SETAC PRESS

Environmental Toxicology and Chemistry, Vol. 27, No. 4, pp. 1006–1012, 2008
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Printed in the USA
0730-7268/08 $12.00 + .00

SPECIES SENSITIVITY DISTRIBUTIONS FOR SUSPENDED CLAYS, SEDIMENT BURIAL, AND GRAIN SIZE CHANGE IN THE MARINE ENVIRONMENT

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(*Received* 5 *June* 2007; *Accepted* 16 *November* 2007)

Abstract—Assessment of the environmental risk of discharges, containing both chemicals and suspended solids (e.g., drilling discharges to the marine environment), requires an evaluation of the effects of both toxic and nontoxic pollutants. To date, a structured evaluation scheme that can be used for prognostic risk assessments for nontoxic stress is lacking. In the present study we challenge this lack of information by the development of marine species sensitivity distributions (SSDs) for three nontoxic stressors: suspended clays, burial by sediment, and change in sediment grain size. Through a literature study, effect levels were obtained for suspended clays, as well as for burial of biota. Information on the species preference range for median grain size was used to assess the sensitivity of marine species to changes in grain size. The 50% hazardous concentrations (HC50) for suspended barite and bentonite based on 50% effect concentrations (EC50s) were 3,010 and 1,830 mg/L, respectively. For burial the 50% hazardous level (HL50) was 5.4 cm. For change in median grain size, two SSDs were constructed; one for reducing and one for increasing the median grain size. The HL50 for reducing the median grain size was 17.8 μm. For increasing the median grain size this value was 305 μm. The SSDs have been constructed by using information related to offshore oil- and gas-related activities. Nevertheless, the results of the present study may have broader implications. The hypothesis of the present study is that the SSD methodology developed for the evaluation of toxic stress can also be applied to evaluate nontoxic stressors, facilitating the incorporation of nontoxic stressors in prognostic risk assessment tools.

Keywords—Species sensitivity distributions   Nontoxic stressors   Marine sediments   Drilling activities

INTRODUCTION

As a result of risk-mitigating measures, the chemical state of the North Sea has substantially improved over the last 20 years [1]. Other nonchemical, nontoxic stressors, however, can also affect the ecological status of water bodies. Discharges with high particulate matter concentrations, for instance, can cause adverse effects in the receiving water environment due to elevated concentrations of suspended particulate matter, rapid deposition of solids in sediments, and changes in physical or chemical properties of the sediments [2,3]. These discharges arise, for instance, at oil well drilling and dredging activities.

Drilling oil and gas wells requires use of drilling fluids (mud). This process generates large volumes of drill cuttings [4], which may be discharged to the sea from offshore drilling platforms. Currently, there are two primary types of drilling fluids in use: water-based muds and muds with oil or a synthetic fluid as the main constituent [2,5]. Because of their potential environmental harm, discharging drilling muds (and associated cuttings) other than water-based is no longer allowed in the region falling under the 1992 Oslo–Paris Convention. This convention currently guides international cooperation on the protection of the marine environment of the Northeast Atlantic (www.ospar.org).

The two major ingredients in water-based drilling mud, bentonite clay and barite, are toxicologically practically inert [6]. Furthermore, these muds contain chemicals that are assumed to pose little or no risk (Oslo–Paris agreement 2004–10, www.ospar.org). This implies that the primary concern at discharge is suspended particles, which are generally released in large quantities. Marine organisms are found to be particularly sensitive to the suspended particulate phase of water-based drilling fluids, indicating that physical effects of suspended particles should not be neglected [3].

Species sensitivity distributions (SSDs) of toxicants are commonly used in the risk assessment of toxic mixtures [7,8]. The SSD approach might also be useful for quantifying the effects of nontoxic stressors. To date, SSDs of nontoxic stressors related to marine drilling discharges are, however, not available. The goal of the present study was to develop SSDs for three nontoxic stressors, i.e., suspended clays, burial by sediment, and change in sediment grain size. Selected stressors for drilling discharges are described, followed by an overview of reported effect data. Then, SSDs based on collected effect levels are presented. Finally, uncertainties present in the SSDs

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Published on the Web 12/11/2007.

for nontoxic stressors and their use in risk assessment are discussed.

MATERIALS AND METHODS

Identification of stressors

Three stressors that relate to the emission of particles were identified: suspended clay concentrations in the water column, the thickness of the deposited layer on the seabed, and the change in grain size to represent the changing characteristics of the sediment.

High mud and cuttings concentrations can be found in the water column only in the vicinity of the discharge point. Dilutions of 1,000-fold or more are encountered within 1 to 3 m of the discharge [6]. Particles less than 0.01 mm settle very slowly and can persist in the water column for weeks and months. As a result, large zones of increased turbidity may be created around drilling platforms [3]. These plumes of suspended particles may have an impact on marine organisms [6].

Large amounts of drilling solids may be discharged from a platform leading to accumulation of large cuttings piles on the sea floor that might cause chronic alteration of the local benthic environment [9,10]. The potential ecological effects of cuttings and smaller particles (bentonite clay and barite) settling onto the seabed has been explained primarily as the temporary effects of physical burial of benthic fauna [11]. Species with burying behavior, experience little or no effect [12], while sedentary organisms, which have a low capability to move through the sediment, such as certain bivalve species, are much more sensitive [13]. The nature and effects of burial of species appear to be determined by the depth of burial; burial rate; tolerance of species, such as life habitats, escape potential, and low oxygen tolerance; nature of material, such as grain size different from native sediment; and season, e.g., mortality rate by burial higher in summer than winter [14–17]. Effects data describing the impacts of these factors separately were not available. Therefore in the present study the thickness of the burial layer was used as an indicator for all the effects related to burial by deposited material.

Although bioturbation and physical mixing (e.g., by currents) results in mixing of drill cuttings with the original sediment, the sedimentation of drill cuttings will change the texture and structure of the sediment. Such change renders the substrate less suitable as habitat for some benthic species and more suitable for others [6]. Here the change in median grain size was used to represent the overall changes in sediment characteristics and it was considered a determining factor of the specific community inhabiting an area.

Species sensitivity distribution

In environmental risk assessment the SSDs can be applied by predicting the potentially affected fraction of species (PAF) at a certain level of exposure [8]. An SSD is defined by the average log-effect concentration and the standard deviation of the log-effect concentrations for biota towards a specific stressor [18]. Several distributions can be used to define the SSD. The choice of a distribution is arbitrary and usually selected based on best-fit results [19–21]. In the present study, the log-normal distribution (natural logarithm) was used [22]. In case more than one effect value was reported for one species, the geometric mean value for that species was taken as the input for the SSD. For the change in grain size, two thresholds per species exist, so two SSDs were derived, one for increasing and one for decreasing grain sizes. The hazardous concentration (or level) leading to a potentially affected fraction of 5% (HC5) and 50% was derived based on the procedure described by Aldenberg and Jaworska [23].

Determination of effect levels

In order to develop SSDs for the three identified nontoxic stressors, effect level data were collected. For toxicity, standardized test protocols exist to determine effect levels (no-observed-effect concentrations and/or concentrations causing 50% effect [EC50s]). However, for the testing of nontoxic stressors such protocols are not available. In spite of the lack of standardization, effects of clay particles in the water column as well as effect levels related to burial of biota are studied with species from several taxonomic groups. Effect levels related to suspended particles and burial of sediment were obtained from literature available from the internal literature database of the Dutch Organisation for Applied Scientific Research, Institute for Marine Resources and Ecosystem Studies (Den Helder, The Netherlands), Current Contents, and the internal literature database at Battelle (Duxbury, MA, USA). The U.S. Environmental Protection Agency's AQUIRE database (www.epa.gov/ecotox) was also consulted.

Suspended clays

For suspended clays the data collection resulted in a database with effect concentrations for marine species for different effect types, such as survival, feeding behavior, growth, mobility, reproduction, oxygen consumption, and effects on the gastrointestinal tract. Data were obtained from exposure studies with clay-sized particles (i.e., attapulgite, bentonite, clays, and barite) and also with various types of water-based drilling fluids. Most data were available for the species groups phytoplankton, zooplankton, crustaceans (excluding zooplankton), molluscs, and fish. Filter feeding molluscs are most sensitive to increased particle concentrations. See the Supplemental Data for an overview of the effect data (http://dx.doi.org/10.1897/07-339.S1).

Due to the absence of standardized laboratory test protocols for suspended solids, the test conditions were variable or not reported at all. Effect magnitudes were poorly quantified and none of the studies reported information on the effects in the controls. If quality criteria to select effect data for toxicity assessment would have been applied to the data available for suspended solids (see Klimisch et al. [24]), only some of the collected effect data would have been accepted.

The few no-observed-effect concentration data (only available for water-based drilling fluids) and values with no quantified effect magnitude were excluded from further analysis. Instead, the EC50s for mortality were used to construct the SSDs for respectively barite and bentonite. For barite and bentonite, data on 15 and 12 different species were available, respectively. For attapulgite, only EC50 values for fish species were available and these data were excluded from the analysis as they were considered as not being representative for marine species in general. The EC50 data from exposure studies with complete drilling fluids were also excluded from the analysis, as the varying composition of fluids, depending on the characteristics of the formation, might influence the effect levels.

Burial

The collected effect data for burial of sediment included depths of burial tested in mainly chronic exposure tests with

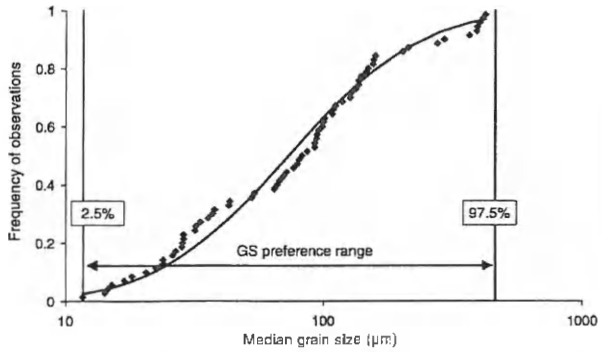

Fig. 1. Determination of the grain size (GS) preference range for the marine polychaete *Octobranchus floriceps* from the benthic field monitoring observations. The preference range is presented as the 95% interval of a log-normal distribution. ♦ = observations; — = fitted log-normal distribution.

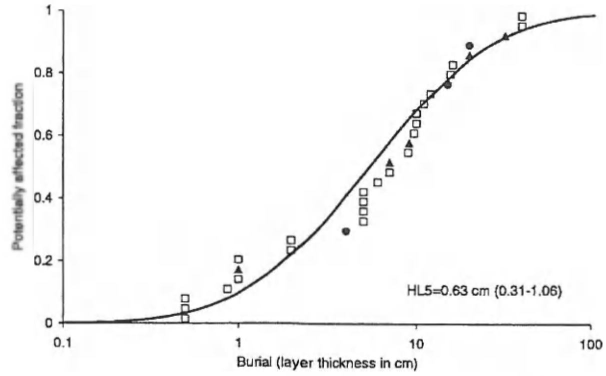

Fig. 3. Species sensitivity distribution of benthic species for burial expressed as thickness of an instantaneous burying layer and the corresponding hazardous level for 5% of the species (HL5) (median value and 5–95% confidence interval) (n = 32). □ = mollusc; ▲ = crustacean; ● = polychaete.

marine species. The effects magnitudes reported ranged from 0 to a 100% effect [12,15,25,26]. No EC50 values have been reported for burial. Kranz [16], however, used an indicator with a comparable concept: the escape potential of a given species can be identified as the probability (x) that the organism can escape with a given depth of burial (EPx).

As the availability of no-effect levels was limited to four species, only effect values with quantified and nonquantified effect magnitudes (including EP10 values) were considered in the present study. The obtained EP10 values were directly used in the SSD, except for three species for which EP10 values of zero were reported. For those species half of the lowest-observed-effect level was used in the SSD. For example, epifaunal suspension feeders, permanently attached to hard substrate could not escape burial of 1 cm depth, which was the lowest exposure level included in the experiments. In this case, the effect level for inclusion in the SSD was set at 0.5 cm. The final data set contained data on 32 marine species.

Change in grain size

No standardized tests focusing on the effect of altered median grain size were found. However, substantial information on the preference of species for a specific range of median grain sizes was available from benthic field surveys. The preference range of median grain sizes for different species was derived from the observed median grain sizes at locations where a species occurs. The data were obtained from benthic surveys in the Norwegian part of the North Sea, Norwegian Sea, and Barents Sea and stored in the Environmental Monitoring Database of the Norwegian Oil Industry Association. It contained information on 2,206 species collected in 2,428 sediment samples from standardized monitoring surveys around oil platforms on the Norwegian Continental Shelf in the period 1990 to 2002. The samples collected at reference stations, which were considered uncontaminated, were selected from the database.

Information on the preference for the median grain size was obtained for 404 marine species. As a limited number of observations might influence the assessment of the width of the grain size preference range, only species that were observed at more than 10 stations were taken into consideration (300 species). For each species, the preference range was assessed from the available data by determining the 95% interval based on a lognormal distribution of the data (see for an example Fig. 1 for the marine polychaete *Octobranchus floriceps*). By this procedure, two grain-size thresholds were derived for each species. One for fine grain sizes corresponding to the 2.5 percentile of the distribution, and one for course grain sizes corresponding to the 97.5 percentile of the distribution.

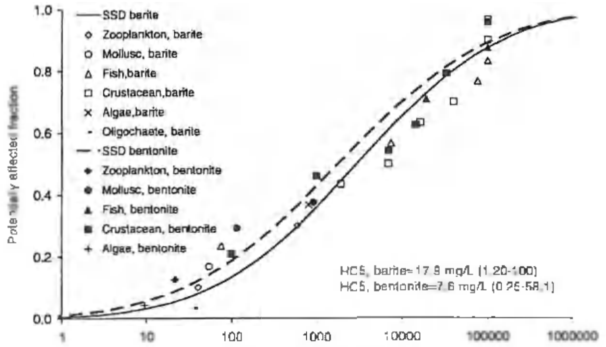

Fig. 2. Species sensitivity distributions (SSD) and the corresponding hazardous concentration for 5% of the species (HC5) (median values and 5–95% confidence intervals) based on 50% effect concentrations for barite (n = 15) and bentonite (n = 12).

RESULTS

The SSDs based on collected EC50 values for mortality resulting from suspended barite and bentonite exposure, presented in Figure 2, show that species are slightly more sensitive to bentonite than to barite. However, this difference is not statistically significant (analysis of variance, significance level 5%). The SSD for barite is based on data for 15 species in five taxonomic groups and for bentonite 12 species and four taxonomic groups. For barite the 50% hazardous concentration and HC5 correspond to 3,010 (752–12,000) and 17.9 (1.2–100) mg/L respectively (median value and 5–95% confidence interval). For bentonite these values are 1,830 (340–9,855) and 7.6 (0.25–58.1) mg/L respectively.

The search for effect data for burial resulted in a dataset containing 39 effect values (different effect magnitudes) for 32 species (24 molluscs, five crustaceans, and three polychaetes). The SSD for burial by sediment is presented in Figure 3. For burial the 50 and 5% hazardous levels were determined

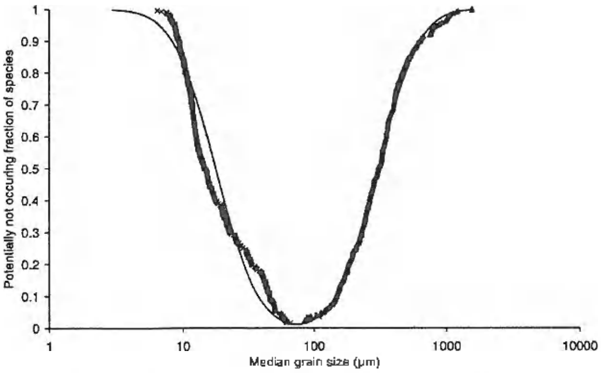

Fig. 4. Relationship between the potentially not-occurring fraction of sediment species and the median grain size derived from the presence of marine species at different grain sizes, registered during seabed monitoring activities in the North Sea, Norwegian Sea, and Barents Sea ($n = 300$). × = observed lower grain size thresholds for North Sea, Norwegian Sea, and Barents Sea species; ▲ = observed upper grain size thresholds for North Sea, Norwegian Sea, and Barents Sea species.

at 5.4 (3.7–7.9) and 0.63 (0.31–1.06) cm respectively (median and 5–95% confidence interval).

The narrowest grain size preference range determined in the present study equals 16 μm and the widest, 1,545 μm. The median value is 277 μm. Figure 4 shows the relationship of the fraction of benthic species not occurring in marine sediments as a function of median grain size. The fit is the combination of the probability distribution curves for both the lower and the upper grain size thresholds as presented in Figure 5. The cumulative distributions of the lower and upper grain size thresholds for 300 marine species (Fig. 5) can be considered as a SSD for respectively a reduction and an increase in the median grain size. The 50 and 5% hazardous levels of the SSD of lower grain size thresholds correspond to 17.8 (16.7–18.9) and 47.8 (43.7–52.8) μm respectively. For the SSD of the upper grain size thresholds these values are 305 (288–325) and 115 (104–126) μm respectively (median and 5–95% confidence interval).

DISCUSSION

The present study shows that the statistical extrapolation methodologies developed for the evaluation of toxic stress can be applied to evaluate nontoxic stressors. The application of these procedures to nontoxic stressors harmonizes the evaluation of toxic and nontoxic stressors. Including both types of stressors in one overall evaluation scheme will facilitate the comparison of risks related to emissions and give possibilities to rank and prioritize among the various stressors (see Harbers et al. [8] for a similar approach, but for toxicants only). The success of the application of the SSD approach depends, however, on the quantity and quality of the available input data. For the three stressors evaluated in the present study the availability and quality of data are discussed below.

Suspended clay concentrations

The quality of the available data is difficult to judge for suspended clays because of the absence of standardized laboratory test protocols. However, selecting only EC50 values still resulted in a dataset sufficient for generation of SSDs [18]. By including results from nonstandardized tests in the SSD we might have increased the variation in effect values. The standard deviation of the log-effect concentrations based on ln-transformed data for barite (3.05) and bentonite (3.25) correspond to β values (slope parameter for a log-logistic distribution) of 0.73 and 0.78. These values are relatively high compared to the values for groups of chemicals with different toxic mode of action presented by De Zwart [27]. For 23 groups with different toxic modes of action, De Zwart [27] reported β values between 0.28 and 0.71 with an average of 0.49. Apart from the inclusion of data from nonstandardized tests, the scatter in effect data might also be caused by the fact that organisms respond differently to elevated concentrations of suspended particulate matter (SPM) and therefore have different susceptibility to concentrations of SPM. Some functional groups of organisms are more adapted to deep water or coastal zones and thus to different naturally occurring background concentrations of SPM. Mobile organisms, such as fish have the ability to flee from clouds of SPM from drilling discharges, while sessile organisms such as benthic filter feeders are immobile and therefore more exposed [14]. In the SSDs for barite and bentonite, filter feeding zooplankton and molluscs are, together with algae, among the sensitive taxonomic groups, while benthic crustacean and siphon feeding molluscs are relatively insensitive. This supports the hypothesis that organisms living in the benthic boundary layer of fine sediments are accommodated to deal with elevated turbidity and sedimentation [28]. A concern why barite might not be directly comparable to other sources of SPM is its metal content. Barite contains metal impurities that might lead to other effects than just physical effects. The fact that the SSDs for barite and bentonite are not significantly different supports the assumption that metals in barite are in highly insoluble forms, so little leaches from the particles into the water where they might affects water column organisms [29]. It could be argued that the shape and constitution of particles have a strong bearing on their effects (especially concerning physical effects). A comparison with effect data for other types of SPM should indicate the generic applicability of the derived SSDs for activities other than offshore oil and gas drilling.

Burial

No effect data were available referring to the thickness of a deposited layer or to the deposition rate. Therefore test results using depth of burial as the endpoint were selected to derive the SSD. These effect data are based on instantaneous and complete burial, while for drilling discharges the formation of the burying layer is a slow process. Normally (nonsessile) species are slowly covered by the deposition, and have time to escape burial and move upwards with a rate equal to the deposition rate. The difference between the way the exposure is expressed in the experiments (depth of burial) and the way the exposure is defined in the present study (thickness of deposited layer), probably results in an overestimation of effects related to a deposited layer. This means that the application of the SSD for burial may result in a conservative risk assessment (see also the Supplemental Data; http://dx.doi.org/10.18977/07-339.S1). The fact that the calculated HC5 based on chronic effect data (0.63 cm) lies in the same range as a reported threshold level for no effects of 1 cm for sessile sediment species [17], supports this hypothesis.

Sediment structure

Although a relationship between sediment characteristics and infaunal community structure exists, there is considerable

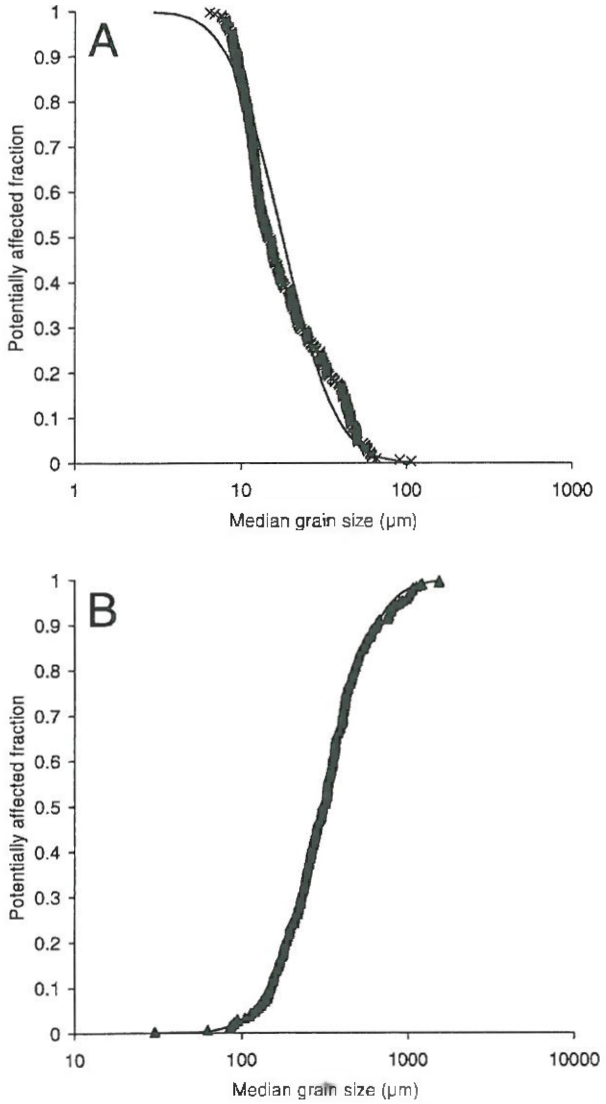

Fig. 5. Species sensitivity distributions based on the lower grain size thresholds (**A**), corresponding to the 2.5 percentile (×) of the individual distributions (determined as described in Fig. 1) and based on the upper grain size thresholds (**B**), corresponding to the 97.5 percentile (▲) of the individual distributions (determined as described in Fig. 1) for 300 North Sea, Norwegian Sea, and Barents Sea benthic species.

variability in species responses to specific sediment characteristics [30]. Factors ultimately controlling infauna distributions may not be sediment grain size per se or factors correlated to it (such as organic content), but rather interactions between hydrodynamics, sediments, and infauna and how these affect sediment distribution, larval supply, particle flux, and porewater chemistry [31]. This implies that other factors, besides the median grain size, also need to be considered to interpret the results of the risk assessment and assess the actual presence of species in sediments.

Using the information from the monitoring surveys in a generic risk assessment procedure assumes that the preference ranges for the 300 marine species, obtained in the present study, are representative for marine benthic species in general (e.g., different geographical regions). Figure 4 suggests that a median grain size of approximately 90 µm is appropriate for nearly all species. This is due to the fact that locations with silt/clay specialists or course specialists are not present in the data set taken from the Environmental Monitoring Database. As the grain size ranges are determined for species in soft bottom sediments from the North Sea, the Norwegian Sea, and the Barents Sea, the developed SSD is only applicable to regions with a comparable range of median grain sizes. An SSD for grain size changes could be specified for different locations or environments with characteristic biota (arctic species, tropical species, deep sea species etc.). However, the required data as used in the present study are not readily available for different types of environments. Further analysis of the monitoring data stored in the Environmental Monitoring Database is suggested in order to refine the SSD for grain size changes by taking into account factors like geographical area, water depth, and fraction organic carbon.

Implications for risk assessment

In the present study, the PAF is an indicator for effects. Given certain exposure, the derivation of PAF levels from the SSDs for suspended clays and burial is straightforward. The determination of the PAF from a certain change in median grain size needs, however, further discussion. If, for example, the median grain size changes from 30 to 200 µm the fraction of nonoccurring species remains the same (~20%, Fig. 4). This is caused by the increase of occurring species from 30 up to 90 µm, followed by a decrease of occurring species up to 200 µm. However, independent of the potential increase of occurring species, the species present at 30 µm have a probability of 20% of being affected by the change to 200 µm. This probability is actually the decrease in occurring species derived from the SSD based on the upper grain size thresholds. As long as an increase in the fraction of occurring species is considered as a positive effect and ignored in the risk assessment and only a reduction of the fraction of occurring species considered as a negative effect, the two SSDs for grain size change can be applied independently in risk assessment. Comparable considerations can be made to the work published by Latour et al. [32] and Van Zelm et al. [33] both using the concept of two-sided SSDs.

One of the criticisms of the use of SSDs in risk assessment is the lack of ecosystem dynamics incorporated in these models. In other words, "how representative is the potentially affected fraction of species (PAF) for the actual effect in the field?" [34]. One of the benefits of using field data for the construction of SSDs, similar to what is done for change in grain size, is the fact that species interactions will be accounted for. If a change in median grain size results in an increase in PAF, the new occurring species might out-compete the species that were originally present. These processes are incorporated in the SSD for grain size change.

Struijs et al. [35] described a methodology to incorporate naturally occurring background concentrations in the risk assessment using SSDs. The inclusion of natural background levels is also relevant for nontoxic stressors, particularly for suspended clay concentrations with background concentrations of suspended matter (for example, in the open North Sea up to 20 mg/L) [36]. However, the applicability of the added risk approach to nontoxic stressors needs further study.

An important advantage of the use of the PAF is the possibility to combine effects from single toxic stressors into one effect indicator, the multistressor PAF (msPAF) [8]. With the SSDs for nontoxic stressors in place, msPAF values based on the combined exposure to toxic and nontoxic stress can be calculated. Using the msPAF approach, the contribution of all stressors to the overall effect can be visualized. This facilitates risk communication and prioritization of stressors in the light of defining the right risk-mitigating measures [37]. However, for combinations of toxicants it remains to be established how robust predictions of msPAF are when compared to field or mesocosm data and how uncertainties proliferate through the whole protocol of the msPAF approach [7]. This also applies to combinations of toxic and nontoxic stressors.

SUPPORTING INFORMATION

S1. Overview of the collected effect data for suspended clays.

Found at DOI: 10.1897/07-399.S1 (36 KB PDF).

Acknowledgement—The present study is based upon work performed in the Environmental Risk Management System program, financed by ConocoPhillips, Eni, ExxonMobil, Hydro, Petrobras, Shell, Statoil, and Total. Contractors in the program have been Akvaplan-niva, Battelle, MUST, Rogaland Forskning-Akvamiljø, the Dutch Organisation for Applied Scientific Research and University of Oslo, with SINTEF acting as the coordinator of the program. The present study has been technically reviewed by the oil companies but its contents and conclusions do not necessarily reflect their views and practices.

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