerian) near-field plume in accordance with their sizes and densities (and hence sinking velocities). Up to 24 different particle classes can be used. Chemicals may be represented in the model as “particles” which are either very small or with neutral buoyancy.

In the far field (after the termination of the near-field zone), the particles are transported via ambient currents and diffusion. The model calculates a new position of each particle, dependent on the advecting current velocity and direction, the sinking velocity of the particle and some statistical motion due to horizontal and vertical turbulence. At each time step, *ParTrack* has an overview of all particle locations. From these data, it computes the mass distribution of the effluent along with its concentrations in both water and sediments (Rye, 2002).

# Appendix 2 Quality criteria for the selection of toxicity data

The quality of literature data on physical effects of SPM from WBM can be assessed using a number of criteria according to TNO, which were also used for the internal database Maritox. The database with effect data has been evaluated and ranked ‘A’, ‘B’, ‘C’ or ‘D’. The final quality score also depends on the correctness and completeness of the test conditions reported in literature.

**Quality criteria**

1. Tested substance or mixture

The name of the toxicant or composition of the mixture (WBM) must be reported

2. Solution

Information needs to be given on the tested solution
N: In case the nominal concentration is used to determine the effect concentration, no concentration has been measured. The nominal concentration is the amount of substance or mixture added.
M: In case the nominal concentration is used to determine the effect concentration and the concentration has been measured
O: In case the concentration has been measured and is used to determine the effect concentration
U: In case information on the tested solution is lacking

3. Test species

The (Latin) name of the test species must be reported

4. Effect

The type of effect, i.e. effect on reproduction, needs to be specified

5. Effect size

The size of the effect (0-100%) needs to be reported, i.e. $L(E)C_{50}$

6. Unity

The unity of the tested concentration or volume i.e. mg/l must be specified

7. Exposure route

The exposure route needs to be specified, i.e. via water, sediment, feed

8. Time span

The duration of the exposure must be reported

9. Life stage

The life stage of the test species must be known

10. Scale

The scale of the experiment - laboratory, mesocosm or field - must be specified

11. Blanc

The mortality of organisms exposed to the test medium without the test substance (blanc) must be below 10% for a test duration of ≤ 4 days and below 20% for a test duration of ≥ 4 days (multicellular organisms). The growth rate must be reported for unicellular organisms and needs to be at least a factor of 16.

12. Test conditions

The pH, salinity, hardness, type of medium (fresh- or saltwater), temperature and grain size of the test substance need to be reported.
The pH needs to be between 5.5 and 8.5, the oxygen concentration must be higher than 4 mg/l and the hardness of the water needs to be reported for freshwater experiments. The salinity must be reported for saltwater experiments.

**Final quality score**

A: All data and test conditions are reported and are valid
B: All data and test conditions are reported but are invalid
C: Not all data and test conditions are reported but the experiment can be considered valid
D: Not all data and test conditions are reported and the experiment can be considered unvalid

# Appendix 3 Acute toxicity data of different types of WBM or clay components for marine organisms

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| attapulgite | *Spisula solidissima* | Molluscs | adverse effect on feeding and digestive efficiency | ? | ? | 100.00 | 3-21 | Robinson *et al.*, 1984 | A | A/C | W | U | D | effect size and salinity not reported |
| attapulgite | spot | Pisces | mortality | 50 | LC | 11115 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | white perch | Pisces | mortality | 50 | LC | 9850 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | striped killifish | Pisces | mortality | 50 | LC | 38190 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | common mummichog | Pisces | mortality | 50 | LC | 39000 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | atlantic silversides | Pisces | mortality | 50 | LC | 10000 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | menhaden | Pisces | mortality | 50 | LC | 2470 | 1 | Sherk *et al.*, 1975 | J | A | W | U | C | grainsize not reported |
| attapulgite | bay anchovy | Pisces | mortality | 50 | LC | 4710 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | white perch | Pisces | mortality | 50 | LC | 2960 | 1 | Sherk *et al.*, 1975 | A | A | W | U | C | grainsize not reported |
| attapulgite | *Ciona* | tunicates | inhibition of growth | ? | ? | 25.00 | ? | Robbins, 1985 | A | A | W | U | D | effect size, grainsize, temperature, salinity and time span not reported |
| attapulgite | *Ciona* | tunicates | mortality | ? | ? | 600.00 | 5 | Robbins, 1985 | A | C | W | U | D | effect size, grainsize, temperature, salinity and time span not reported |
| barite | ? | ? | no observed effect at < 2 mg/l | ? | ? | 4.95 | ? | Patin, 1999 | ? | C | ? | U | D | test species not known, life stage, effect size, exposure route, temperature, salinity and time span not reported |
| barite | *Skeletonema costatum* | Algae | mortality | 50 | LC | 825.00 | 4 | Swan *et.al.*, 1994 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Skeletonema costatum* | Algae | agitation | 50 | LC | 1650.00 | 4 | EG&G, 1976 | A | A | W | U | C | temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| barite | *Skeletonema costatum* | Algae | no agitation | 50 | LC | 385.00 | 4 | EG&G, 1976 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Cancer anthonyi* | Crustacea | hatching success | ? | ? | 550.00 | 7 | Acquire | ? | C | W | U | D | effect size, temperature, salinity and life stage not reported |
| barite | *Cancer anthonyi* | Crustacea | mortality | ? | ? | 550.00 | 7 | Acquire | ? | C | W | U | D | effect size, temperature, salinity and life stage not reported |
| barite | *Cancer magister* | Crustacea | inhibition of swimming activity | ? | ? | 1940.00 | 1-5 | Neff, 1987 | L | A | W | U | D | effect size, temperature and salinity not reported |
| barite | *Cancer magister* | Crustacea | mortality | 50 | EC | 22075.00 | 4 | Carls & Rice, 1984 | L | A | W | U | A | |
| barite | *Cancer magister* | Crustacea | ? | 50 | EC | 71400.00 | 4 | Bohem *et.al.*, 2001 | A | A | W | U | C | effect, temperature and salinity not reported |
| barite | dock shrimp | Crustacea | inhibition of swimming activity | ? | ? | 1940.00 | 1-5 | Neff, 1987 | L | A | W | U | D | effect size, temperature and salinity not reported |
| barite | lobster | Crustacea | mortality | ? | ? | 9000.00 | 99 | Kenchington, 1997 | J | C | S | U | D | effect size, temperature and salinity not reported |
| barite | lobster | Crustacea | suppressed growth | ? | ? | 9000.00 | 98 | Kenchington, 1997 | J | C | S | U | D | effect size, temperature and salinity not reported |
| barite | mysid | Crustacea | mortality | 50 | LC | 100000.00 | 4 | Leuterman *et.al.*, 1989 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Pandalus danae* | Crustacea | | 50 | EC | 16200.00 | 4 | Bohem *et.al.*, 2001 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Pandalus hypsonotus* | Crustacea | mortality | 50 | LC | 100000.00 | 4 | Dames & Moore, 1978 | A | A | W | U | C | temperature and salinity not reported |
| barite | - | marine organisms | mortality | 50 | LC | 7000.00 | 4 | Neff, 1987 | ? | A | W | U | D | test species not known, temperature, salinity and life stage not reported |
| barite | several fish & inverts | marine organisms | mortality | 50 | LC | 7500.00 | 4 | Daugherty, 1951 | A | A | W | U | D | test species not known, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| barite | *Crassostrea virginica* | Molluscs | mortality | 50 | LC | 55.00 | 216 | Cabrera, 1971 | A | C | W | U | C | temperature and salinity not reported |
| barite | *Placopecten magellanicus* | Molluscs | reduction of somatic and/or reproductive tissue growth | ? | ? | 0.50 | 28 | Cranford *et al.*, 1999 | A | C | W | U | D | effect size not reported |
| barite | *Tubifex tubifex* | oligochaeta | immobilisation | 50 | EC | 44.98 | 1 | Acquire | ? | A | W | U | D | life stage, temperature and salinity not reported |
| barite | *Tubifex tubifex* | oligochaeta | immobilisation | 50 | EC | 33.65 | 2 | Acquire | ? | A | W | U | D | life stage, temperature and salinity not reported |
| barite | *Tubifex tubifex* | oligochaeta | immobilisation | 50 | EC | 33.65 | 4 | Acquire | ? | A | W | U | D | life stage, temperature and salinity not reported |
| barite | flounder | Pisces | suppressed growth | ? | ? | 9000.00 | 98 | Kenchington, 1997 | J | C | S | U | D | effect size, temperature and salinity not reported |
| barite | *Mollienisia latipinna* | Pisces | mortality | 50 | LC | 100000.00 | 4 | Grantham & Sloan, 1975 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Onchorhynchus mykiss* | Pisces | mortality | 50 | LC | 76000.00 | 4 | Acquire | A | A | W | U | C | temperature and salinity not reported |
| barite | *Poecilia* | Pisces | mortality | 0 | LC | 59000.00 | 4 | Acquire | ? | A | W | U | D | life stage, temperature and salinity not reported |
| barite | *Salmo gairdneri (avg weight 1.9g)* | Pisces | mortality | 50 | LC | 76.00 | 4 | Sprague & Logan, 1979 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Acartia tonsa* | Zooplankton | mortality | 50 | LC | 590.00 | 4 | EG&G, 1976 | A | A | W | U | C | temperature and salinity not reported |
| barite | *Daphnia magna* | Zooplankton | immobilisation | 50 | EC | 52.82 | 1 | Acquire | ? | A | W | U | D | life stage, temperature and salinity not reported |
| barite | *Daphnia magna* | Zooplankton | immobilisation | 50 | EC | 32.00 | 2 | Acquire | ? | A | W | U | D | life stage nor reported |
| bentonite | *Skeletonema costatum (alga)* | Algae | mortality | 50 | LC | 9.60 | 4 | EG&G, 1976 | A | A | W | U | C | grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| bentonite | *Cancer magister* | Crustacea | inhibition of swimming activity | ? | ? | 1940.00 | 1-5 | Neff, 1987 | L | A | W | U | D | effect size, grainsize, temperature and salinity not reported |
| bentonite | *Cancer magister* | Crustacea | mortality | 50 | EC | 32955.00 | 4 | Carls & Rice, 1984 | L | A | W | U | C | grainsize not reported |
| bentonite | *Crangon crangon* | Crustacea | mortality | 50 | LC | 1000.00 | 4 | Hudgins, 1994 | A | A | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | dock shrimp | Crustacea | inhibition of swimming activity | ? | ? | 1940.00 | 1-5 | Neff, 1987 | L | A | W | U | D | effect size, grainsize, temperature and salinity not reported |
| bentonite | dock shrimp | Crustacea | mortality | 50 | EC | 14410.00 | 4 | Carls & Rice, 1984 | L | A | W | U | C | grainsize not reported |
| bentonite | mysid | Crustacea | mortality | 50 | LC | 100000.00 | 4 | Leuterman *et al.*, 1989 | A | A | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | *Pandalus hypsinotus (shrimp)* | Crustacea | mortality | 50 | LC | 100.00 | 4 | Dames & Moore, 1978 | A | A | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | - | marine organisms | mortality | 50 | LC | 7000.00 | 4 | Neff, 1987 | ? | A | W | U | D | test species not known, life stage, grainsize, temperature and salinity not reported |
| bentonite | *Crassostrea virginica* | Molluscs | mortality | 50 | LC | 7500.00 | 4 | Daugherty, 1951 | A | A | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | *Crassostrea virginica* | Molluscs | mortality | 50 | LC | 114.50 | 192 | Cabrera, 1971 | A | C | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | *Placopecten magellanicus* | Molluscs | feeding activity | ? | ? | 2.00 | 68 | Cranford & Gordon, 1992 | A | C | W | U | D | effect size not reported, grainsize and salinity not reported |
| bentonite | *Placopecten magellanicus* | Molluscs | reduction of somatic and/or reproductive tissue growth | ? | ? | 6.00 | 68 | Cranford *et al.*, 1999 | A | C | W | U | D | effect size and grainsize not reported |
| bentonite | *Cynoscion nebulosus* | Pisces | mortality | ? | ? | 7500.00 | 0.92 | Acquire | A | A | W | U | D | effect size and grainsize not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| bentonite | *Mollienisia latipinna* | Pisces | mortality | 50 | LC | 100000.00 | 4 | Wallen, 1951 | A | A | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | *Onchorhynchus mykiss* | Pisces | mortality | 50 | LC | 19000.00 | 4 | Acquire | A | A | W | U | C | grainsize, temperature and salinity not reported |
| bentonite | *Acartia tonsa (copepod)* | Zooplankton | mortality | 50 | LC | 22.00 | 4 | EG&G, 1976 | A | A | W | U | C | grainsize, temperature and salinity not reported |
| clay | *Temora longicornis* | Crustacea | 15-25% reduction of food uptake | ? | ? | 10.00 | ? | MARE | A | ? | W | U | D | exact composition not known, effect size, grainsize and time span not reported |
| clay | *Acartia clausi* | Crustacea | 15-25% reduction of food uptake | ? | ? | 10.00 | ? | MARE | A | ? | W | U | D | exact composition not known, effect size, grainsize and time span not reported |
| clay | *Crangon nigromaculata* | Crustacea | mortality | 50 | LC | 5000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| clay | *Cancer magister* | Crustacea | mortality | 50 | LC | 32000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| clay | *Anisogammarus confervicolus* | Crustacea | mortality | 50 | LC | 78000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| clay | *Mytilus californianus* | Molluscs | mortality | 50 | LC | 96000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| clay | *Cymatogaster aggregata* | Pisces | mortality | 50 | LC | 48000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| clay | *Neanthes succinea* | Polychaeta | mortality | 50 | LC | 48000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| clay | *Ascidia ceratodes* | tunicates | mortality | 50 | LC | 38000.00 | 8.33 | McFarland & Peddicord, 1980 | A | C | W | U | D | exact composition not known |
| silt, clay | *Crassostrea virginica* | Molluscs | decrease in pumping rates | 50 | EC | 100.00 | ? | Loosanoff, 1962 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| drilling fluids of different types | ? | invertebrates | 100% mortality | 100 | LC | 150000 | ? | Patin, 1999 | A | A | W | U | D | exact composition, time span, grainsize, temperature, salinirt and test species not known |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| drilling fluids of different types | ? | Pisces | 100% mortality | 100 | LC | 150000 | ? | Patin, 1999 | A | A | W | U | D | exact composition, time span, grainsize, temperature, salinirt and test species not known |
| Freshwater Lignosulfonate Mud | mysid | Crustacea | mortality | 50 | LC | 980 | 4 | Duke & Parrish, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Freshwater Lignosulfonate Mud | *Palaemonetes intermedius (Larvae)* | Pisces | mortality | 50 | LC | 4.51 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Freshwater Lignosulfonate Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 80043 | 4 | Ayers *et al.* , 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Freshwater Lignosulfonate Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 12588 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| HDLS (MAF) | *carcinus maenas* | Crustacea | mortality | 50 | LC | 100000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| HDLS (MAF) | *Mytilus edulis* | Molluscs | mortality | 50 | LC | 100000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| HDLS (suspended WM) | *Mytilus edulis* | Molluscs | mortality | 50 | LC | 15000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| HWL | *Crassostrea gigas* | Molluscs | mortality | 50 | LC | 73500 | 4 | Patin, 1999 | 3-10 mm | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imco LDLS/SW | *Skeletonema costatum* | Algae | | 50 | EC | 3012.5 | ? | Patin, 1999 | ? | ? | ? | U | D | exact composition not known, life stage, effect, time span, exposure route, grainsize, temperature and salinity not reported |
| Imco lime/SW | *Skeletonema costatum* | Algae | | 50 | EC | 1375 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, effect, grainsize, temperature and salinity not reported |
| Imco non-dispersed/ SW | *Skeletonema costatum* | Algae | | 50 | EC | 5700 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, effect, grainsize, temperature and salinity not reported |
| Imnac gel XC-polymer | *Salmo gairdneri* | Pisces | mortality | 50 | LC | 42000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| KCl Polymer Mud | mysid | Crustacea | mortality | 50 | LC | 1500 | 4 | Duke & Parrish, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| KCl Polymer Mud | *Palaemonetes intermedius* (Larvae) | Pisces | mortality | 50 | LC | 2.58 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| KCl Polymer Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 78100 | 4 | Ayers *et al.*, 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| KCl Polymer Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 1608 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KCl Polymer Mud (suspended particulate phase) | *Salmo gairdneri* | Pisces | mortality | 50 | LC | 33000 | 4 | Swan *et.al.* ,1994 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| KCL-XC polymer | *Salmo gairdneri* | Pisces | mortality | 50 | LC | 34000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Kipnik-KCl polymer | *Salmo gairdneri* | Pisces | mortality | 50 | LC | 330000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| LDLS | *carcinus maenas* | Crustacea | mortality | 50 | LC | 89100 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| LDLS (MAF) | *carcinus maenas* | Crustacea | mortality | 50 | LC | 100000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| LDLS (suspended WM) | *carcinus maenas* | Crustacea | mortality | 50 | LC | 15000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lightly Treated Lignosulfonate Mud | mysid | crustacea | mortality | 50 | LC | 377 | 4 | Duke & Parrish, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lightly Treated Lignosulfonate Mud | *Palaemonetes intermedius (Larvae)* | Pisces | mortality | 50 | LC | 296 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lightly Treated Lignosulfonate Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 140000 | 4 | Ayers *et al.* , 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lightly Treated Lignosulfonate Mud (suspended particulate phase) | mysid | crustacea | mortality | 50 | LC | 75012 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lightly treated LS/SW-FM | *Skeletonema costatum* | Algae | | 50 | EC | 3700 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, effect, temperature and salinity not reported |
| Lime Mud | mysid | Crustacea | mortality | 50 | LC | 47 | 4 | Gaetz *et al.* 1986 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lime Mud | *Palaemonetes intermedius (Larvae)* | Pisces | mortality | 50 | LC | 658 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lime Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 73954 | 4 | Gaetz *et al.* 1986 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lime Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 7849 | 4 | Gaetz *et al.* 1986 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Lygnosulfonate drilling fluids | cod fry | Pisces | Persistent disturbances of physiological functions and bahavioural responses | ? | ? | 65 | ? | Patin, 1999 | J | C | W | U | D | exact composition not known, time span, effect size, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lygnosulfonate drilling fluids | flounder | Pisces | Persistent disturbances of physiological functions and bahavioural responses | ? | ? | 65 | ? | Patin, 1999 | A | C | W | U | D | exact composition not known, time span, effect size, grainsize, temperature and salinity not reported |
| Lygnosulfonate drilling fluids | salmon | Pisces | Persistent disturbances of physiological functions and bahavioural responses | ? | ? | 65 | ? | Patin, 1999 | A | C | W | U | D | exact composition not known, time span, effect size, grainsize, temperature and salinity not reported |
| MDLS | *carcinus maenas* | Crustacea | mortality | 50 | LC | 84000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| MDLS (MAF) | *carcinus maenas* | Crustacea | mortality | 50 | LC | 100000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| MDLS (suspended WM) | *carcinus maenas* | Crustacea | mortality | 50 | LC | 15000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| MDLS (suspended WM) | *Mytilus edulis* | Molluscs | mortality | 50 | LC | 15000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| MWL | *Crassostrea gigas* | Molluscs | mortality | 50 | LC | 51500 | 4 | Patin, 1999 | 10-25 mm | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Non-Dispersed Mud | mysid | Crustacea | mortality | 50 | LC | 1500 | 4 | Duke & Parrish, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Non-Dispersed Mud | *Palaemonetes intermedius (Larvae)* | Pisces | mortality | 50 | LC | 100000 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Non-Dispersed Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 137500 | 4 | Ayers *et al.*, 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Non-Dispersed Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 110000 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| polymer clay muds | amphipod | Crustacea | mortality | 50 | LC | 17500 | 2-4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| polymer clay muds | salmon fry | Pisces | mortality | 50 | LC | 17500 | 2-4 | Patin, 1999 | J | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| polymer muds | amphipod | Crustacea | mortality | 50 | LC | 69000 | 2-4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| polymer muds | salmon fry | Pisces | mortality | 50 | LC | 69000 | 2-4 | Patin, 1999 | J | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Lignosulfonate Mud | mysid | Crustacea | mortality | 50 | LC | 367 | 4 | Duke & Parrish, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Lignosulfonate Mud | *Palaemonetes intermedius* (Larvae) | Pisces | mortality | 50 | LC | 2.33 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seawater Lignosulfonate Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 82981 | 4 | Ayers *et al.* , 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Lignosulfonate Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 2071 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| seawater LS (MAF) | *Mytilus edulis* | Molluscs | mortality | 50 | LC | 100000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| seawater polymer | *Salmo gairdneri* | Pisces | mortality | 50 | LC | 130000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Spud Mud | *Gammarus locusta* | Crustacea | mortality | 50 | LC | 100000 | 4 | Gaetz *et al.* 1986 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Spud Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 150000 | 4 | Ayers *et al.* , 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Spud Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 133333 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater Spud Mud (suspended particulate phase) | *Mytilus edulis* | Molluscs | mortality | 50 | LC | 100000 | 4 | Swan *et.al.* ,1994 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seawater/Freshwater Gel Mud | mysid | Crustacea | mortality | 50 | LC | 263 | 4 | Gaetz *et al.* , 1986 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater/Freshwater Gel Mud | *Palaemonetes intermedius (Larvae)* | Pisces | mortality | 50 | LC | 3.57 | 4 | EPA, 1985 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater/Freshwater Gel Mud (liquid phase) | mysid | Crustacea | mortality | 50 | LC | 137500 | 4 | Ayers *et al.* , 1983 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Seawater/Freshwater Gel Mud (suspended particulate phase) | mysid | Crustacea | mortality | 50 | LC | 40018 | 4 | Duke *et al.*, 1984 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| used WBM | *Placopecten magellanicus* | Molluscs | reduction of somatic and/or reproductive tissue growth | ? | ? | 10 | 68-72 | Cranford *et al.*, 1999 | A | C | W | U | D | exact composition not known, grainsize and effect size not reported |
| Water-based (lygnosulfonate and ammonium) drilling fluids | amphipod | Crustacea | mortality | 50 | LC | 13500 | 2-4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water-based (lygnosulfonate and ammonium) drilling fluids | salmon fry | Pisces | mortality | 50 | LC | 13500 | 2-4 | Patin, 1999 | J | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| Water-based clay bentonite fluids | cod | Pisces | threshold changes in respiratory and cardiac activities | ? | ? | 27.5 | 2-5 min | Patin, 1999 | A | A | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |
| Water-based clay bentonite fluids | haddock | Pisces | threshold changes in respiratory and cardiac activities | ? | ? | 27.5 | 2-5 min | Patin, 1999 | A | A | W | U | D | exact composition not known, effect size, temperature and salinity not reported |
| Water-based clay bentonite fluids | ray | Pisces | threshold changes in respiratory and cardiac activities | ? | ? | 27.5 | 2-5 min | Patin, 1999 | A | A | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |
| Water-based clay bentonite fluids | salmon | Pisces | threshold changes in respiratory and cardiac activities | ? | ? | 27.5 | 2-5 min | Patin, 1999 | A | A | W | U | D | exact composition not known, effect size, temperature and salinity not reported |
| Water-based clay fluids | cod | Pisces | reduced survival | ? | ? | 5 | 10-30 | Patin, 1999 | A | C | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |
| Water-based clay fluids | flounder | Pisces | reduced survival | ? | ? | 5 | 10-30 | Patin, 1999 | A | C | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water-based clay fluids | salmon fry | Pisces | changes in the rates of respiration and hart contraction | ? | ? | 8.5 | 1-2 min | Patin, 1999 | J | A | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |
| WBM | *Thalassiosira pseudonana* | Algae | no observed effect on algal biomass and physiological condition | ? | ? | 50 | 10 | Cranford *et al.*, 1998 | A | C | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |
| WBM | *Paracyathus stearnsii* | Coral | 60% reduced viability | ? | ? | 0.02 | 8 | Raimondi *et al.*, 1997 | A | ? | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |
| WBM | *Paracyathus stearnsii* | Coral | mortality | 100 | EC | 200 | 6 | Raimondi *et al.*, 1997 | A | ? | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| WBM | amphipod | Crustacea | no observed effect | | NOEC | 505 | ? | Patin, 1999 | A | C | W | U | D | exact composition not known, time span, grainsize ,temperature and salinity not reported |
| WBM | *Homarus americanus* | Crustacea | decrease in survival | 50 | LC | 100 | 4 | Cranford *et al.*, 1998 | L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| WBM | lobster | Crustacea | decreased response of walking leg chemosensors to food cues | ? | ? | 10 | ? | Lincoln, 2002 | A | ? | W | U | D | exact composition not known, time span, grainsize, temperature, salinity and effect size not reported |
| WBM | lobster | Crustacea | increase in larval development | ? | ? | 2000 | 3 | Lincoln, 2002 | L | A | W | U | D | exact composition not known, effect size, grainsize, temperature and salinity not reported |

| WBM type or clay component | Test species | Taxonomic group | Effect | Effect size | Effect parameter | mean effect concentration (mg/l) | Time span (days) | Reference | Life stage | Scale | Exposure route | Score solution | Final score on quality | Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WBM | lobster | Crustacea | mortality | 50 | LC | 5000 | | Lincoln, 2002 | stage 5 | ? | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| WBM | lobster | Crustacea | partial inhibition of molting, delayed detection of food cues | ? | ? | 8 | ? | Lincoln, 2002 | stage 4 | ? | W | U | D | exact composition not known, time span, grainsize, temperature, salinity and effect size not reported |
| WBM | zooplankton | Crustacea | mortality | 50 | LC | 5500 | 4 | Lincoln, 2002 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| WBM | bivalve | Molluscs | no observed effect | | NOEC | 505 | ? | Patin, 1999 | A | C | W | U | D | exact composition not known, time span, grainsize, temperature and salinity not reported |
| WBM | scallop | Molluscs | decreased rate of shell growth | ? | ? | 49 | ? | Lincoln, 2002 | L | ? | W | U | D | exact composition not known, time span, grainsize, temperature, salinity and effect size not reported |
| WBM | cod fry | Pisces | no observed effect | | NOEC | 505 | ? | Patin, 1999 | J | C | W | U | D | exact composition not known, time span, grainsize, temperature and salinity not reported |
| WBM | *haddock* | Pisces | decrease in survival | 50 | LC | 100 | 4 | Cranford *et al.*, 1998 | J/L | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| WBM | copepod | Zooplankton | no observed effect | | NOEC | 505 | ? | Patin, 1999 | A | C | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |
| spud mud (MAF) | *Mytilus edulis* | Molluscs | mortality | 50 | LC | 100000 | 4 | Patin, 1999 | A | A | W | U | D | exact composition not known, grainsize, temperature and salinity not reported |