



ELSEVIER

Journal of Hazardous Materials 61 (1998) 43–51

**JOURNAL OF
HAZARDOUS
MATERIALS**

Dynamic assessment of the ecological risk of the discharge of produced water from oil and gas producing platforms

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Abstract

Since 1991 the North Sea countries (UK, Netherlands, Norway and Denmark) have put a lot of effort in the development of a decision support system for the legislation of the use and discharge of offshore exploration, drilling and production chemicals. The heart of this so-called 'harmonised mandatory control system' is the 'chemical hazard assessment and risk management' (CHARM) model. This model enables the ranking of chemicals on the basis of their intrinsic properties, using a realistic worst-case scenario. To meet the prerequisites of the model (simple and transparent calculation rules), the CHARM model uses a fixed dilution factor, assuming equal and constant dispersion of chemicals around the platform. In reality, however, the chemical follows a three-dimensional dispersion pattern which will change over time. To be able to use the principles of the CHARM model in such a dynamic situation for risk management, a new model has been developed by TNO in cooperation with Dutch Oil (NAM). This model gives a probabilistic estimation of the ecological risk of produced water, based upon a realistic calculation of the fate of components of produced water after discharge from the platform. Spatial and temporal variation in the concentration of chemicals is summarised in frequency distributions. The ecological risk is calculated for aquatic life, benthic life and the food chain. The model aims to support the selection of cost-effective mitigating measures for risk reduction. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Ecological risk assessment; Time variable exposure; Produced water; Effluents

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1. Introduction

In the offshore production of oil and gas, production chemicals are added to the water pumped into the well to enhance the production, to protect the equipment and to maintain safety on the platform. Part of these chemicals may end up in the marine environment as they are discharged with the produced water, and adverse effects to the

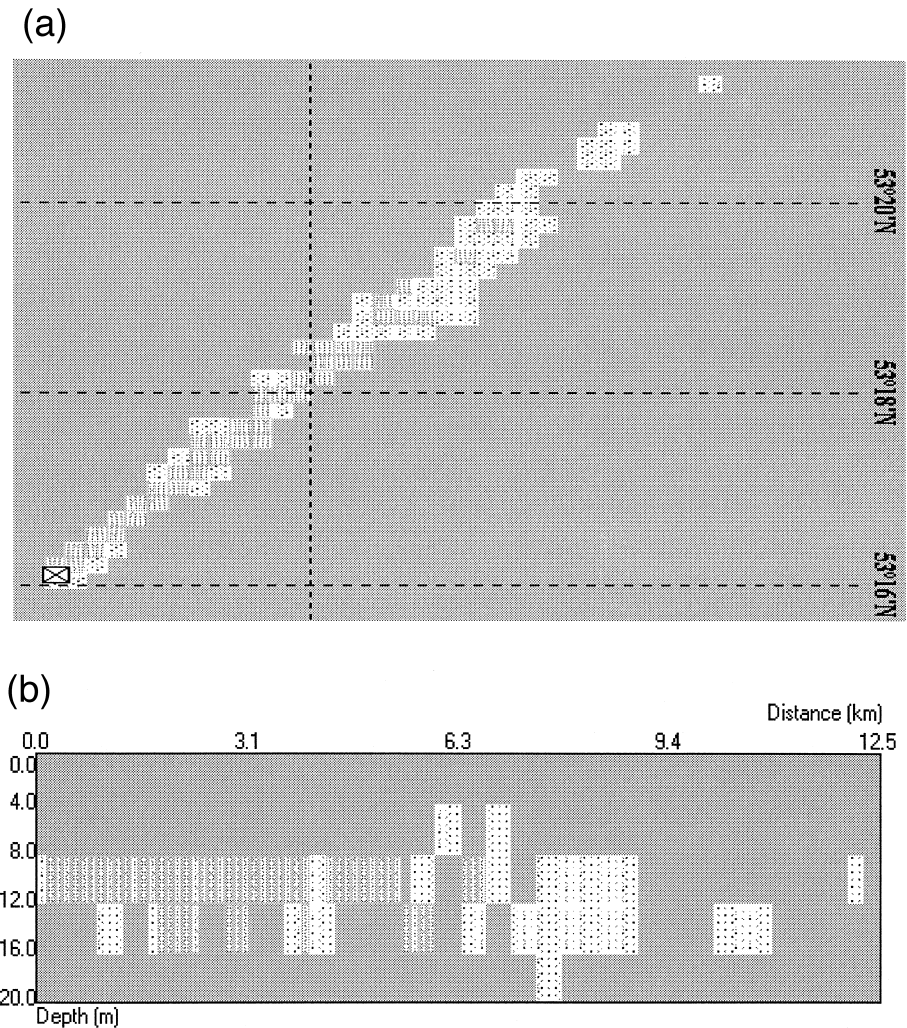


Fig. 1. Concentration pattern of a plume of produced water continuously discharged from an offshore gas-production platform: (a) maximum concentration seen from the top; (b) concentrations in a cross section of the water layer in the direction of the plume. The figures are generated using a software package suitable for 3-dimensional modelling of discharges into the marine environment [5].

biota in the ambient environment may occur. To prevent pollution caused by exploration and production activities, each North Sea country has developed a legislative system regarding the use of chemicals in the offshore exploration and production of oil and gas. By developing the systems individually, the policy became very inconsistent within the North Sea countries. It was therefore decided, in the North Sea Ministers Conference in 1990, to harmonise the legislation of the use of offshore exploration and production (E and P) chemicals. In 1991 the 'chemical hazard assessment and risk management' (CHARM) project was initiated, in which authorities of the North sea countries, the chemical suppliers and operating companies cooperated in the development of a model for evaluating the environmental impact of the discharge of offshore E and P chemicals. The CHARM model [1] calculates the concentration of a chemical in the water at 500 m from the platform, based upon worst-case platform characteristics, which is compared with the toxicity threshold of biota. The CHARM model is accepted by PARCOM as a valid model for performing hazard assessment of offshore E and P chemicals, as required by the harmonised mandatory control system.

To calculate the concentration of a chemical at 500 m from a platform the concentration of the chemical in the discharged produced water is multiplied with a fixed dilution factor. In the hazard assessment module (using worst-case assumptions) a default dilution of 0.001 is used [2]; in risk assessment experimentally determined figures may be used [3,4] instead (i.e. rhodamine experiments). But in both cases the spatial and temporal distribution of the chemical is not taken into account, and a constant exposure concentration of the chemical is assumed at a fixed distance from the platform. In reality, however, the produced water will form a plume within the ambient seawater. The concentration will be higher in the center of the plume and decrease with the distance from the center and the distance from the plume (see Fig. 1). Even the position

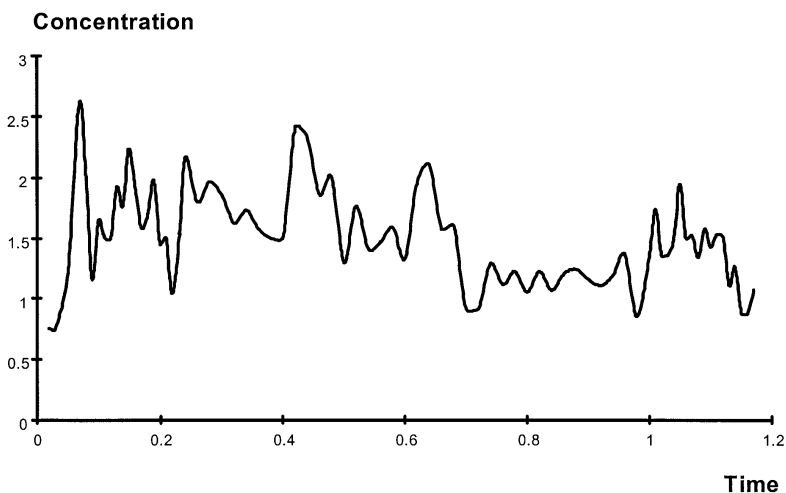


Fig. 2. Plot of the concentration of a chemical at a random point in the discharge plume shown in Fig. 1 over a 24-h period.

of the plume may change over time due to influence of currents and wind. Fig. 2 shows the concentration of a chemical in the produced water over time during a 24-h discharge of produced water in a tidal area.

This paper describes a method which can be used for estimating the environmental impact of a chemical discharged with produced water or even of complete produced-water discharges. The method is based upon the generally applied PEC:PNEC ratio [6] in which the PEC (predicted environmental concentration) is compared with a toxicity threshold level, also referred to as the PNEC (predicted no-effect concentration). For the method described in this paper, the PEC is replaced by a time-integrated exposure concentration, and the PNEC is adjusted for the actual time of exposure to a certain concentration of a chemical.

2. Time-integrated exposure concentration

Fig. 2 shows that the concentration of a chemical at a certain point within a plume of produced water can be very variable and unpredictable. The variation in concentration is

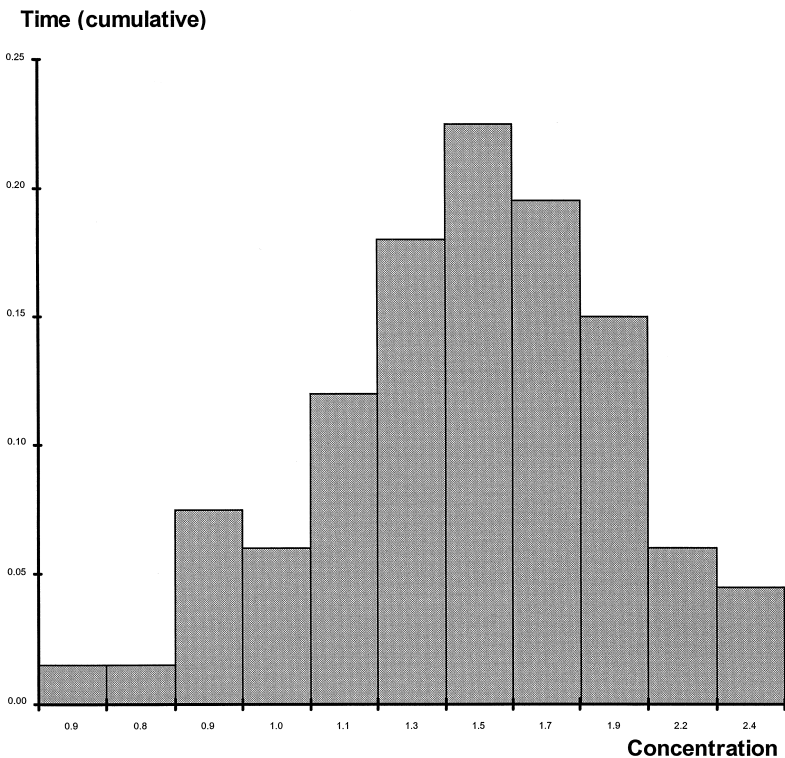


Fig. 3. Time distribution of the concentration curve presented in Fig. 2. The X-axis represents the concentration range divided into logarithmic classes. The Y-axis represents the cumulative exposure time to the specified concentration class.

caused by factors such as wind and currents which may in turn cause complicated turbulence patterns in the water column. A sessile organism located at this point also experiences these variations in its exposure concentration. It is clear that an accurate hazard assessment should acknowledge these variations instead of assuming a constant exposure concentration. The relationship between concentration and time is too complicated to be described by a mathematical function. It is, however, possible to split up the exposure period into very short periods in which the variation in exposure concentration can be considered negligible. If the concentration range is divided into a series of (logarithmic) classes, a time-distribution pattern can be generated by accumulating the actual time that the exposure concentration lies within the a specific concentration class. Assuming the effect of repetitive short exposure (i.e. 4 times 6 h) equals the effect of continuous exposure for a period as long as the short exposure periods together (i.e. $4 \times 6 = 24$ h), the concentration–time curve may be replaced by the time-distribution curve. Fig. 3 shows the time distribution generated from the concentration–time curve presented in Fig. 2.

To perform a hazard assessment conform the PEC:PNEC approach, each concentration class can be compared with a predicted no-effect concentration, representative for the cumulative exposure time of that concentration class.

3. Time adjusted effect concentration

For most chemicals used on offshore production platforms ecotoxicity data has to be provided for regulatory purposes [7]. These are in general LC_{50} or EC_{50} values for algae, crustaceans or fish determined in standardised toxicity tests. In these tests, organisms are exposed to a constant concentration of the chemical for a predetermined period (e.g. 48 h for the crustacean *Acartia tonsa*, 72 h for the algae *Skeletonema costatum* and 96 h for most fish larvae tests). As could be seen from Section 2, organisms are seldom exposed to a constant concentration for that long. To enable a valid comparison of the exposure concentration with a no-effect concentration, the latter should be determined with a representative exposure period. As in general only standardised ecotoxicity data are available for a chemical, these data should be adjusted for a shorter (or longer) exposure time.

The theoretical relationship between exposure time and effect concentration was first described by Haber [8] in 1924, who studied the effect of different times of exposure to poisonous gasses on cats. In theory a very high concentration is needed at short exposure times to achieve the same effect as long exposure to a low concentration (see Fig. 4). This relationship can be derived in both a mechanistic [9,10] and empirical [11,12] manner. In this paper an empirical approach will be used which is relatively simple and gives an appropriate description of the relation between exposure time and effect [13]:

$$LC_{50,t} = LC_{50,T} / (t/T) \quad (1)$$

where t = actual exposure time; $LC_{50,t}$ = lethal concentration for 50% of the exposed individuals at the actual exposure time t ; T = exposure time used in the toxicity test;

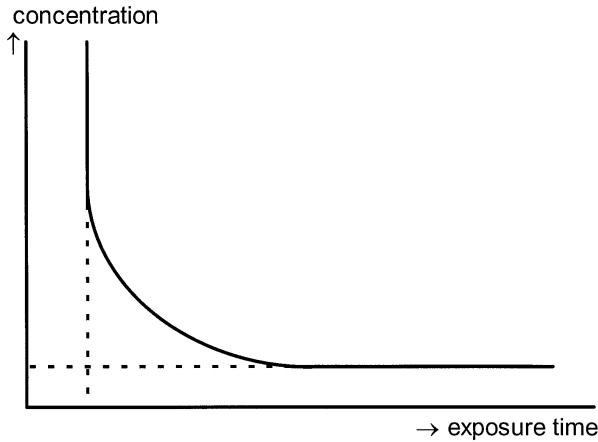


Fig. 4. Relationship between the concentration at which a defined effect is observed and the corresponding exposure time.

$LC_{50,T}$ = lethal concentration for 50% of the exposed individuals as determined in the toxicity test using exposure time T .

Eq. (1) can also be used to calculate a time-adjusted EC_{50} or PNEC by replacing LC_{50} in the equation by these figures. Several methods are available for calculating a PNEC from the available toxicity data [13], but these will not be described in this paper.

4. Risk calculation

The previous chapters showed how to deal with fluctuating exposure concentrations by calculating the concentration–time distribution. An organism located at the point shown in Fig. 2 is exposed to a concentration within each concentration class for a total period as shown in Fig. 3. The exposure time per class could be used to calculate a representative PNEC value for each class in the distribution, as was shown in the previous chapter. The ecological risk of being exposed to fluctuating concentrations can now be calculated using the following steps.

(1) Each class in the distribution can be represented by the geometric mean of the upper and lower boundaries (referred to as PEC_{class}). For each class a $PEC_{class}:PNEC_{class}$ ratio can be calculated by dividing PEC_{class} by the PNEC adjusted for the cumulative exposure time of that class.

(2) The $PEC:PNEC$ ratio per class can be transformed into a probabilistic risk estimate per class, using the relationship presented in Fig. 5.

(3) Finally the risk estimates for each class can be combined into a single overall risk estimate for the period of exposure to the fluctuating concentration shown in Fig. 3. As the risk estimate is a probability value, the statistical rule for combining probabilities can be used to combine the risk estimates:

$$R(c1 + c2) = R(c1) + R(c2) - R(c1) \times R(c2) \quad (2)$$

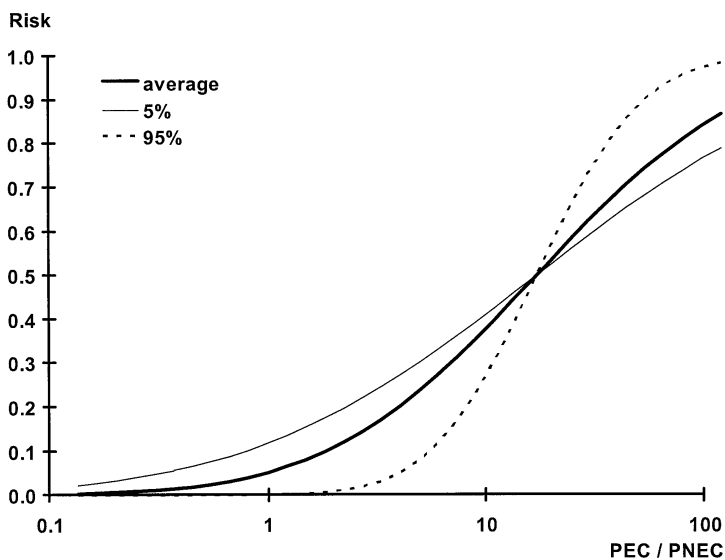


Fig. 5. The relationship between PEC:PNEC ratio and an ecological risk estimate, calibrated using toxicity data of 17 chemicals.

where $R(c1 + c2)$ = environmental risk of a mixture of 1 and 2; $R(c1)$ = environmental risk of compound (or mixture) 1; $R(c2)$ = environmental risk of compound (or mixture) 2.

These three steps can be repeated for each cell in the distribution pattern; Table 1 shows an example of the calculation steps. Finally this yields a (time integrated) risk

Table 1

Sample calculations performed with the model for the time variable exposure as shown in Fig. 2

Class (mg l^{-1})	Cumulative exposure time (s)	Time adjusted PNEC (mg l^{-1})	PEC:PNEC ratio (-)	Risk (%) (-)
0.7	0.02	128	0.005	0.00
0.8	0.02	128	0.006	0.00
0.9	0.08	26	0.035	0.01
1.0	0.06	32	0.032	0.00
1.1	0.12	16	0.072	0.03
1.3	0.18	11	0.122	0.11
1.5	0.23	9	0.173	0.24
1.7	0.20	10	0.170	0.23
1.9	0.15	13	0.148	0.18
2.2	0.06	32	0.067	0.03
2.4	0.05	43	0.057	0.02
Combined risk				0.85

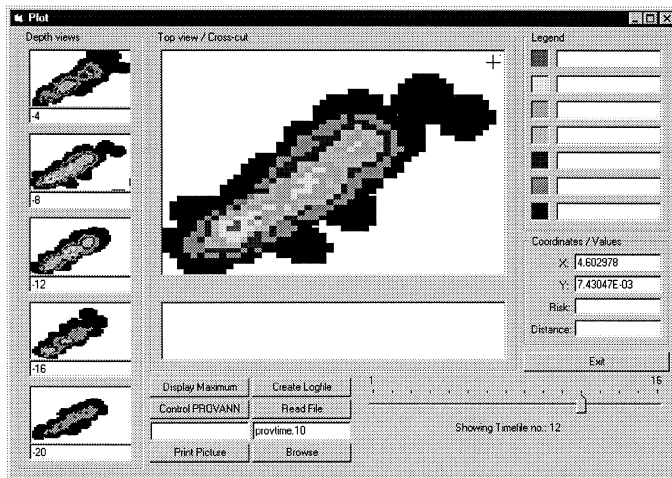


Fig. 6. Graphical representation of the risk of approximately 20 h exposure to a plume of produced water (see Fig. 1). The small figures on the left are the average concentration in a depth-layer of the plume. This programme distinguishes five depth layers. The large figure in the centre is an enlargement of the second depth layer from the surface area.

estimate for a three-dimensional pattern of cells, which can be displayed as shown in Fig. 6.

5. Conclusions

Although not validated yet, this method seems to be promising for implementation in risk-assessment modeling of dynamic concentration patterns. It is not too complex, which makes it applicable to various situations in which the fluctuations in the exposure concentration are measured or modeled.

The best approach for dynamic risk assessment would be to model the uptake and elimination of a chemical in an organism to estimate the internal concentration of a chemical which can constantly be compared with a critical body residue, i.e., the internal concentration of a chemical above which effects can be expected. However, such a method requires information on the uptake and elimination parameters for each combination of a species and a chemical. In most cases these data are not available, and figures have to be used based upon QSAR estimates.

The method described in this paper is an intermediate step between the traditional PEC:PNEC approach and the approach using uptake and elimination information. It can provide a more accurate estimation of the environmental risk of the discharge of a chemical (or produced water) without the requirement of a lot of unavailable or uncertain information.

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