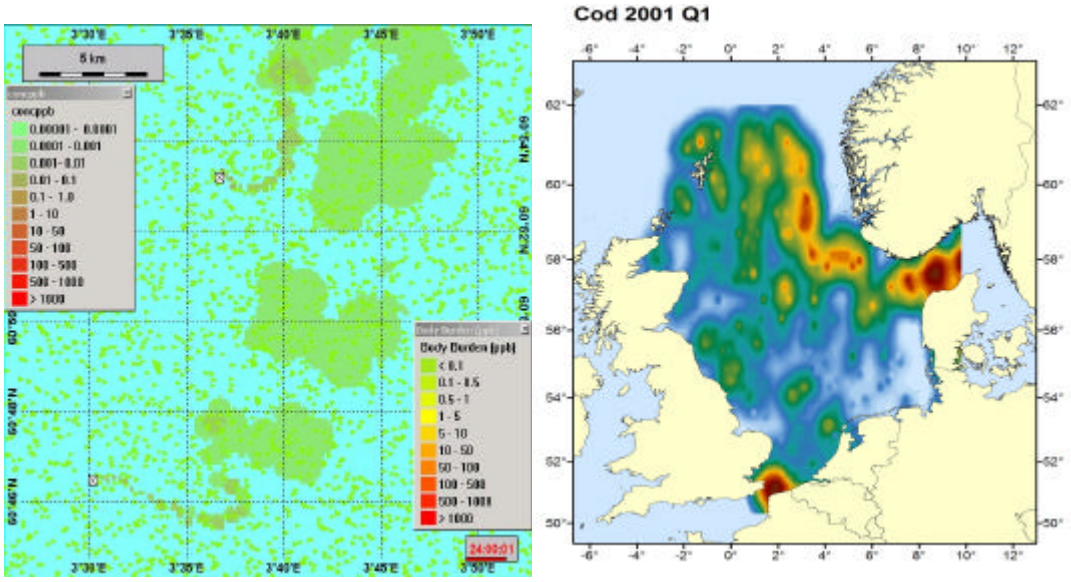
Risk Assessment
of reproductive effects
# of alkyl phenols in produced water
on fish stocks in the North Sea



Report AM-2004/018

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RF-Akvamiljø

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Objectives:

- To compile the most relevant existing data and assess the environmental risk of alkyl phenol discharges in produced water related to hormonal effects and reproduction effects on fish, taking advantage of the best currently available methods and tools regarding risk assessment.
- To make a critical evaluation of the assumptions made in the risk analysis and identify possible gaps in knowledge as a basis for an environmental risk assessment with an acceptable quality, and to make a recommendation for further work.

Key-words: Risk assessment, alkyl phenols, reproductive effects, simulations, discharges of produced water,

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Contents

1 Summary

Previous studies have revealed reproductive effects on cod exposed to a dietary dose of 5 µg of alkyl phenols per kg of fish. These compounds are present in produced water discharges from the oil installations in the North Sea. It has been raised questions whether the discharges could have an effect on the reproduction successes of cod, saithe and haddock populations in the North Sea.

This project has performed an environmental risk assessment of reproductive effects from alkyl phenol discharges on population levels of cod, saithe and haddock in the North Sea, representing the best currently available methods and data. For assessing the present risk we have used discharge data for 2002 and for assessing the future risks we have used estimated discharge data for 2006 (after implementing measures to reduce the discharges of produced water).

The exposure regimes of fish have been simulated using the DREAM software in two steps. First we used the DREAM-EIF software as a screening step to pinpoint the areas with potential risk. Then the full capabilities of the DREAM-Risk assessment model were used taking into account fish movement and uptake/elimination rates for the areas with potential of risk. The fish stock distributions have been gathered and organised by IMR using the International bottom trawl survey's (IBTS) database. The risk assessment combined the amount of fish that were exposed to alkyl phenols over the critical body burden with the fish abundances indexes provided by IMR.

The simulations show that there is no significant risk of reproductive effects on the population levels of cod, saithe and haddock in the North Sea as a result of alkyl phenol discharges in produced water.

In our judgement the overall assumptions made for the assessment seems sound and reasonable.

It is still important that the alkyl phenols discharges will be followed up with monitoring as soon as the methods for this are sufficiently developed.

In the simulations no significant effects on fish in the close vicinity of the discharges were calculated. However, low resolution in the fish stock data forced an assumption of even distributions of fish in these areas. This is not necessarily a valid assumption.

This study has assessed the reproductive effects of alkyl phenols grouped in C4-C5 and C6+. Other compounds of produced water have not been included in this assessment.

2 List of symbols

AP – alkyl phenols

BAF – Bio Accumulation Factor

Bb – Body burden

BCF – Bio Concentration Factor

BOD – Biological Oxygen Demand

BP - butylphenol

CBB – Critical Body Burden

DREAM – Dose-related Risk and Effects Assessment Model

EIF – Environmental Impact Factor

ERA – Environmental Risk Assessment

K1 – Uptake rate

K2 – Elimination rate

NP – nonylphenol

OP – octylphenol

PEC – Predicted Effect Concentration

PNEC - Predicted No Effect Concentration

NOEC – No Observable Effect Concentration

PP - pentylphenol

ppb – parts per billion

ppm – parts per million

PW- produced water

3 Introduction and background

3.1 Introduction

This work was proposed at the request (11/4-03) of the Norwegian Oil Industry Association's (OLF) working group for discharges to sea ('arbeidsgruppen for utslipp til sjø' v/Marianne Tangvald). The work is a follow up of recent studies with produced water-related alkyl phenols and aims to assess their possible environmental impact on fish reproduction after discharge to the sea. The project has performed an environmental risk assessment of reproductive effects from alkyl phenol discharges on population levels of cod, saithe and haddock in the North Sea, utilising the best currently available methods and data.

3.2 Background

Alkyl phenols are one of the groups of chemical substances naturally present in produced water which are of environmental concern, as they are known to have the capacity to have harmful effects on marine life. Different alkyl phenol substances are known from literature to have toxic and hormone disrupting properties.

The Institute of Marine Research (IMR) tested four of the alkyl phenol substances which are among the most abundant in produced water, and demonstrated their inherent capacity to cause adverse effects (environmental hazard) that may lead to reduced reproductive output in cod. The uptake, dose and bioconcentration corresponding to the assumed dose conditions in these studies were tested on the same substances by RF-Akvamiljø after initiative by OLF. The results obtained during these studies together with literature data are assumed to form a sufficient basis to establish realistic dose:response relationships and hence perform dose:response assessments for alkyl phenols.

Such a dose:response assessment is an integrated part of an 'Environmental Risk Assessment' (ERA), a methodology which is at present the most scientifically and politically accepted method to base environmental management decisions on. According to the definitions adopted by the EU and OSPAR, the 'dose:response assessment' constitutes one of a total of four steps in a proper ERA (Fig. 3.1).

Figure 3.1 The four general steps of an environmental risk assessment as required by the EU and adopted by OSPAR.

'Hazard Identification' is generally the first of the four ERA steps (Fig.1). The study by IMR represents a 'hazard identification' for four of the alkyl phenol compounds that are present at low concentrations in produced water together with a complex mixture of other alkyl phenols. It identifies which adverse effects these four compounds have an inherent capacity to cause in cod. The dose that was assumed in IMR's study has been confirmed by the experiments at RF-Akvamiljø, and this represents part of the basis for undertaking the second step of the risk assessment (the dose:response assessment).

However, the synthesis between laboratory data and real exposure situations in the field has not been established. This requires an 'Exposure assessment', defined as another of the four steps in an ERA. 'Risk characterisation' is the final step, in which the incidence and severity of adverse effects of a predicted discharge are described. In our case, the output of the 'Risk characterisation' is a highly significant basis for making decisions about how to manage discharges of alkyl phenols in produced water.

The software model DREAM, developed by Sintef, RF-Akvamiljø and TNO in collaboration with (and financed by) Total, Agip, Hydro and Statoil, is a state-of-the-art tool for analysing environmental risk and effects related to produced water discharges. This tool, the related model tool EIF, and the data obtained in laboratory studies in the course of its development have been used to perform the assessment for alkylated phenols.

Since models represent a simplification of the conditions actually found in the field, it will be necessary to perform a critical evaluation of the assumptions made in the risk analysis and identify possible gaps in knowledge as a basis for an environmental risk assessment with an acceptable quality.

3.3 Objectives

- To compile the most relevant existing data and assess the environmental risk of alkyl phenol discharges in produced water related to hormonal effects and reproduction effects on fish, taking advantage of the best currently available methods and tools regarding risk assessment.
- To make a critical evaluation of the assumptions made in the risk analysis and identify possible gaps in knowledge as a basis for an environmental risk assessment with an acceptable quality, and to make a recommendation for further work.

4 Theory

4.1 Discharge data

In an environmental risk assessment, the exposure and dose:response assessments must be put into a realistic context regarding discharge and fate conditions. Therefore, discharge data have been gathered to reflect the present discharge situation. It was natural to find a basis in the assessments of 'Environmental Impact Factor' (EIF) performed in 2003 for the evaluations to obtain 'Zero harmful effect discharges' in the North Sea. These discharge data represent the situation as it was in 2002, and the fish stock data are also available for 2002 (and earlier years); International Bottom Trawl Survey (IBTS) data, ICES database.

The oil companies have reported measures to reduce the discharges of produced water and the chemical components which have an environmental risk potential. These measures will be completed in 2006 and include several actions such as re-injection and/or cleaning technology (c-Tour, EPCON, CETCO, Pect-F Mares Tail or Cyceo). We performed simulations for 2006 representing the future situation based on estimated discharges from the oil companies.

The discharge data of alkyl phenols area used, sub-divided into two groups (C4+C5, and C6+, as in the standard EIF simulations. These data (also including specifications of discharge depths) have been used to perform an exposure assessment for dose related risk simulations (using the full capabilities of the DREAM model). The discharge data used for screening simulations is applicable for this purpose without major modifications. The data are publicly available and have been gathered and configured for the assessments with assistance from Norsk Hydro, Statoil, ConnocoPhillips, BP, ESSO and SINTEF.

4.2 Fish distribution

Estimations of fish distributions within the North Sea have been performed for the following three species: *cod*, *saithe* and *haddock*. The part of the North Sea considered is defined to be bounded by 50°-62° N and 4°E- 10°W. Distribution values located in the "Skagerak" area and eastward are not included in this study. The total area of the North Sea considered corresponds to about 1138 908 km^2. Within the North Sea the distribution of the three different species has been evaluated in more detail within the three oil production areas *"Tampen"*, *"Ekofisk"* and *"Sleipner"*. Distribution values have been organized into two-dimensional grids covering the North Sea area. Each grid cell has therefore been assigned with an *abundance index* value indicating the relative abundance of the population distributed within each cell or area.

The data sets used to form distributions of fish in two-dimensional grids, are trawl data from the International bottom trawl survey's (IBTS) database held by ICES (International Council for Exploration of the Sea), where countries including Scotland, England, France, Netherlands, Germany, Denmark, Norway and Sweden provide data based on several trawl stations. In total sampling is carried out from about 350-400 stations two times a year; given as first (Q1) and third (Q3) quarter. This raw data includes a lot of information about the trawl haul, and length distributions for several fish species. Some of the information in this raw data has been extracted and used in this study. Data sets from both quarters including the years 1999, 2000, 2001, 2002 and 2003 have been used separately to form distribution maps of cod, saithe and haddock. Altogether 10×3=30 different grids or distribution maps were produced (appendix 3).

4.2.1 Definition of Abundance Indexes

The abundance indexes established in this study are based on the total number of fish caught per hour given by each station. This is a normalized measure given for each species for each trawl haul. Each trawl haul is generally conducted for about 3.6 km. Each station has then a given position within the North Sea boundary, given by the starting position of trawl haul, i.e. they are point indexes. Stations are not located exactly at the same position from one survey to the next. The stations are however distributed similarly covering the North Sea area with about two stations for every 55×55 km. The resolution of this data is therefore very low. However, they are still the best data sets consistently covering different areas of the North Sea similarly for repetitive years. An example of how the stations are distributed within the North Sea is shown in figure 4.1.

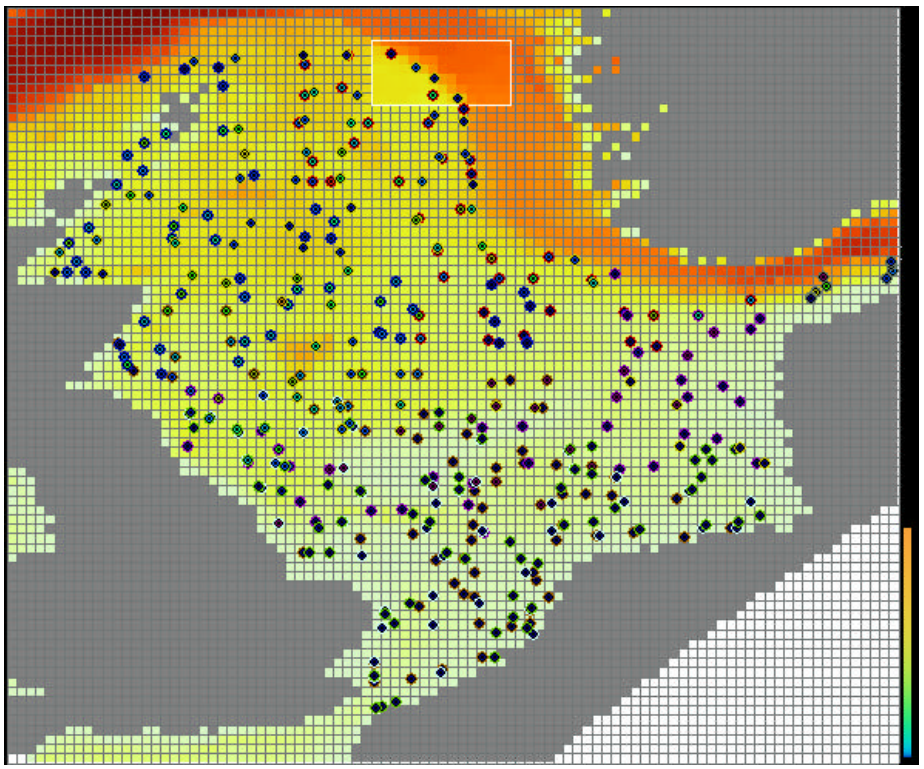


Figure 4.1: North Sea bottom depth profile with the Tampen area indicated by a white square. Stations for year 2001 first-quarter are indicated by circles. Bottom trawls are normally not conducted in areas deeper than about 200 meters. This is seen from the location of the stations as orange to red indicates depth > 200 meters while yellow ranges from about 50 -150 meters. The grid resolution is 0.15°×0.15°.

Separate software has been developed capable of extracting the index for each actual species for each year and quarter and distributing these indexes into two-dimensional grids covering the North Sea. The index numbers comply with the sum of age group 1+ 2+ 3^+ as reported in grids of 1° E-W x 0.5° N-S from the "International bottom trawl survey in North Sea, Skagerak and Kattegat" (eg. ICES CM 1999/D:6 Ref G).

The indexes are used as a basis for the relative distribution of fish within different areas and are normalized and converted to density values given as *percentage per km*^{2} (d). Each grid cell with a given area, A (km^2), is then associated with a density value (?) or relative abundance index which gives the ratio of the population within the cell:

$?^{ij} = d^{ij} \times A^{ij}$, where ij indicates the cell index in the grid.

The percentage of the population within each cell is then given by $100 \times ?^{ij}$.

4.2.2 Distributions in finer grid cells

The standard grid resolution used by IBTS working group is 1° E-W × 0.5° N-S. This corresponds to 55.6×55.6 km grid cells at 60°N, since the length of 1° Longitude in km is given by 55.6×cos(Lat). We have attempted to produce grids with finer resolutions than this, however, due to the low resolution of the data (the large distance between neighboring stations) this creates grids with several undefined cells. In order to solve this problem, grids could either be defined with even lower resolution (1°) in order to cover the finer oil production area grids completely, or density values could be extrapolated into surrounding cells. We have applied an extrapolation method, using a simplified Gaussian expansion method. Values are not extrapolated into land. In areas with depth exceeding 200 m values have been scaled-down since there are fewer fish in deeper areas than on the North Sea Plateau. How much less is not known quantitatively, but instead of assuming absence of fish in these areas an asymptotic function is assumed (200/depth) for scaling down the values.

We have applied a standard resolution of 0.15°× 0.15°, equal in degrees in the N-S and E-W direction, and generated *density distribution maps* of the three species for all years. This resolution is based on the maximum resolution of the depth data used when adjusting for depths above 200 meters and land areas. Additional grids with finer resolutions have been defined for the different oil production areas. A resolution of 0.05° × 0.05° is used for these grids covering the oil production areas. This resolution corresponds to 5.6 km×2.8 km at 60° N.

There are studies indicating that fish tend to have a pronounced aggregation close to platforms (Løkkeborg et.al., 2002). The density of fish in the 0-250 meter vicinity of a platform may be in the order of 2-4 times that of the normal background density (Løkkeborg et.al., 2002).

There are studies documenting that fish tend to aggregate close to platforms (Løkkeborg et al. 2002; Soldal et al. 2002), although these aggregations are difficult to quantify. Fishing experiments with gillnets at the Ekofisk field showed that the catch rates of cod in the range of 0-250 m from the platform were in the order of 2-4 times that of the catch rates in the adjacent area (Løkkeborg et al. 2002). Video observations underneath a North Sea steel platform (Albuskjell 2/4 F, Ekofisk) at day showed that demersal fish, particularly cod, aggregate along the steel structures close to the sea bottom, where standard acoustic quantification methods using research vessels are impossible (Soldal et al. 2002). In a study were acoustic transducers were hung from the platform sides, no aggregations were measured during day, probably because the fish stayed too close to the bottom and platform structures. At night the fish spread throughout the water column, making them easier detectable by echo sounders. Measurements showed that several tonnes of demersal fish (cod and saithe) were aggregated at the limited space occupied by each platform (Soldal et al. 2002), estimates ranging from 6,8 to 108 tonnes per platform. These observations were supported by a study of fish residency at a

platform site using acoustically tagged fish (Jørgensen et al. 2002). It was shown that cod tagged and released close to a platform tend to reside at the site for prolonged periods up to at least one year.

To conclude, two factors are important when considering the risk of reproductive effects from alkyl phenols on fish staying local to the installations:

- The concentration of demersal fish at each platform is higher than the average fish density in the adjacent area. The part of the risk area in the vicinity of the platforms could therefore contain ca. 2 times higher fish density than the average fish density of the whole area
- A high proportion of the fish located around the platforms is found to be resident at the platform sites for prolonged periods, resulting in a prolonged exposure times to maximum discharge concentrations.

The resolution of this phenomenon is too high compared to the data material on fish distribution in the North Sea. As shown in from figures 4.2 and 4.3, even the finer grid cells of 0.05°×0.05° corresponding to ~10km^2 would give a density value for cells containing platforms only slightly higher. If we for instance consider the Gullfaks platforms in figure 4.3, the three platforms would give rise to a slight increase in the area density of fish increasing the abundance to slightly above 0.005% for the given cell. Exact calculations of these influences are not provided, due to the rough resolution of the IBTS data.

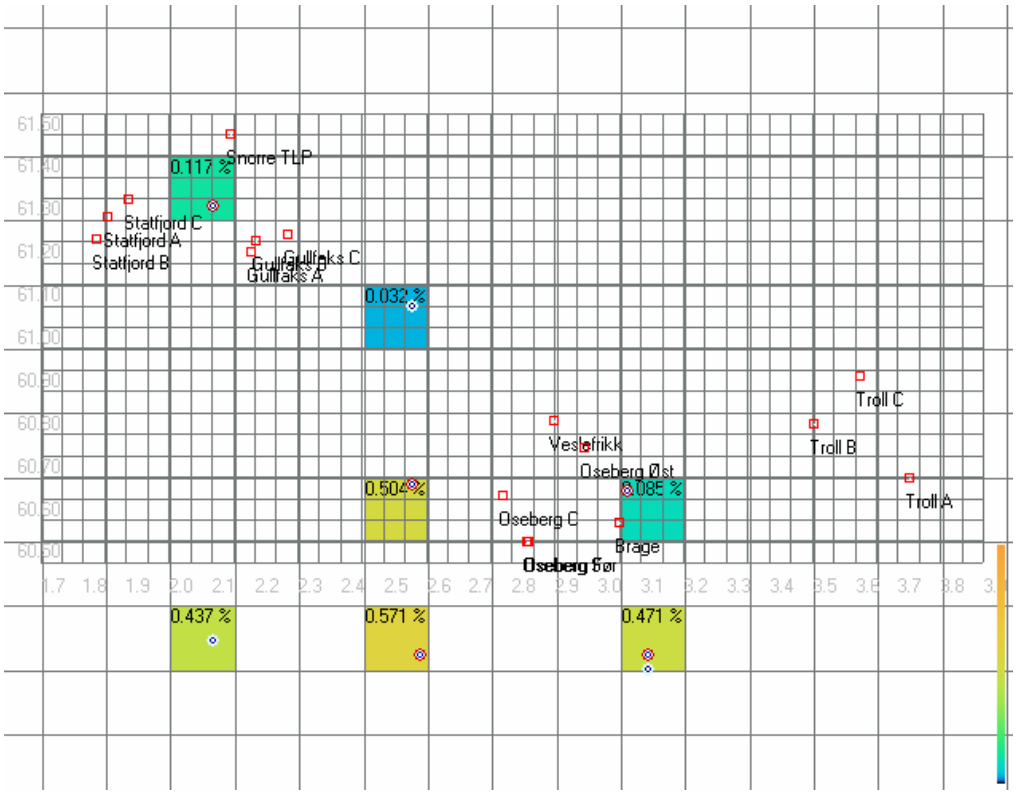


Figure 4.2. Illustration of the rough distribution of stations within an area before extrapolation of values. This figure shows the Tampen area for haddock third-quarter 2003. Grid cells of 0.15°×0.15° are given values from the data sets associated with each station. Warm colouring indicates higher density per area. The percentage values indicate the part of the population within the given cell area when values are not extrapolated into surrounding cells.

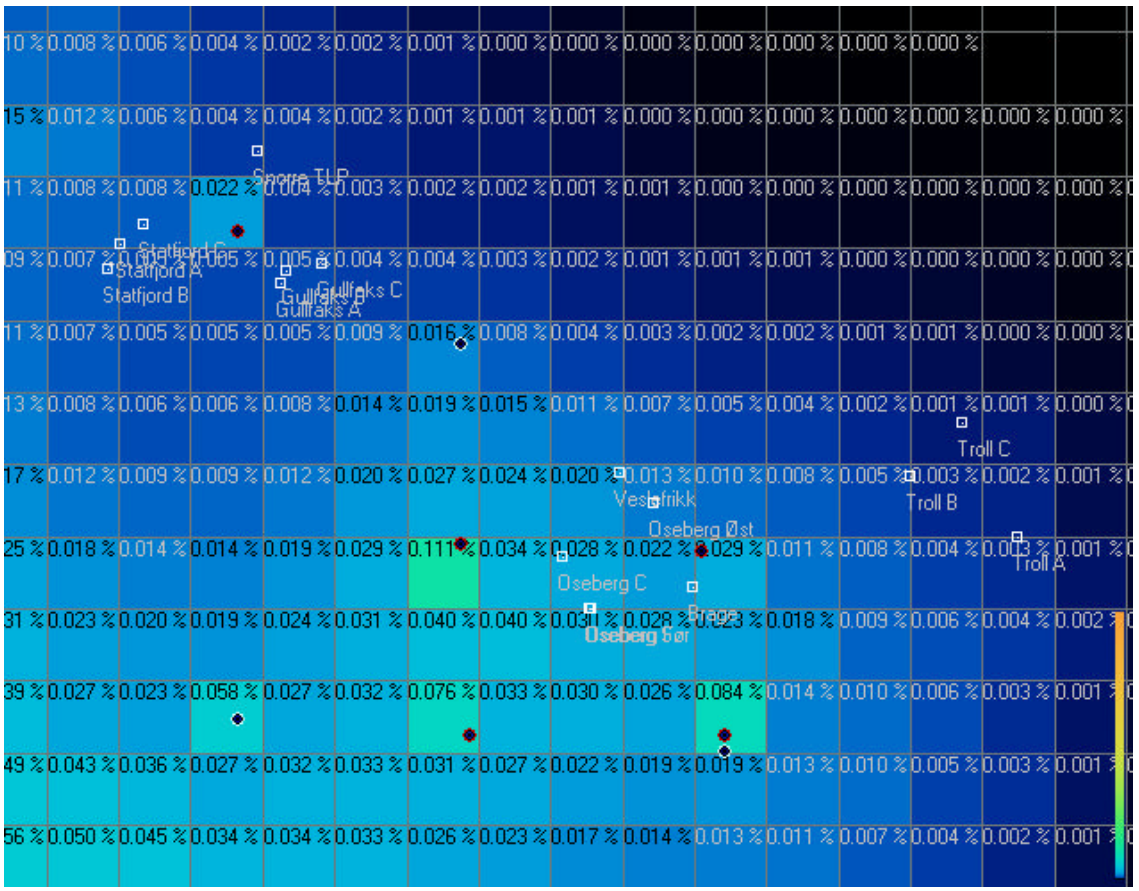


Figure 4,3. Following figure 4.2 values are now extrapolated into surrounding cells, giving rise to fish distributions in the whole area. All cells in the North Sea add up to 100%. The dark region in the upper right part of the picture is a deep-sea area.

4.3 Literature studies and background for environmental hazard potential

4.3.1 Environmental hazard potential

A wide range of effects have been observed in fish experimentally exposed to alkyl phenols. Effects include different forms of both morphological and ethological feminization, induction of female specific proteins in males, changes in gametogenesis and histopathological alterations. Appendix 3 gives a brief overview of observed effects in the literature.

Many of the studies summarized here have been initiated based on concern around AP detergent residues observed in the aquatic environment, therefore octyl phenol (C_8) and nonyl phenol (C_9) dominate as exposure components. Due to the relatively low water solubility of these heavier AP components they are present in produced water only in relatively low levels. Expected differences in effects caused by OP/NP and effects caused by lighter produced water related APs reduce the relevance for direct comparison.

4.3.2 Rationale for choosing NOEC values in the present study

Laboratory experiments show endocrine disruption and a reproduction effect in fish down to 100 ng/L, and the typical levels of effects is down to 1 - 5 ppb (µg/L). However exposure conditions both with regard to type of exposure compounds, duration of exposure and the effects investigated differ between the different studies, but indirect effect parameters are most commonly used. In most experiments relatively short exposure duration has been used. Approaches used in most studies are not directly comparable with field exposures of alkyl phenols from produced water.

Experiments conducted by IMR (Meier *et al*. 2002) revealed the lowest effect doses reported, namely 20 ppb body burden. Converted to water concentration using a BCF=500 that gives a PNEC of 40 ng/L. In that study the exposure components were administered orally. Studies show that the absorption efficiency of the AP compounds over the gut wall is only about 10% (Pickford *et al.* 2003; Sundt and Baussant 2003). This suggests that Meier *et al.* 2002 could have overestimated the actual body burden in their study. Consequently, the observed effects may have occurred at a lower body burden level than the 5 µg AP/kg fish that was assumed. Since approximately 10% of what is ingested is really absorbed, the estimated body burden of fish fed 20 ppb would be 2,0 ppb. With 500 BCF it will be 4,0 ng/l.

For further use in the risk assessment we choose to use both 40 ng/l and 4 ng/l to give a range of risk estimations. 40 ng/l corresponds to the NOEC level determined by IMR based on their experiments with cod (Meier *et al*. 2002) 4 ng/l is derived from the 40 ng/l above but modified to fit a possible ten times lower body burden level in their experiments (Pickford *et al.* 2003; Sundt and Baussant 2003).

4.3.3 Uptake kinetics, bioconcentration and effects of produced water-related alkyl phenols in biota – A short review from laboratory experiments in DREAM and OLF projects

This chapter summarizes the results found from experiments performed at Akvamiljø with produced water-related alkyl phenols exposed to marine organisms. The uptake rates and bioaccumulation factors used in the simulations are based on a selection of these results.

The input is from two projects, the DREAM project – a large project financed by a consortium of oil companies to build a dose-related risk assessment model and the OLF project based on the findings by IMR in Bergen.

Compound	Concentration * [ppm]		LC50 [ppm]
p-cresol	0.4225	63 %	0.39
m-Ethylphenol	0.0818	12 %	5.97
3,5 dimethylphenol	0.0818	12 %	0.93
2,4,6-Trimethylphenol	0.0475	7 %	0.76
2-(1,1-dimethyl)ethylphenol	0.0047	1 %	13.2
3-(1,1-dimethyl)ethylphenol	0.0047	1 %	4.19
4-butylphenol	0.0047	1 %	2.62
4-penthylphenol	0.0203	3 %	0.31
Sum (mix alk. phenols)	0.6677		0.92

Table 4.1 – List of single alkylated phenols (AP) used in DREAM. The four last compounds of the list were tested at Akvamiljø. The AP mixture was composed of the sum of these compounds. In *Acartia*, this sum was 0.67 ppm (highest nominal concentration tested). LC50 values: data from ENI/AGIP, Milano, Italy

In DREAM, we used two species, namely the copepod *Acartia tonsa* and the fish *Cyprinodon variegatus* as model species for zooplankton and fish respectively. *Acartia tonsa* was exposed to a range of sub-acute/chronic concentrations of either single alkyl phenols (AP) and a mixture of them (see report AM 2001/004 and report AM 2000/016 for a detailed description of the results and table 4.1). At Akvamiljø, we tested 4 single AP from C4- toC5 (see table 4.1) and a mixture. The research centre of Statoil (Trondheim) used C0 to C3 AP. The mixture was based on a realistic composition of AP in produced water (see table 4.2).

Compound	Concentration * [ppm]	
p-cresol	0.8450	63 %
m-Ethylphenol	0.1635	12 %
3,5 dimethylphenol	0.1635	12 %
2,4,6-Trimethylphenol	0.0950	7 %
2-(1,1-dimethyl)ethylphenol	0.0093	1 %
3-(1,1-dimethyl)ethylphenol	0.0093	1 %
4-butylphenol	0.0093	1 %
4-penthylphenol	0.0405	3 %
Sum (mix alk. phenols)	1.3354	

Table 4.2 – AP mixture composition tested in the experiment with *Cyprinodon variegatus.*

The fish were exposed only to the mixture. In both species, the exposure was done through the water. *Acartia* were exposed for 15 days during sexual maturation and fish were exposed for 5 weeks. Both bioaccumulation of AP and fitness parameters were monitored during the course of the studies. In *Acartia*, these parameters were monitored during the last 5 days of the exposure and, in fish, they were monitored once a week. Yet, in fish, bioaccumulation was not measured. Radio-labelled (H^3) compounds were used to measure uptake in *Acartia*. The fitness parameters consisted of egg production, hatching success and larval deformities *(fish only)*. In the OLF project, we used juvenile and adult cods (*Gadus morhua*) and exposed them to 4 single alkyl H^3- labelled phenols either via dietary or waterborne pathways (see report AM 2003/001 and table 4.3). The fish were exposed for 8 days followed by 8 days of elimination. Uptake and elimination

were computed using a non-linear first order kinetic model. In addition, specific tissue distribution was measured at the end of the exposure period and the end of the elimination period.

Compound	Concentration * [ppb]
4-butylphenol	0.0080
4-penthylphenol	0.0080
4-n-hexylphenol	0.0080
4-n-heptylphenol	0.0080
Sum	0.0320

Table 4.3 – Compounds and concentration tested in OLF uptake experiment.

4.3.4 Summary of results in DREAM experiment

4.3.4.1 Acartia experiment

Single compound experiment – We will only present the mean bioaccumulation factors (BAF) found for each individual component and report the results of the fitness parameters in the experiment with the AP mix. The compounds tested and the nominal concentrations used are shown in table 4.4. There was a linear or curvilinear relationship between uptake of these compounds in *Acartia* and the dose present in the water. On average, based on wet weight and considering data from all concentrations tested, we found BAFs of 67, 69, 99 and 866 respectively for 2-tert-, 3-tert-, 4-n-butyl- and 4-pentylphenol (see table 4.5). However, the r^2 for the latter compound indicates that there was variability in the data set. Indeed BAFs calculated at the lowest and highest concentrations tested for that compound were significantly different. Hence the value of 866 is indicative.

Type of alkylated phenols	chain length of radical R	LC50 (ppb)	LC16 [a] (ppb)	nominal concentration range in test (ppb)	concentration [b] in produced water (ppb)
2-tert-butylphenol	C4-phenol	13200	2430	500-6,2	9.3
3-tert-butylphenol	C4-phenol	4190	950	950-12	9.3
4-n-butylphenol	C4-phenol	2620	880	880-10	9.3
4-pentylphenol	C5-phenol	310	180	40-0,5	40.5

[a] from Buffagni *et al.* (this issue)
[b] from Utvik *et al.* (1996,1999)

Table 4.4 – LC50, LC16 and concentration range tested to *Acartia tonsa*

Type of alkylated phenols	*n*	r^{2*}	BAF (*lipid-based*)	stderr	BAF (*wet weight-based*)	stderr
2-tert-butylphenol	18	0.71	2528	303	67	8
3-tert-butylphenol	24	0.83	10820	793	69	5
4-n-butylphenol	22	0.74	7100	633	99	9
4-pentylphenol	23	0.44	69244	11166	866	140

** P< 0,001 in all cases*

Table 4.5 – Bioaccumulation factor estimated from the slope of the linear regression between measured seawater concentration and measured internal concentration. All regression were statistically significant at the level of 0.05.

AP mixture experiment – The nominal concentration range tested was from 680 ppb down to 8 ppb but the measured concentration range was on average slightly higher than nominal concentration, between 981 ppb and 12 ppb. The cumulative egg production plotted against time is shown in figure 4.4. Compared to the control individuals, egg production was reduced at 12 and 36 ppb AP mix. A reduction was also seen in the acetone control. However, the reduction was only significant in the 12 and 36 ppb groups (see fig. 4.5 ; Kruskal-Wallis test; $p<0.05$). Compared to the control (mean egg production ≈ 11±4 egg/day/female), egg production in these two groups was ≈50% reduced. A U-shaped dose response was observed. In the exposure group at 981 ppb APmix, all the individuals died after exposure day 12. Hence, the decrease in egg production is a result of the acute effect of the mixture.

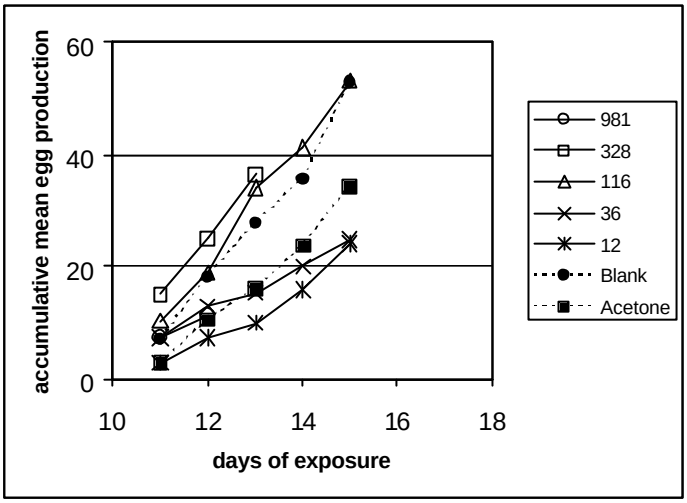


Figure 4.4 – Cumulated egg production of *Acartia tonsa* exposed to a concentration range of APmix plotted against exposure days.

There was a 20 % reduction in hatching success between the control and the 981 ppb AP mix exposure group. Also, there was a 13%increase at the 36 ppb AP mix. Hence a bell-shaped dose response characterized the hatching success. However there was no significant difference in hatching success between the control and any of the exposed groups.

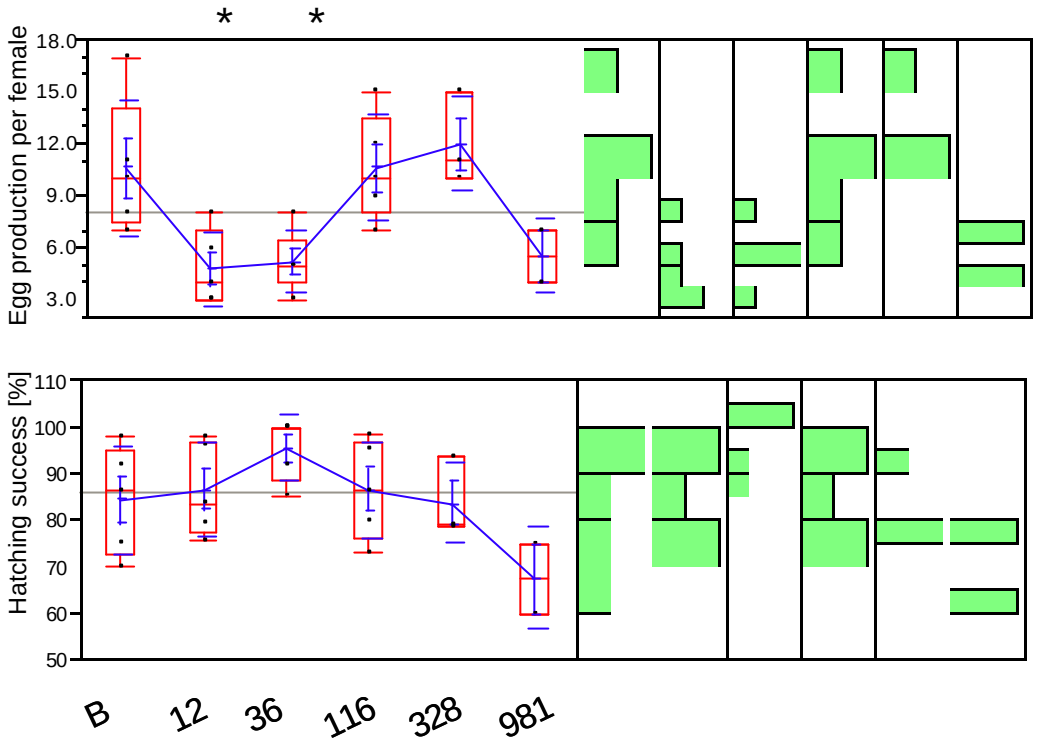


Figure 4.5 – Whisker box plots of the mean egg production and mean hatching success (%) in *Acartia tonsa* exposed to a mixture of alkylated phenols. B: Control group; * significant difference (Kruskall Wallis, $p<0.05$)

4.3.4.2 Fish experiment

1. Uptake rate/elimination rate measured in *Cyprinodon variegatus* exposed to a low and high concentration of 4-pentylphenol.

k1 and *k2*were estimated during a 24 hours exposure to 25 ppb and 123 ppb of H^3-radiolabelled 4-pentylphenol, followed by a 24 hours depuration period. The kinetic rates were calculated using a first-order kinetic model. Table 4.6 indicates the kinetic rates and the corresponding BCF values. Similar values were found at the two concentrations tested.

Concentration µg.L	k_1	k_2	BCF
25	41±2	0.16±0.008	256
123	38±2	0.16±0.012	238

Table 4.6 – kinetic rates of uptake (*k*1) and elimination (*k*2) as well as corresponding BCF values in fish exposed to 4-pentylphenol at 25 and 123 ppb.

Still, BCF is only indicative because steady-state may not have been reached within the 24 hours exposure period.

2. AP mixture experiment

The mean concentrations during the exposure period were 1, 5, 21, 52 and 505 ppb APmix. The cumulative egg production during the whole exposure period is shown in figure 4.6.

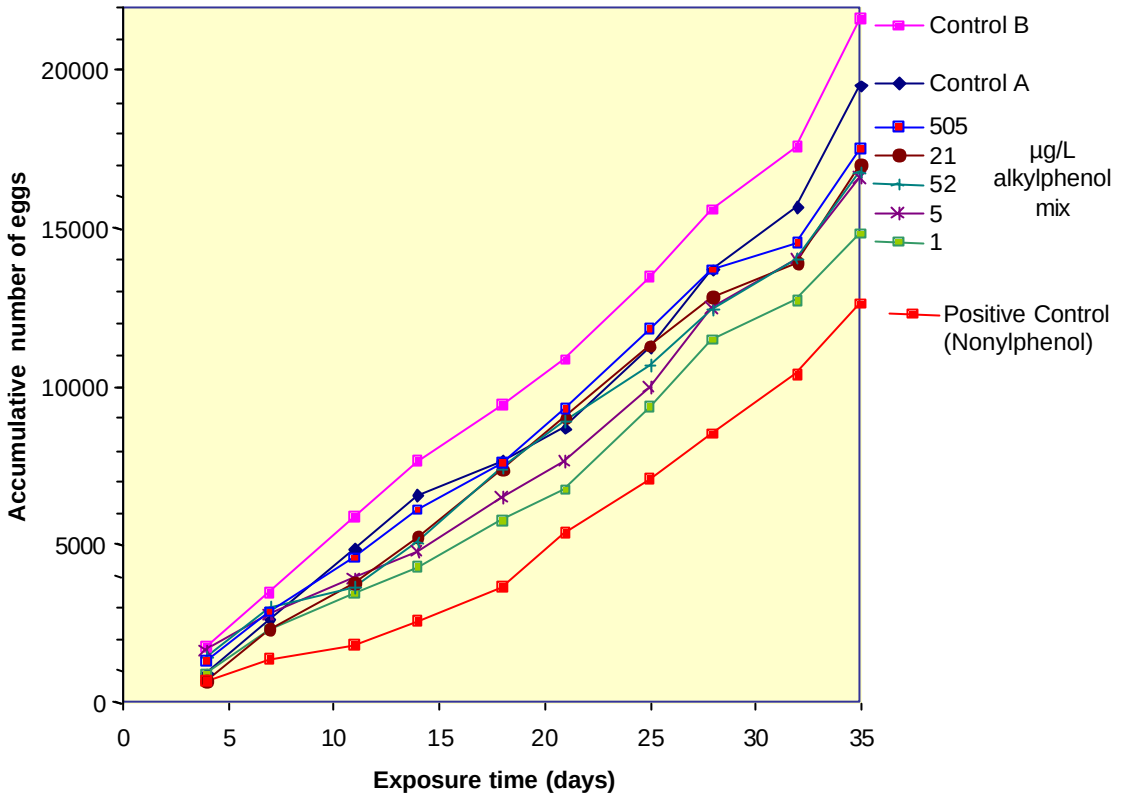


Figure 4.6 – Cumulative egg production in *Cyprinodon variegatus* exposed for 5 weeks to AP mix in the range 1 to505 $\mu g.L^{-1}$.

In all exposure groups, there was a reduction of egg production compared to control groups. The lowest AP mix exposure concentration was the treatment that caused most reduction of egg production. On average, we found a 28% reduction. In all other groups, egg production was between 15% and 19% lower than in the controls. Hatching success was also reduced in the low dose range of AP mix after the first week of exposure. Again, the dose-response was not linear but rather bell-shaped. Hatching success was close to the control level in the 52 $\mu g.L^{-1}$ group. However, despite the trends observed, no significant statistical difference in either egg production or hatching success was observed when compared to the control group (see fig. 4.7).

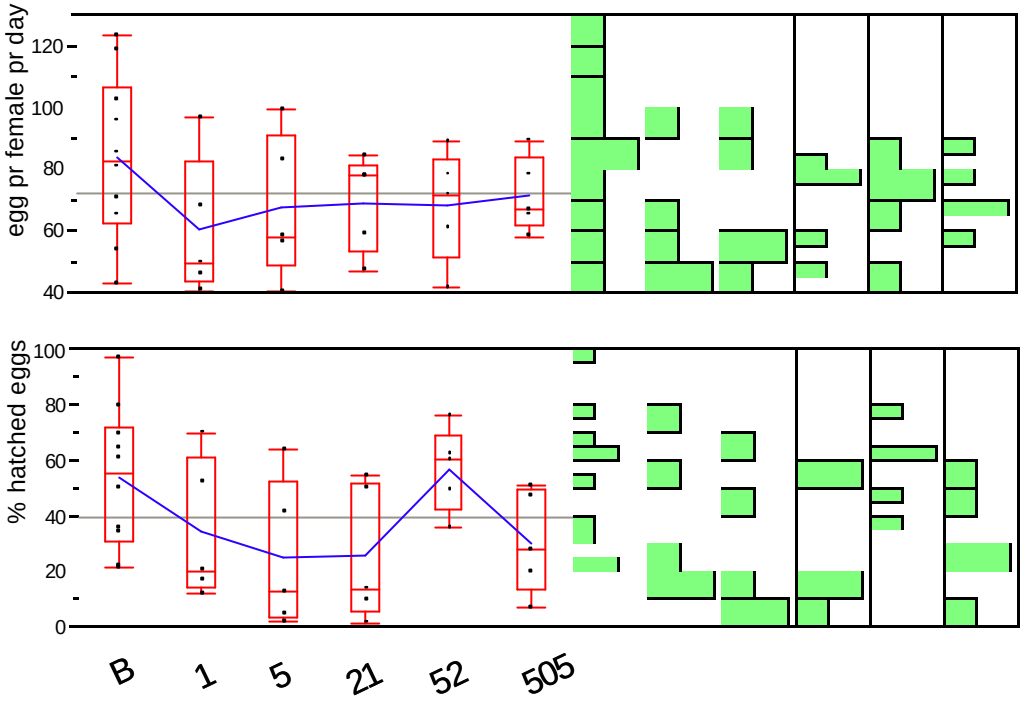


Figure 4.7 – Whisker box plots of the mean egg production per female and % hatching success in *C. variegatus* exposed to AP mix for 5 weeks. The line joining the mean values for each data group has no statistical significance and is only represented to show trends.

4.3.5 Summary of results of the OLF experiment

Table 4.7 summarizes uptake (*k*1) and elimination (*k*2) rate constants and both modelled and experimental bioconcentration factors for each compound in water-borne and dietary exposure.

Compound	Code	log K_{ow}	k_1	n	l	$t a_{1/2}$	k_2	n	$t b_{1/2}$	BCF_{ss}	BCF_{exp}
						days			hours		
Seawater exposure											
4-tert-butylphenol	C4-AP	3.04-3.31	**233** ± 32	21	0.30	2	**0.91** ± 0.2	15	**18**	**194** ± 25	125 ± 16
4n-pentylphenol	C5-AP	-	**159** ± 17	21	0.15	5	**1.08** ± 0.14	15	**15**	**107** ± 10	90 ± 18
4n-hexylphenol	C6-AP	3.60	**712** ± 138	21	0.12	6	**1.60** ± 0.42	15	**10**	**450** ± 58	592 ± 174
4n-heptylphenol	C7-AP	4.00	**643** ± 96	20	0.09	8	**1.32** ± 0.15	15	**13**	**509** ± 44	520 ± 197
Diet exposure											
4-tert-butylphenol	C4-AP	3.04-3.31	**0.20** ± 0.03	15	-	-	**1.44** ± 0.27	15	**12**	**0.14** ± 0.020	0.20 ± 0.09
4n-pentylphenol	C5-AP	-	**0.04** ± 0.003	15	-	-	**0.57** ± 0.15	13	**29**	**0.08** ± 0.007	0.06 ± 0.018
4n-hexylphenol	C6-AP	3.60	**0.13** ± 0.016	15	-	-	**1.10** ± 0.18	15	**15**	**0.12** ± 0.014	0.10 ± 0.051
4n-heptylphenol	C7-AP	4.00	**0.13** ± 0.007	15	-	-	**1.04** ± 0.25	15	**16**	**0.13** ± 0.013	0.13 ± 0.035

Table 4.7 – Kinetic rate constants parameters and both modelled (BCFss) and experimental (BCFexp) bioconcentration factor estimated in *G. morhua*.

We found higher uptake rates in water-borne exposure compared to exposure via dietary route. Elimination rate constants were for all compounds of the same order of magnitude in both exposure routes. Consequently, the results showed that absorption efficiency was ≈ 10-fold less than the dose provided via the dietary route. BCFs in water borne exposure varied from ≈ 100 to ≈ 500.

4.3.6 General summary

Table 4.8 indicates kinetic rates, bioconcentration factors, experimental LOEC and NOEC found in *A. tonsa*, *C. variegatus* and *G. morhua* in DREAM and OLF projects with produced water-related alkylated phenols in waterborne exposures.

Compound	species	*k* 1	*k* 2	BCF	LOEC [1] µg.L-1	NOEC	type of effect
2-tert-butylphenol	*A. tonsa*	-	-	67	ns	-	
3-tert-butylphenol		-	-	69	1032	367	*reduction*
4-n-butylphenol		-	-	99	ns	-	
4-pentylphenol		-	-	866	1.5	0.5	*stimulation*
4-pentylphenol	*C. variegatus*	≈ 40	0.16	250			
AP mix	*A. tonsa*	-	-	-	12	<12	*reduction*
AP mix	*C. variegatus*	-	-	-	ns	-	
4-tert-butylphenol	*G. morhua*	233	0.91	194	-	-	
4-n-pentylphenol		159	1.08	107	-	-	
4-n-hexylphenol		712	1.6	450	-	-	
4-n-heptylphenol		643	1.32	509	-	-	

[1] experimental LOEC value based on statistical difference to the control at p=0.05

Table 4.8 Summary of uptake (*k*1) and elimination (*k*2) rate constants, bioconcentration factor (BCF), experimental LOEC and NOEC found in DREAM and OLF projects using alkylated phenol compounds in waterborne exposure. Only LOEC with statistical significance are indicated. ns: no significant result

Based on table 4.7 and 4.8 we have found k1 (uptake) and k2 (elimination) rates that will correspond to C4-C5 and C6 + in table 2.9

Table 4.9 Average of uptake (*k*1), elimination (*k*2) rate and bioconcentration factor (BCF) for further use in the simulations

Compound	k1	k2	BCF
AP C4 - C5	200	1	200
AP C6+	680	1,5	453,33

4.4 Simulation tools

Simulations have been done using the DREAM software, and the assessments were done in two different modes with different complexity.

In the simplest mode, a screening of the potential risk volume (the volume where the risk expressed as a PEC:NOEC>1) compared to the total fish stock volume in the North Sea was carried out. This is in principle analogous to the previous EIF calculations, but focused only on alkyl phenols in relation to actual fish stocks.

In the more complex mode, the fate of the alkyl phenols in the sea were taken more into account, and the dose/effect/risk calculation capabilities in DREAM was used. This represent the best obtainable and most realistic risk estimate, while the results obtained by the screening method can be regarded as a screening step since it is much more simplistic and conservative.

The interest in using the complex assessment mode is in order to utilize the available information better by taking more advantage of DREAMs built-in simulation capability. This allows the differences in effects at different dose levels (uptake and elimination), and the removal of the alkyl phenols in the water column by different fate processes (e.g. sedimentation, degradation) to be taken into account.

4.4.1 Screening simulations

The simulations have been carried out for the two discharge scenarios 2002 and 2006 with different NOEC values, 40 ng/l and 4 ng/l where 40 ng/l is thought to be the more realistic value. 40 ng/l corresponds to the NOEC level determined by IMR based on their experiments with cod (Meier *et al*. 2002) 4 ng/l is derived from the 40 ng/l above but modified to fit a possible ten times lower body burden level in their experiments (Pickford *et al*. 2003; Sundt and Baussant 2003).

The Norwegian part of the North Sea is in this project divided into three regions; Tampen area with Oseberg and Troll, Sleipner area and Ekofisk area. Some of the regions are further divided into sub regions to improve the resolution of the simulations. As shown in table 4.10 we have performed 35 simulations. From each simulation we have two types of output.

- The Environmental Impact Factor (EIF) which gives us a hint of the level of risk, but is not considered in further risk assessment.
- The Risk area derived from the time step with highest contributions to risk which gives us the maximum area with a level of contaminants higher than the NOEC in the simulation period.

Table 4.10 Matrix of simulations for the first level of risk assessment

	Environmental Impact Factor				**Risk area, time step with largest area**				**Total risk area over simulation period**			
	2002		2006		2002		2006		2002		2006	
Region	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**
Tampen	x	x	x	x								
Statfjord/Gullfaks	x	x	x	x	x	x	x	x	x	x	x	x
Oseberg/Troll	x	x	x	x	x	x	x	x	x	x	x	x
Snorre	x	x	x	x	x	x	x	x	x	x	x	x
Sleipner	x	x	x	x								
Sleipner zoom	x	x	x	x	x	x	x	x	x	x	x	x
Jotun Balder	x	x	x	x	x	x	x	x	x	x	x	x
Ekofisk	x	x	x	x	x	x	x	x	x	x	x	x
Ekofisk Zoom				x								x

To estimate the risk area from the discharges it has been necessary to make some simplifications and assumptions. The DREAM model simulates the predicted concentration grid (PEC) based on the discharge data, chemical composition, currents, wind, dilution etc. This concentration grid (PEC) is then compared with the PNEC value (or in this case NOEC value) which gives a simulated instantaneous environmental impact factor (EIF). This value represents the highest risk potential in the simulation period and is a relative number without denomination. In this project we will focus on risk area more than risk volume. For the risk assessment it is necessary to generate a two dimensional area where there is a potential for effect. This is not a normal output from the model, but by using the time integrated sum of area where the PEC/NOEC >1,0 we can estimate areas of risk.

From the risk analysis we find the time step in the simulation where contribution to risk is highest. This means the time step with the largest affected area. (fig. 4.8)

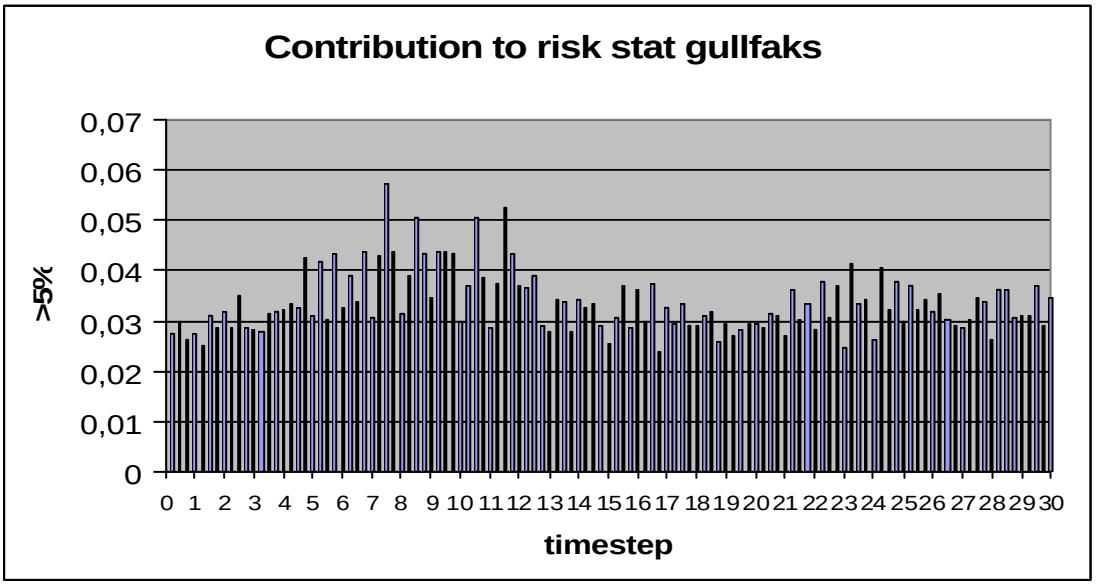


Figure 4.8 Contributions to risk per time step example from simulations of Statfjord and Gullfaks, the time step with highest contribution in this case was at day 7,5 of the 30 days simulation period.

By using the highest value and applying it to the whole time period we obtained a conservative value. The currents and wind will move the plume over a larger area then it is expected to affect instantaneously, which makes this a very conservative approach. The input from the screening simulations is used to eliminate installations and areas with very low or zero risk potential. The output used for this purpose is the area where PEC is higher than NOEC in the time step with the largest contribution to risk.

4.4.2 Simulations with DREAM using fish movement and uptake/elimination rates

To perform a risk assessment of alkyl phenols on fish populations we have to use more specific input data and simulations than with the screening model. The DREAM model has the capability to simulate fish particle movement in a concentration grid simultaneously (Fish "particle" is a technical term for how fish are represented during a computer simulation). This means that the fish particles move randomly in and out of the discharges plumes from the discharge points. Through this random movement the particle is exposed to different levels of chemical concentrations (in this study alkyl phenols). As mentioned in chapter 4.3 we have established data on uptake and elimination rates of alkyl phenols and by giving the fish particles these characteristics the model can simulate the accumulated body burden per fish particle. The dose response curves are not established for these low concentrations so the effect part of DREAM couldn't be used. Instead we used a more direct comparison between accumulated body burden and the critical body burden values.

The simulation tool has an output mode for body burden, but this only gives the momentary percentages of fish particles with a body burden in selected concentration ranges. We needed accumulated body burden over the simulation period. So instead of using the built in tool we used the raw data file from the simulations called "name of simulation".fsh_particle_txt. This file gives the body burden per fish particle and timestep. From this file we can estimate the percentages of fish particles with accumulated body burden over the potential effect level. The data is further used to illustrate the uptake and depuration over time per fish particle.

The output of the risk assessment is then the percentage of fish particles in the simulation which have during the simulation period had a body burden over the potential effect level.

4.5 Biodegradation data

One aspect of the third step of the environmental risk assessment, the exposure assessment, concerns the microbial degradation of the discharged substances. This year a study was initiated to look into microbial degradation of relevant alkyl phenols. The study was undertaken by SINTEF and the results are ready but will not be reported until

September 2004 (Odd G Brakstad in prep.). Preliminary results were available in august in time for the DREAM step of the present project.

For the screening simulations we used degradation data already in the database for ordinary EIF studies, but for the DREAM simulations we used the data from the preliminary report.

Table 4.11 Degradation data for selected single component alkyl phenols, data from the preliminary report, SINTEF.

Compound	**BOD / half time (days)**	**Transformation / half time (days)**	**Used in DREAM**
t-butyl phenol	<0.0001	<0.0001	
n-pentyl phenol	<0.0206 / 33.6	<0.0513 / 13.5	0,0513
n-heksyl phenol	<0.0229 / 30.2	<0.0397 / 17.5	
n-heptyl phenol	<0.0253 / 27.4	<0.0452 / 15.1	0,04

Sintef (Brakstad) have been consulted in the project for correct use of these data in the risk analyses.

We can also see from table 4.11 that the degradation data are similar except for t-butyl phenol which is not degraded at all in the test period. The alkyl phenols can be better grouped with regard to configuration than by the length of the alkyl chain. The alkyl phenols have more or less the same degradation rate independent of the length of the alkyl chain, but if the chain is branched such as t-butyl phenol it is very persistent.

This presents a problem since we have divided the APs into groups regarding chain length, which is the normal way of doing it when running EIF simulations, and since this is the format of the chemicals available. For future projects it would be better to group the chemicals in relation to configuration rather than alkyl phenol chain length.

We have used the data in the last column in the table for our groups of alkyl phenols for the DREAM simulations.

5 Experimental arrangement

5.1 Settings for Screening simulations

The settings for the different simulations vary according to table 5.1. The settings are chosen as a balance between highest possible resolution and simulation time. For simplicity reasons the currents and wind files used are the same as the standard files used in normal EIF simulations;

Current: May 90.DIR

Wind: Ekofisk.wnd at Ekofisk and Sleipner

Gullfaks.wnd for Tampen area.

Table 5.1 settings for screening simulations for the different regions

Tampen		# cells in concentration grid	Output interval: Time step:	Size of habitat area
Region	All installations	400 * 400 * 10	12 hours 60 min	110 * 120 km
Sub-regions	Statfjord/Gullfaks	300 * 300 * 10	6 hours 20 min	46*42 km statgul.hab
	Oseberg/Troll	300 * 300 * 10	6 hours 20 min	79*70 km Osetroll.hab
	Snorre	300 * 300 * 10	6 hours 20 min	26*27 km snoreif.hab
Sleipner				
Region	All installations	400 * 400 * 10	6 hours 20 min	275*300 km SleipAP.hab
Sub-regions	Jotun and Balder	500 * 500 * 10	6 hours 20 min	50 * 50 km, jobaeif
	Sleipner area	500 * 500 * 10	6 hours 20 min	50 *50 km, sleiEIF
Ekofisk				
Region	All installations	400 * 400 * 10	6 hours 20 min	73 km * 160 km, ekofisk.hab
Sub-regions	Ekofisk K and Ekofisk J	300 * 300 * 10	6 hours 20 min	25 * 22 km, nyekozo.HAB

5.2 DREAM simulations with fish particles

The dream simulations were carried out with the same settings as for the screening simulations regarding the scenarios. The only things that differed were settings related to the biological exposure and biodegradation rates.

For comparative reasons we kept as much as possible constant between the two simulation modes.

The fish particles represent a small shoal of fish and not individuals. We used 10000 fish particles in the simulations and gave them a movement pattern in accordance with the manual except for the depths:

- Mean horizontal swimming speed: 1000 m/day
- Mean vertical swimming speed: 50 m/day
- Standard deviation horizontal swimming speed: 500 m/day
- Depth range: 0 – 100 meter
- Output interval: 6 hours
- Time step: 20 min.

During the 30 days of simulations the fish particle can theoretically move 30 km horizontally inside the area defined by the habitat grid (see table 5.1). The depth of the fish particle will change according to the vertical swimming speed of 50 m/day.

6 Results

6.1 Discharge data

6.1.1 Tampen Region

6.1.1.1 Discharge sites

The release sites in the Tampen region are defined as shown in table 6.1. The operators are Statoil and Hydro. We chose to simulate Tampen together with Oseberg and Troll to take into account potential overlapping concentration grids.

Table 6.1 Release sites in the Ekofisk region

		Latitude		Longitude		Release Depth, m
Tampen region	**Operator**	**Deg. º**	**min**	**Deg. º**	**min**	
Statfjord A	Statoil	61	15,3498	1	51.25233	40
Statfjord B	Statoil	61	12,4213	1	49.87117	40
Statfjord C	Statoil	61	17,7948	1	54.15183	40
Gullfaks A	Statoil	61	10,5795	2	11.36333	18
Gullfaks B	Statoil	61	12,1855	2	12.08733	20
Gullfaks C	Statoil	61	12,8892	2	16.46533	28
Veslefrikk	Statoil	60	46,9653	2	53.86767	6
Huldra	Statoil	Part of the Veslefrikk discharge				
Troll A	Statoil	60	38,7497	3	43.58717	20
Oseberg F	Hydro	60	30,0000	2	50.16667	19
Oseberg C	Hydro	60	36,0830	2	46.96033	15
Oseberg Øst	Hydro	60	43,0000	2	58	19
Oseberg Sør	Hydro	60	30,0000	2	50,1667	19
Troll B	Hydro	60	46,4667	3	30.18333	20
Troll C	Hydro	60	53,1666	3	36.7166	12
Snorre TLP	Statoil	61	26,9492	2	8.622833	15
Snorre B	Statoil	61	29,3598	2	13,5806	15
Brage	Hydro	60	32,5500	3	2,8166	1

6.1.1.2 Discharge data

From the Tampen area including Oseberg and Troll approximately 31,4 kg alkyl phenol (C_4 +) in 279 000 m³ of produced water was released per day in 2002. For 2006 a release of 24,8 kg in 309 000 m³ of produced water per day is estimated. The increase in volume is due to the evolution of the field and the decrease in alkyl phenols is expected as a result of actions planned to reduce the discharges of potentially harmful components. These figures are based on reported discharge volumes and concentrations from the oil companies. Table 6.2 gives the input data used in the simulations.

Table 6.2 Discharge volumes and concentrations of alkyl phenols divided into two groups.

Tampen regionen	2002			2006		
	Discharge volume (m^3/day)	AP C_4-C_5 Conc (mg/l)	AP C_6 + Conc (mg/l)	Discharge volume (m^3/day)	AP C_4-C_5 Conc (mg/l)	AP C_6 + Conc (mg/l)
Statfjord A	34781	0,11954	0,00132	35130	0,07170	0,00053
Statfjord B	36277	0,12327	0,00190	27915	0,07396	0,00076
Statfjord C	44538	0,11980	0,00070	61996	0,07190	0,00028
Gullfaks A	18185	0,09200	0,00114	18055	0,05528	0,00046
Gullfaks B	33713	0,07000	0,00070	32027	0,07000	0,00035
Gullfaks C	18940	0,10500	0,00083	26082	0,06292	0,00033
Veslefrikk	12852	0,12300	0,00500	20000	0,07396	0,00214
Huldra	521	0,12320	0,00540	1649	0,12320	0,00540
Troll A	56	0,06800	0,00125	58	0,06800	0,00125
Oseberg F	3800	0,14612	0,00259	1177,5	0,14612	0,00259
Oseberg C	3482	0,10110	0,00176	5280	0,10110	0,00176
Oseberg Øst	429,9	0,11459	0,01458	986,3	0,11459	0,01458
Oseberg Sør	9,3	0,12400	0,00629	690,4	0,12400	0,00629
Troll B	21113	0,11780	0,00260	22958,9	0,11780	0,00260
Troll C	27437	0,10000	0,00200	23013,7	0,04000	0,00030
Snorre TLP	18956	0,14053	0,00330	29742	0,14053	0,00330
Snorre B	1027	0,16078	0,00160	271	0,16078	0,00160
Brage	2760	0,09597	0,00134	1583,5	0,09597	0,00134

6.1.2 Ekofisk region

6.1.2.1 Discharge sites

The release sites in the Ekofisk region are defined as shown in table 6.3. The major operators are ConocoPhillips and BP.

Table 6.3 Release sites in the Ekofisk region

Ekofisk region	Operator	Latitude		Longitude		Release Depth, m
		Deg. º	min	Deg. º	min	
Ekofisk K	ConocoPhillips	56	33.93333	3	12,3500	22
Ekofisk J	ConocoPhillips	56	32.81667	3	13.26667	39
Ekofisk J sentrifuge	ConocoPhillips	56	32.81667	3	13.26667	39
Eldfisk B	ConocoPhillips	56	25.15	3	13,1	2
Eldfisk FTP	ConocoPhillips	56	22.605	3	15.96483	13
Ula	BP	57	6,6885	2	50.84683	2
Gyda	BP/Talisman	56	54.2925	3	5.113667	2
Tor	ConocoPhillips	56	38.51667	3	19.61667	2
Valhall	BP	56	16.6815	3	23.73333	2

6.1.2.2 Discharge data

From the nine discharges in the Ekofisk area approximately 0,35 kg alkyl phenol (C_4 +) in 23600 m^3 of produced water, was released per day in 2002. For 2006 a release of 0,10

kg in 36000m³ of produced water per day is estimated . The increase in volume is due to the evolution of the field and the decrease in alkyl phenols is expected as a result of actions planned to reduce the discharges of potentially harmful components. These figures are based on reported release volumes and concentrations from the oil companies. Table 6.4 shows the input data used in the simulations.

Table 6.4 Discharge volumes and concentrations of alkyl phenols divided into two groups.

	2002			2006		
Ekofisk region	**Discharge volume (m³/day)**	**AP C_4-C_5 Conc (mg/l)**	**AP C_6 + Conc (mg/l)**	**Discharge volume (m³/day)**	**AP C_4-C_5 Conc (mg/l)**	**AP C_6 + Conc (mg/l)**
Ekofisk K	4878	0,0119	0,0008	9534	0,0012	0,0001
Ekofisk J	8800	0,0213	0,0014	20546	0,0021	0,0001
Ekofisk J sentrif	1360	0,0197	0,0014	included in EKO J		
Eldfisk B	460	0,0145	0,0011	1764	0,0087	0,0005
Eldfisk FTP	942	0,0113	0,0009	1880	0,0068	0,0005
Ula	1861	0,0040	0,0009	1475	0,0040	0,0009
Gyda	3393	0,0043	0,0004	0		
Tor	1033	0,0028	0,0010	938	0,0028	0,0010
Valhall	887	0,0163	0,0023	216	0,0163	0,0023

6.1.3 Sleipner Region

6.1.3.1 Discharge sites

The release sites in the Sleipner region are defined as shown in table 6.5. The operators are Statoil, Hydro and Esso.

Table 6.5 Release sites in the Sleipner region

		Latitude		Longitude		Release
Sleipner region	**Operator**	**Deg. º**	**min**	**Deg. º**	**min**	**Depth, m**
Balder	Esso	59	12	2	20	5
Jotun	Esso	59	27	2	23	25
Sleipner A	Statoil	58	22.0387	1	54.51732	15
Sleipner T	Statoil	58	22.03333	1	54.38333	5
Varg	Hydro	58	4	1	54	25
Heimdal	Hydro	59	34,433	2	13,717	1

6.1.3.2 Discharge data

In the Sleipner area six different discharges are defined. Heimdal (table 6.5) has a very low discharge volume and is therefore not taken into account in the simulations. From these five discharges in the Sleipner area approximately 0.29 kg alkyl phenol (C_4 +) in 10600 m³ of produced water was released per day in 2002. For 2006 a release of 0.74 kg in 19300 m³ of produced water per day is estimated . The increase in volume is due to the evolution of the field, and the increase in alkyl phenols is expected as no actions are planned to reduce the discharges of potentially harmful components. These figures are

based on reported release volumes and concentrations from the oil companies. Table 6.6 shows the input data used in the simulations.

Table 6.6 Discharge volumes and concentrations of alkyl phenols divided into two groups

Ekofisk region	2002 Discharge volume (m^3/day)	2002 AP C_4-C_5 Conc (mg/l)	2002 AP C_6 + Conc (mg/l)	2006 Discharge volume (m^3/day)	2006 AP C_4-C_5 Conc (mg/l)	2006 AP C_6 + Conc (mg/l)
Balder	2242	0,00766	0,00024	0	0,00766	0,00024
Jotun	7750	0,01843	0,00057	17400	0,01843	0,00057
Sleipner A	350	0,12690	0,00119	858	0,12690	0,00119
Sleipner T	230	0,29231	0,00152	1014	0,29231	0,00152
Varg	10	0,00437	0,00014	10	0,00437	0,00014
Heimdal	0	0,26760	0,00008	1,6	0,26760	0,00008

6.2 Step1 Screening simulations (DREAM-EIF)

6.2.1 Simulations for the discharge data from 2002, NOEC 40 ng/l

6.2.1.1 Region Tampen area

We began with simulating the whole region and the simulation shows that there are no areas with PEC/NOEC over 1,0 using 40 ng/l as the NOEC value. This is visualized by no black areas. The EIF = 8,4 and even though it doesn't give information about the risk, it is useful to evaluate the accuracies of the simulations.

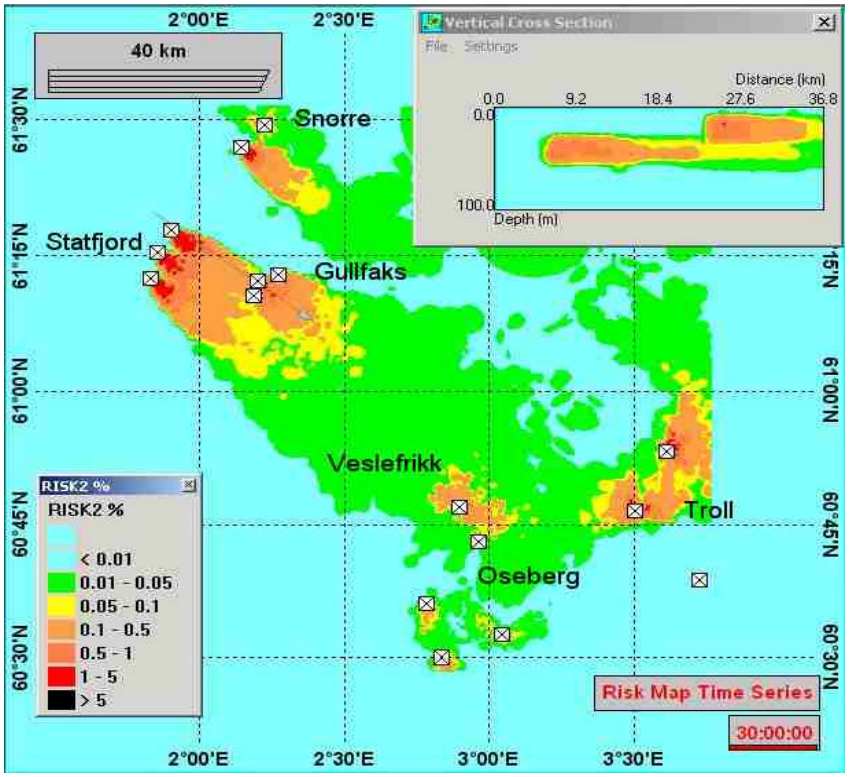


Figure 6.1 Simulation of the Tampen area, NOEC 40 ng/l . Areas with PEC/NOEC>1,0 are shown in black.

The vertical cross section of the area around Statfjord and Gullfaks shows that the plume does not reach the surface. The reason for this, among others, is that Statfjord has a discharge point at – 40 m and Gullfaks at – 20 m.

From figure 6.1 we can see that there are areas where the concentration grid from one installation affects the concentration grid from the other installations. To take this overlap into account we divided the Tampen area into three sub regions to improve the resolution of the simulation.

- Statfjord/Gullfaks
- Oseberg/Troll
- Snorre

6.2.1.2 Sub-region Statfjord and Gullfaks

As we can see from figure 6.2 the concentration grid from the Statfjord installations will overlap with the concentration grid from Gullfaks installations. Each cell in the concentration grid was 140 * 150 m.

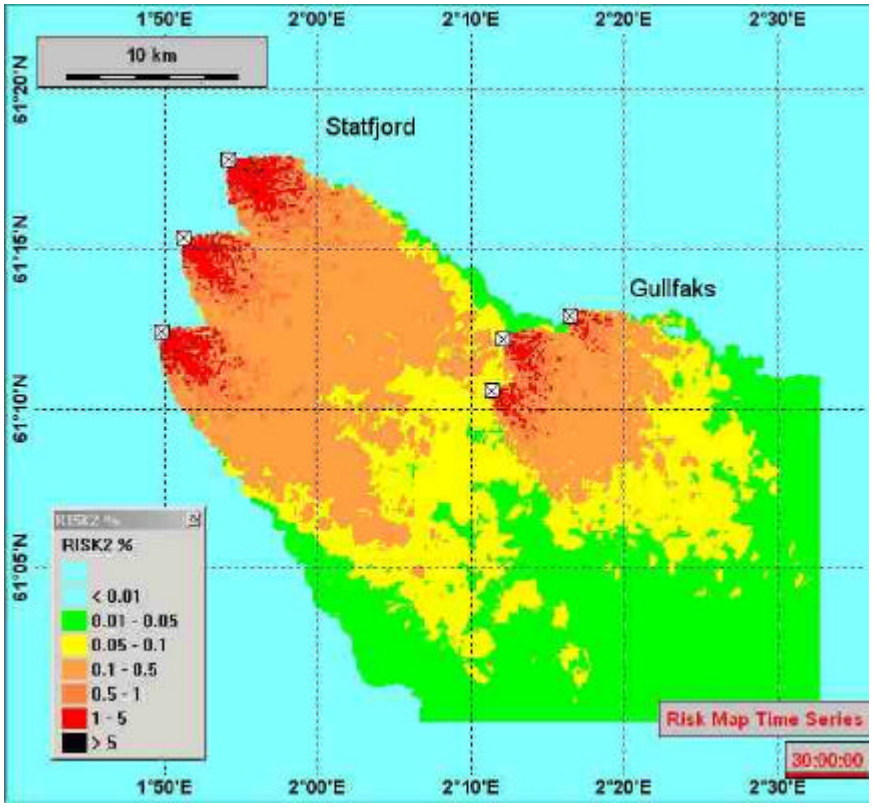


Figure 6.2 Simulation of the Statfjord/Gullfaks area NOEC 40 ng/l.

By increasing the resolution the EIF value in the Statfjord/Gullfaks area was 10,5. This is a low number but indicates that some areas in the close vicinity of the discharge have a PEC that is higher than the NOEC (40 ng/l). By looking at the timestep with highest contribution to risk we find the area with the maximum potential for risk (Figure 6.3).

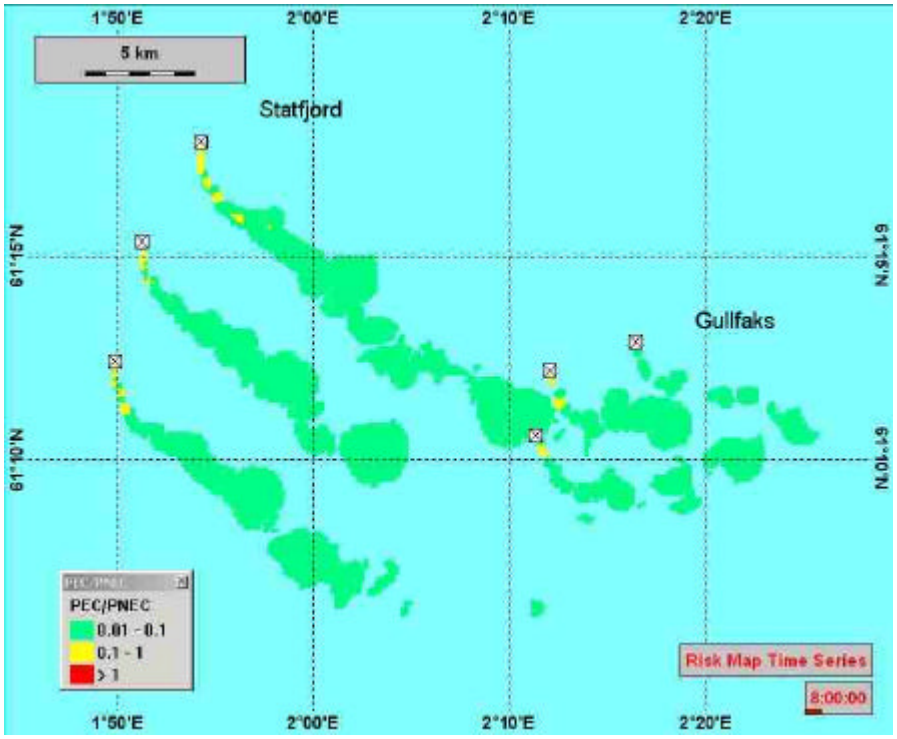


Figure 6.3 PEC/NOEC map showing the time step (8,0 days) with the largest area where PEC/NOEC > 1,0 for the simulation.

From figure 6.3 the total risk area is estimated and added up in table 6.7. As we can see there are contributions from the Statfjord installations and Gullfaks A.

Table 6.7 The area around Sub-region Statfjord/Gu llfaks where PEC/NOEC > 1,0 in the time step 8,0 days.

Installation	Number of squares with PEC/NOEC >1,0	Area, 1 square is 0,021 km²
Gullfaks A	1	0,021 km²
Statfjord B	2	0,042 km²
Statfjord A	0	0
Statfjord C	1	0,021 km²
sum	**4**	**0,084 km²**

6.2.1.3 Sub-region Oseberg Troll

Even with higher resolution in the simulations there were no areas in the vicinity of Oseberg and Troll where the PEC/NOEC >1,0 (figure 4.4). The EIF = 0, which also indicates that the level of risk is lower than the inaccuracies in the simulations.

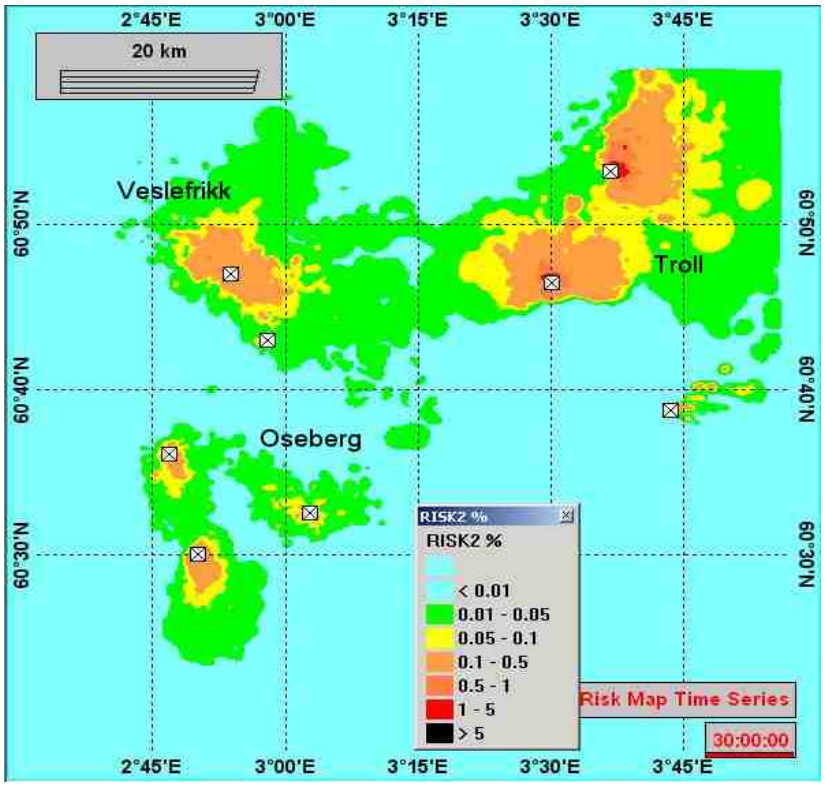


Figure 6.4 Simulation of the Sub-region Oseberg/Troll area, NOEC 40 ng/l.

Even though there was zero risk we wanted to investigate the time step with the highest contribution to risk, which in this case was at 14,75 days.

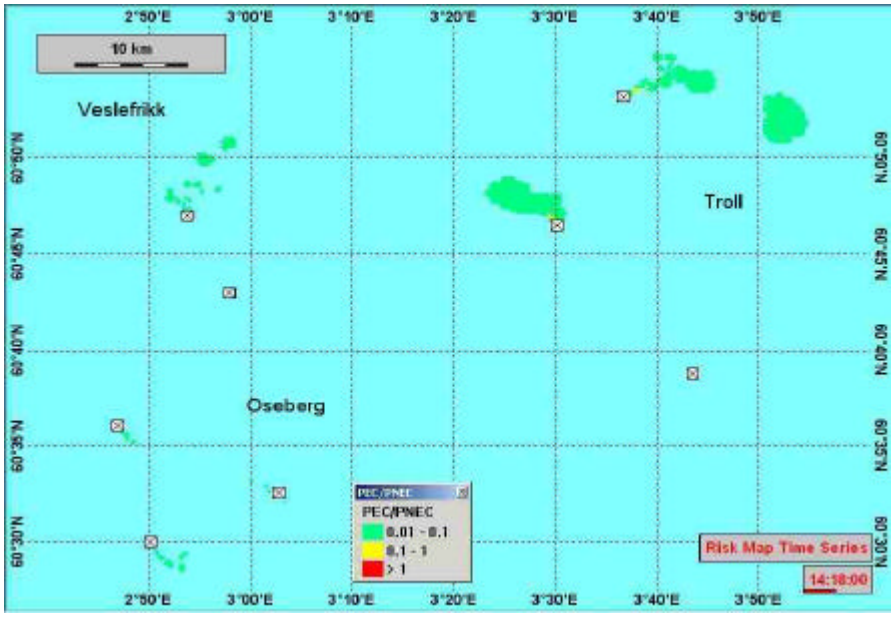


Figure 6.5 PEC/NOEC map showing the time step (14,75 days) with the largest area where PEC/NOEC > 1,0 for the simulation.

6.2.1.4 Sub-region Snorre

The simulation gave an EIF = 2,41 which indicates that there are some areas in the vicinity of the installations where the PEC/NOEC > 1,0

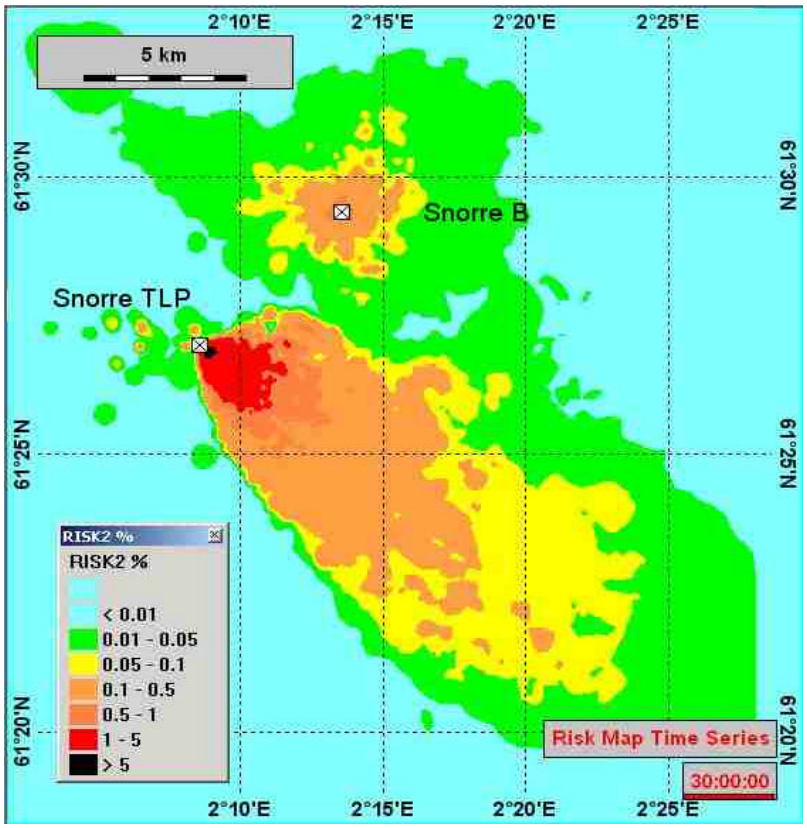


Figure 6.6 Simulation of the Sub-region Snorre, NOEC 40 ng/l.

The time step with highest contribution to risk was 9,5 days and figure 6.7 illustrates the plumes at that time step. Here we can see that there are some inconsistencies in the current file so that the plume from Snorre B in this time step has a different direction than Snorre TLP. We investigated this and concluded that we could overlook this in this case since the highest contributions were from Snorre TLP which has the correct direction.

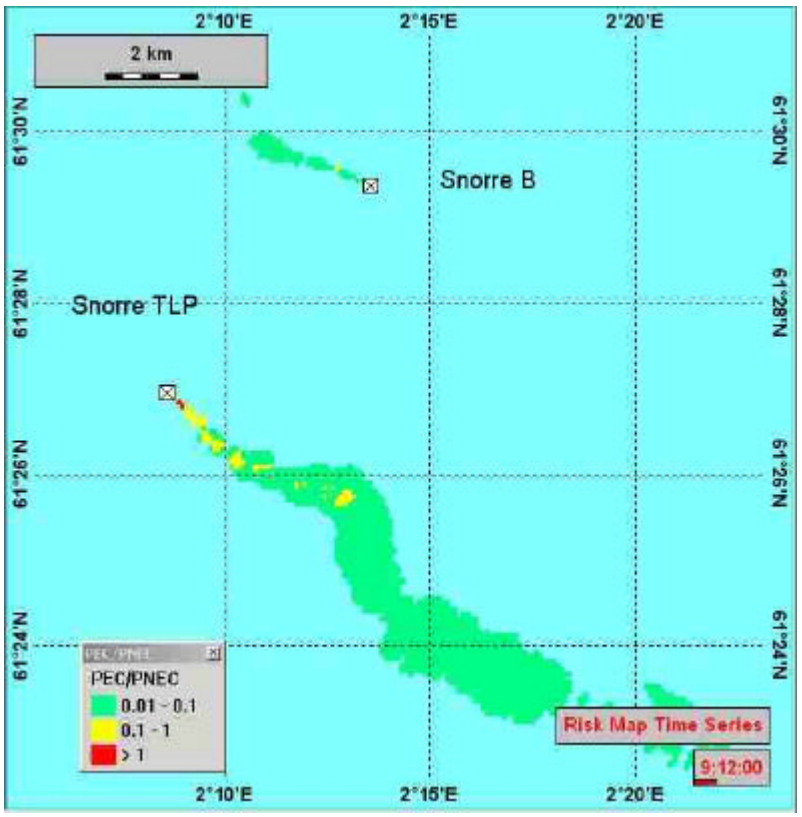


Figure 6.7 PEC/NOEC map showing the time step (9,5 days) with the largest area where PEC/NOEC > 1,0 for the simulation.

Table 6.8 The area around Sub-region Snorre where PEC/NOEC > 1,0 in the time step 9,5 days.

Installation	Number of squares with PEC/NOEC >1,0	Area, 1 square is 0,0081 km²
Snorre TLP	3	0,0243 km²
Snorre B	0	0 km²
Sum	**3**	**0,0243 km²**

6.2.1.5 Region Sleipner area

The simulations gave no indications of potential effect in the Sleipner area with NOEC 40 ng/l as shown with an EIF = 0.

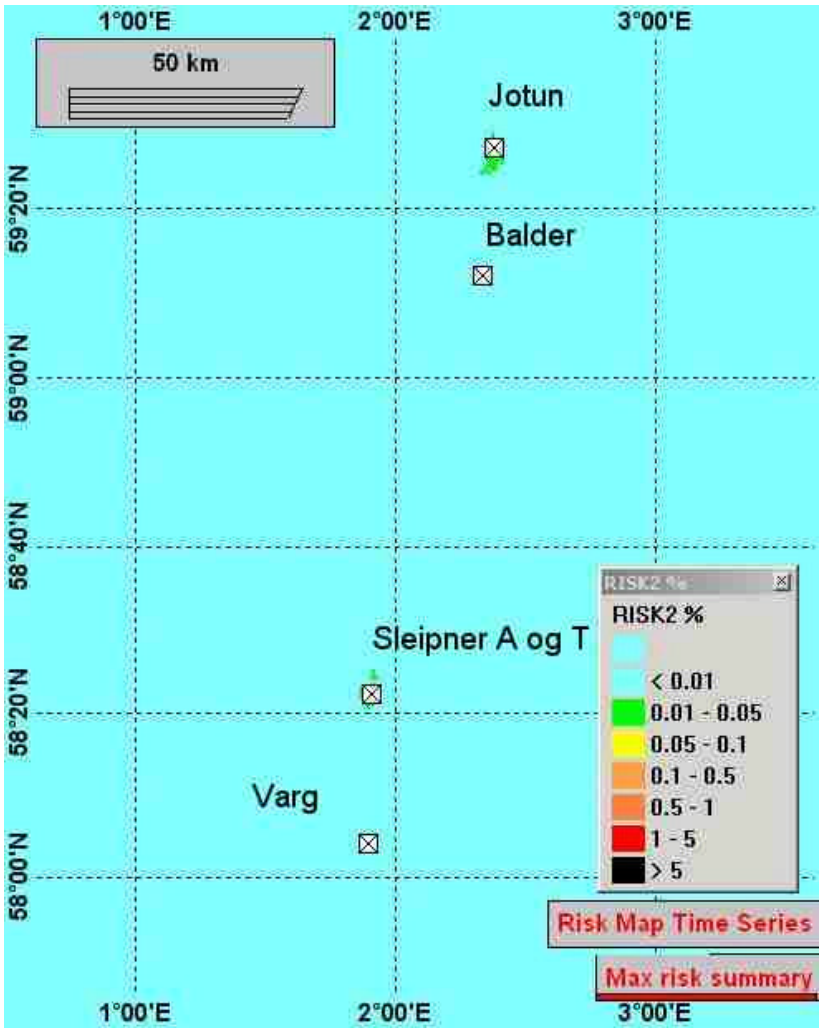


Figure 6.8 PEC/NOEC map of the Sleipner area showing the maximumrisk area for the simulation.

As we can see from the simulation of the Sleipner area there are no overlapping concentration plumes from the Sleipner and Jotun area. We divided the simulation in two and ran Jotun and Balder together and Sleipner zoom to improve the resolution.

6.2.1.6 Sub-region Jotun and Balder

Even with higher resolution it is not possible to identify any effect area with NOEC of 40 ng/l, EIF =0. In the vicinity of Jotun there are elevated concentrations, but clearly much lower than the NOEC.

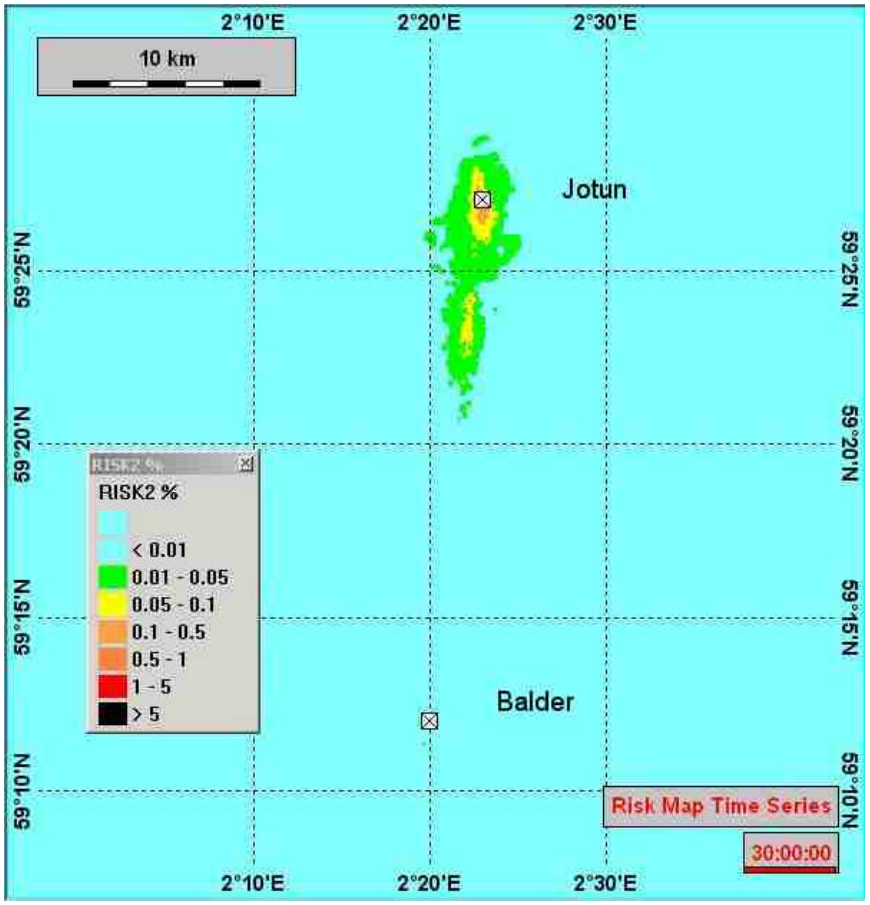


Figure 6.9 PEC/NOEC map of Jotun and Balder showing the maximum risk area for the simulation.

There was no need to illustrate the time step with highest contribution to risk, as it only shows the discharges sites.

6.2.1.7 Sub-region Sleipner and varg

As for Jotun and Balder it is not possible to identify any effect areas with an NOEC of 40 ng/l, EIF =0.

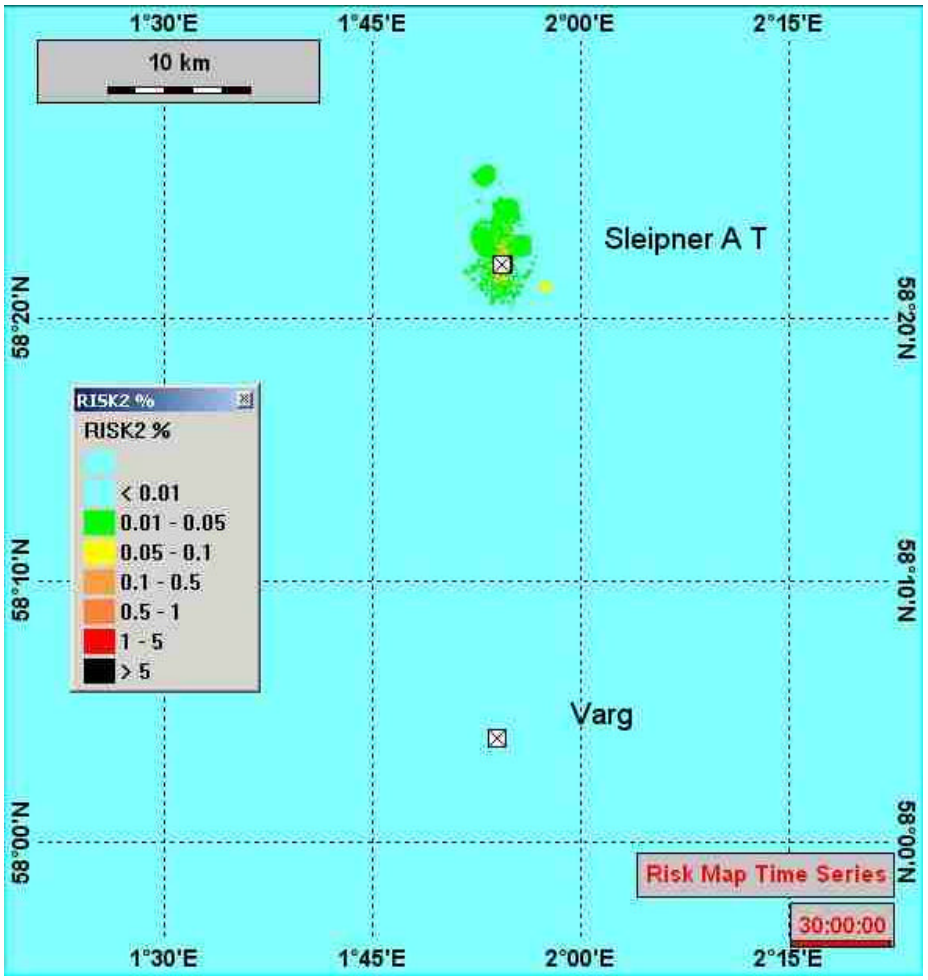


Figure 6.10 PEC/NOEC map of Sleipner and Varg showing the maximum risk area for the simulation.

There was no need to illustrate the time step with highest contribution to risk, as it only shows the discharges sites.

6.2.1.8 Region Ekofisk area

The EIF=0 indicating no observable effect. From figure 6.11 we can also see that there are no overlapping plumes from the different installations. Based on the very low concentration of alkyl phenols from the simulations we concluded that further simulations at higher resolutions were not necessary. This was investigated with simulations of the central Ekofisk area at a higher resolution but the risk potential is insignificant for further simulations

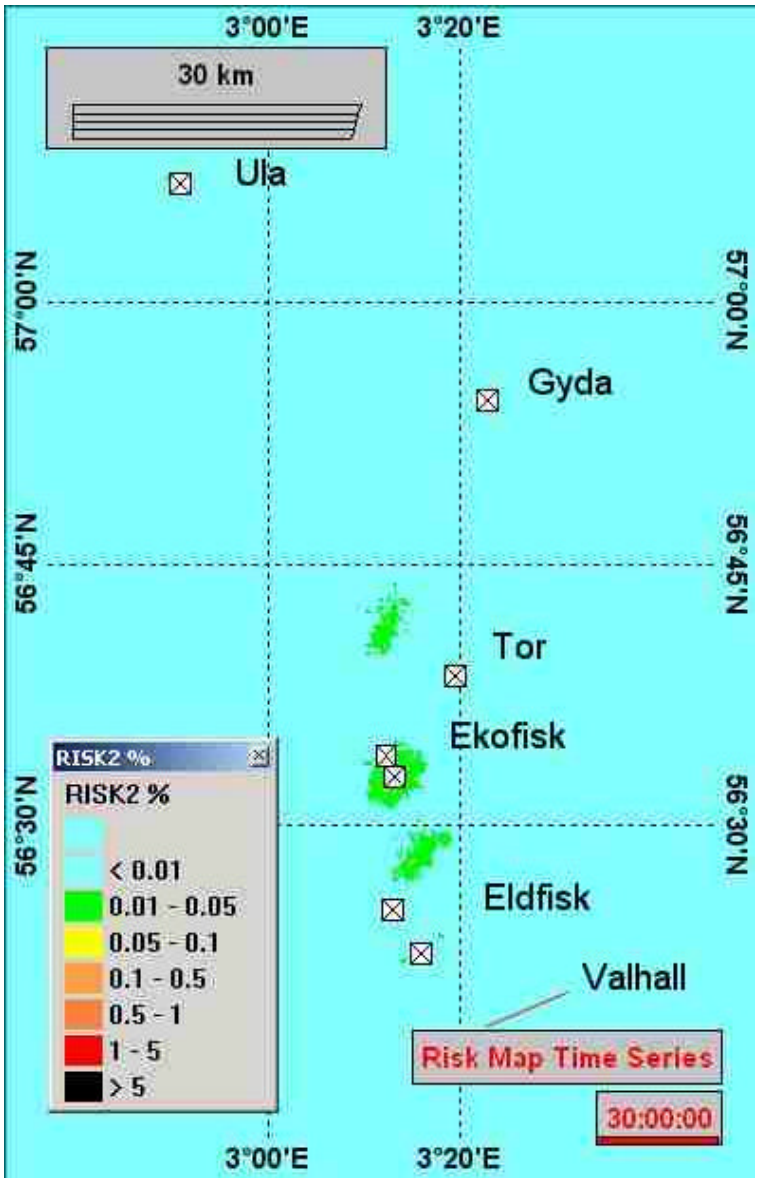


Figure 6.11 PEC/NOEC map for Ekofisk showing the maximumrisk area for the simulation.

6.2.2 Simulations for discharge data 2006 and NOEC 40 ng/l

Simulations were carried out based on estimated discharge data depending on the evolution of the fields and planned reductions in discharges due to cleaning technology and/or re-injection.

6.2.2.1 Tampen area

Just as for 2002 there are overlapping plumes and the same sub-regions have been used, which were Statfjord/Gullfaks, Snorre and Oseberg/Troll. Note that it is only the black areas that have risk over an acceptable level.

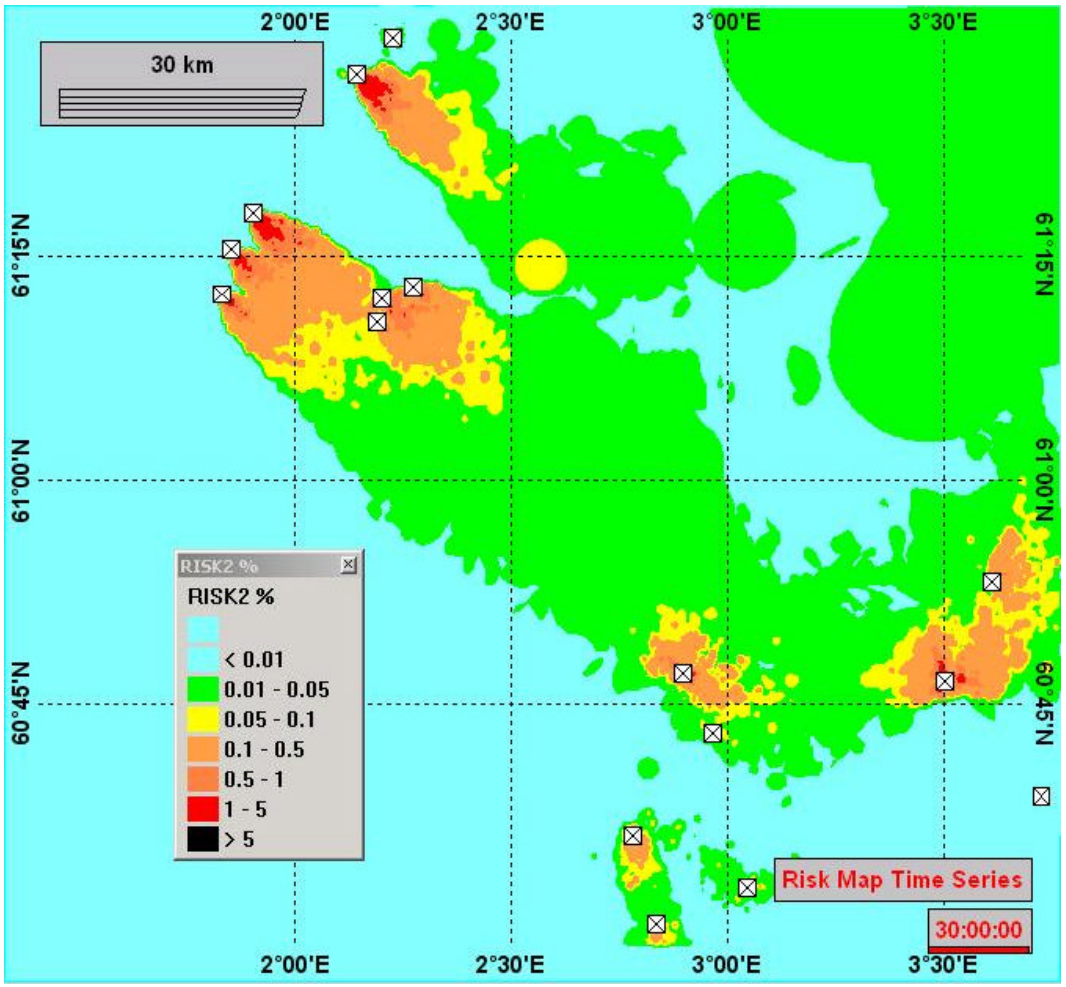


Figure 6.12 Simulation of the Tampen area NOEC 40 ng/l . Areas with PEC/NOEC>1,0 are shown in black.

6.2.2.2 Sub-region Statfjord Gullfaks

As we can see from figure 6.13 the concentration grid from the Statfjord installations will overlap with the concentration grid from Gullfaks installations. Each cell in the concentration grid was 140 * 150 m.

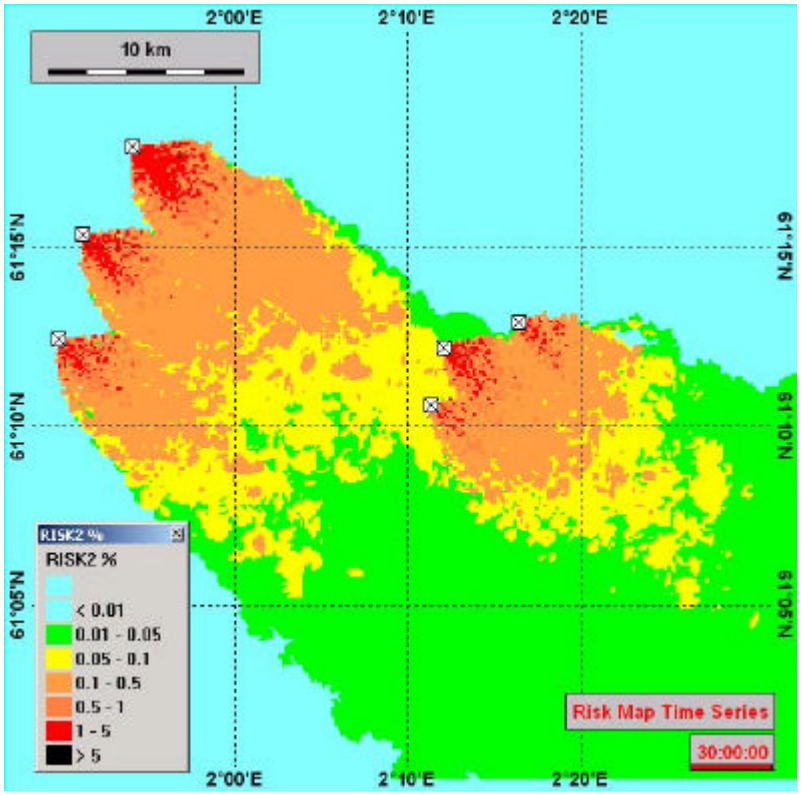


Figure 6.13 Simulation of the Statfjord/Gullfaks area NOEC 40 ng/l.

By increasing the resolution the EIF value in the Statfjord/Gullfaks area was 2.1 which is lower than in 2002. This is a low number but indicates that some areas in the close vicinity of the discharge have a PEC that is higher than the NOEC (40 ng/l). By looking at the timestep with highest contribution to risk (day 8.0) we find the area with the maximum potential for risk (Figure 6.14)

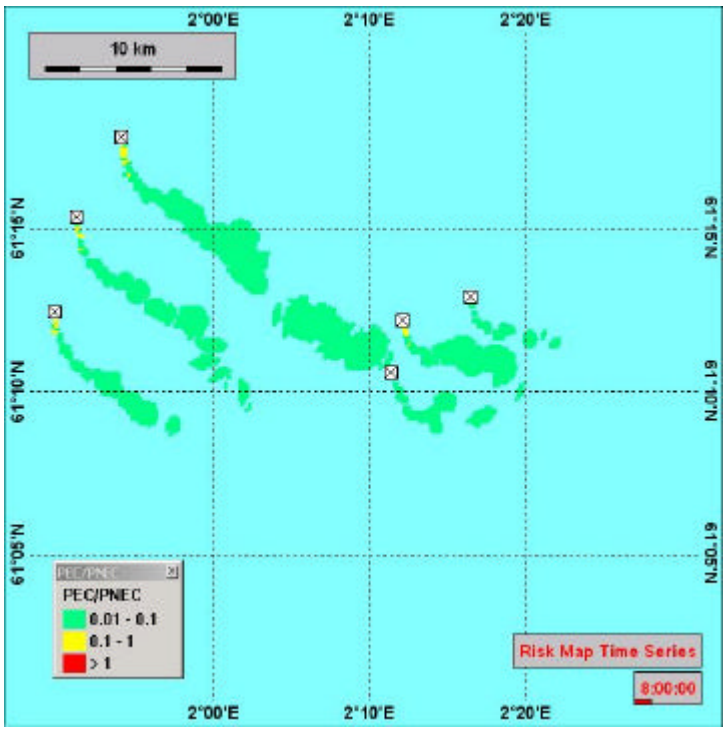


Figure 6.14 PEC/NOEC map showing the time step (8.0 days) with the largest area where PEC/NOEC > 1,0 for the simulation.

At the time step with highest contribution to risk it was only one square that had PEC/NOEC > 1.0 (table 6.9).

Table 6.9 The area around Sub-region Statfjord Gullfaks where PEC/NOEC > 1,0 in the time step 8,0 days.

Installation	Number of squares with PEC/NOEC >1,0	Area, 1 square is 0,021 km²
Gullfaks B	1	0,021 km²
Statfjord B	0	0
Statfjord A	0	0
Statfjord C	0	0
sum	**1**	**0,021 km²**

6.2.2.3 Sub-region Oseberg Troll

Even with higher resolution in the simulations there were no areas in the vicinity of Oseberg and Troll where PEC/NOEC >1,0 (figure 6.15). The EIF = 0 which also indicates that the level of risk is lower than the inaccuracies in the simulations.

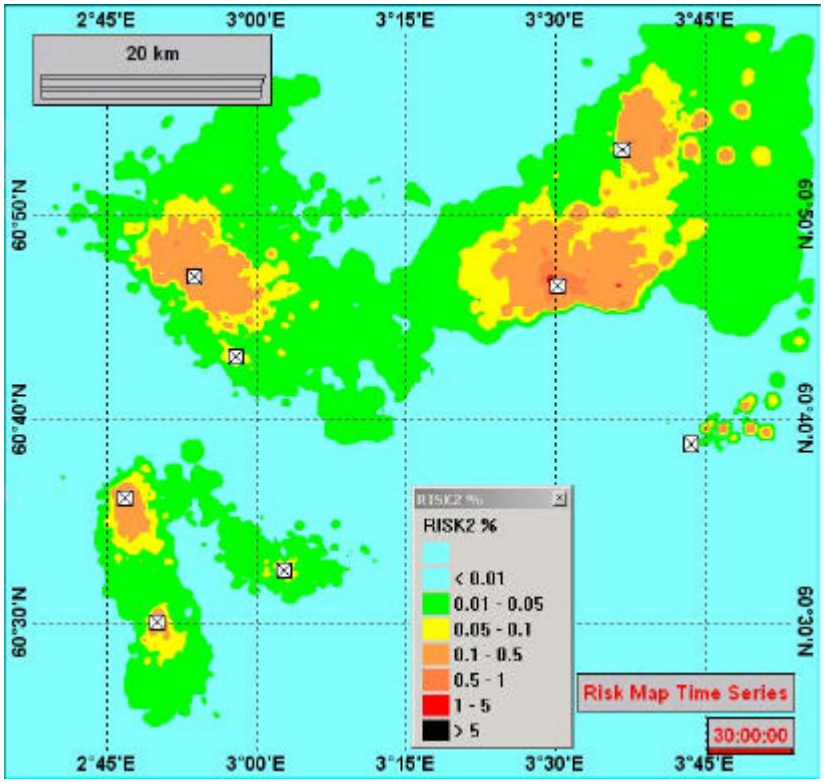


Figure 6.15 Simulation of the Sub-region Oseberg/Troll area, NOEC 40 ng/l.

The time step with the highest contributions to risk (day 23,5) is not illustrated

6.2.2.4 Sub-region Snorre

The simulation gave an EIF = 3,21 which is slightly higher than in 2002 and indicates that there are some areas in the vicinity of the installations where PEC/NOEC > 1,0

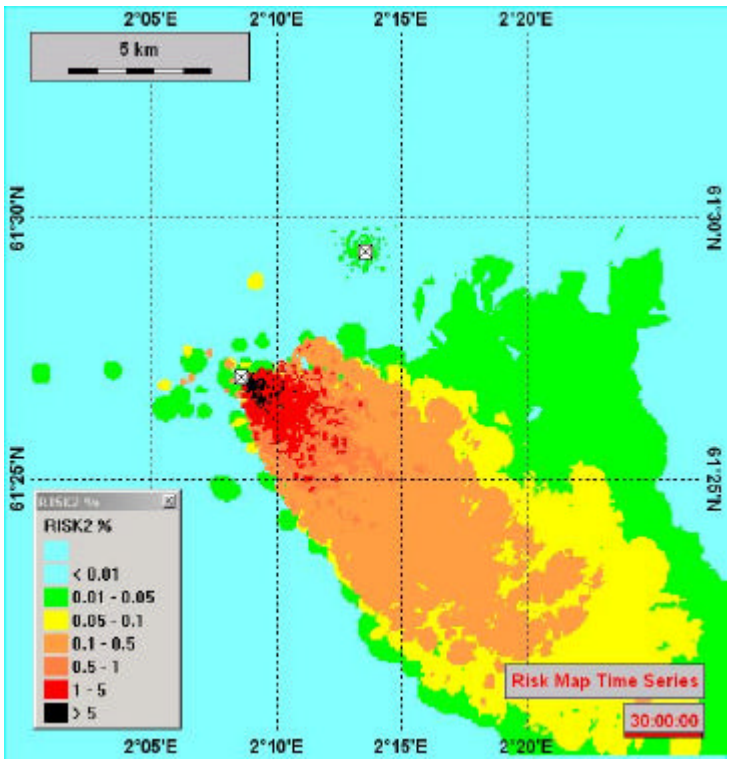


Figure 6.16 Simulation of the sub-region Snorre, NOEC 40 ng/l.

The time step with highest contribution to risk was 25.25 days and figure 6.17 illustrates the plumes at that time step. As we can see from figure 6.10 the plume from Snorre B is not visible which correspond well with the fact that the discharge is very low.

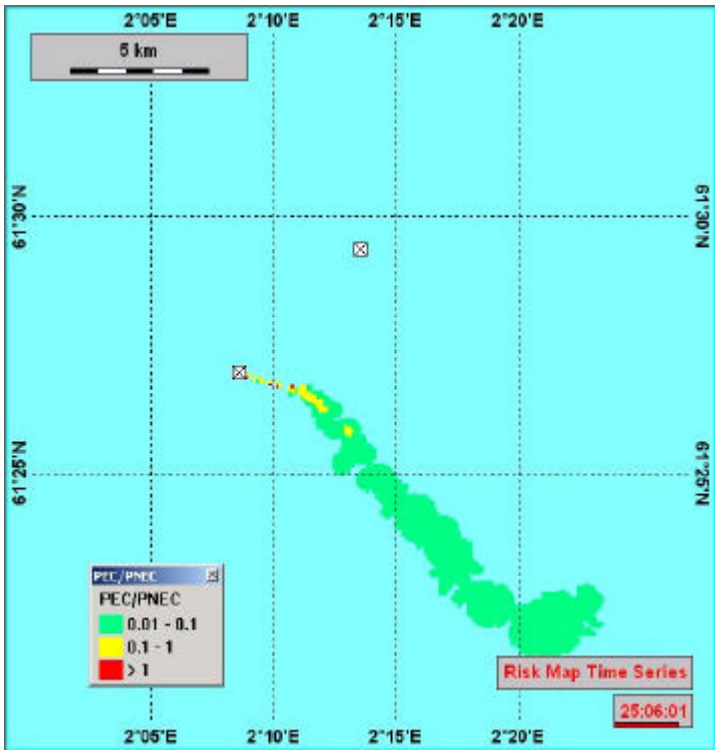


Figure 6.17 PEC/NOEC map showing the time step (25,25 days) with the largest area where PEC/NOEC > 1,0 for the simulation.

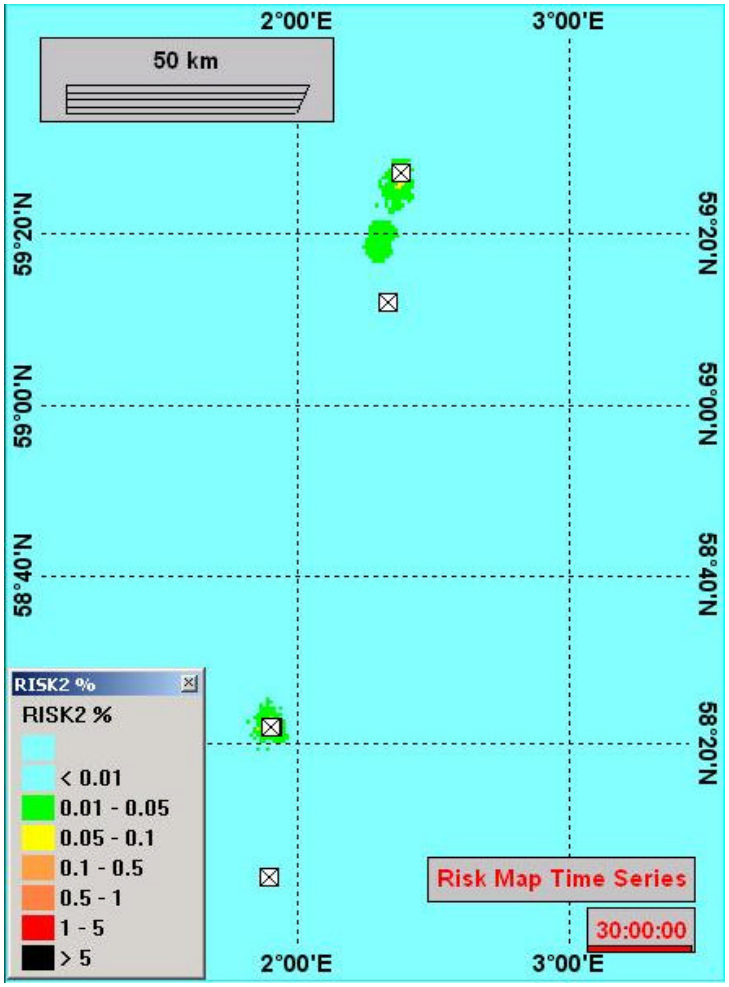
The risk area around Snorre TLP is higher than in 2002 which corresponds to the fact that the discharges are estimated to increase.

Table 6.10 The area around Sub-region Snorre where PEC/NOEC > 1,0 in the time step 25,25 days.

Installation	Number of squares with PEC/NOEC >1,0 1 square 90 * 90 m = 0,0081 km²	Area, km²
Snorre TLP	4	0,032 km²
Snorre B		
Sum		**0,032 km²**

6.2.2.5 Region Sleipner NOEC 40 ng/l 2006

The simulations gave no indications of potential effect in the Sleipner area with an NOEC 40 ng/l as shown with an EIF = 0.



Figur 6.18 Simulation of the Sleipner region, NOEC 40 ng/l

As we can see from the simulation of the Sleipner area there are no overlapping concentration plumes from the Sleipner and Jotun area figure 6.18. We divided the simulation in two and ran Jotun and Balder together and Sleipner/Varg to improve the resolution.

6.2.2.6 Sub-region Jotun/Balder

Even with higher resolution it is not possible to identify any effect area with NOEC of 40 ng/l, EIF =0. The time step with maximum contribution to risk was at day 12,25, but it is not illustrated since it only shows the discharge sites.

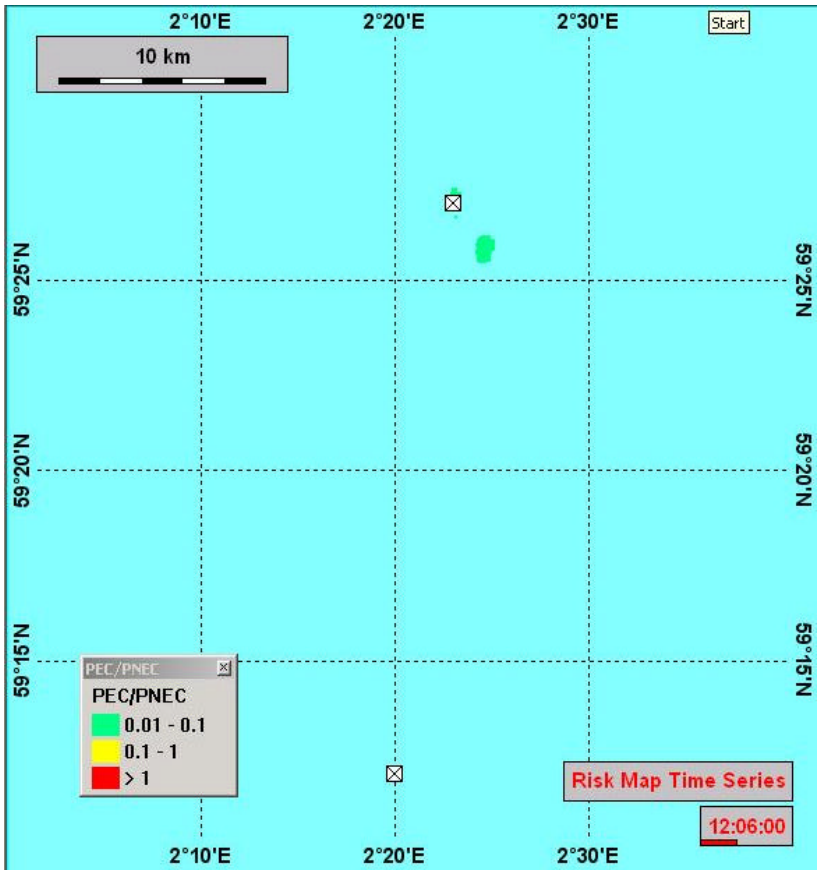


Figure 6.19 PEC/NOEC map of Jotun and Balder showing the maximum risk area for the simulation.

6.2.2.7 Sub-region Sleipner/Varg

As for Jotun and Balder it is not possible to identify any risk areas with an NOEC of 40 ng/l, EIF =0.

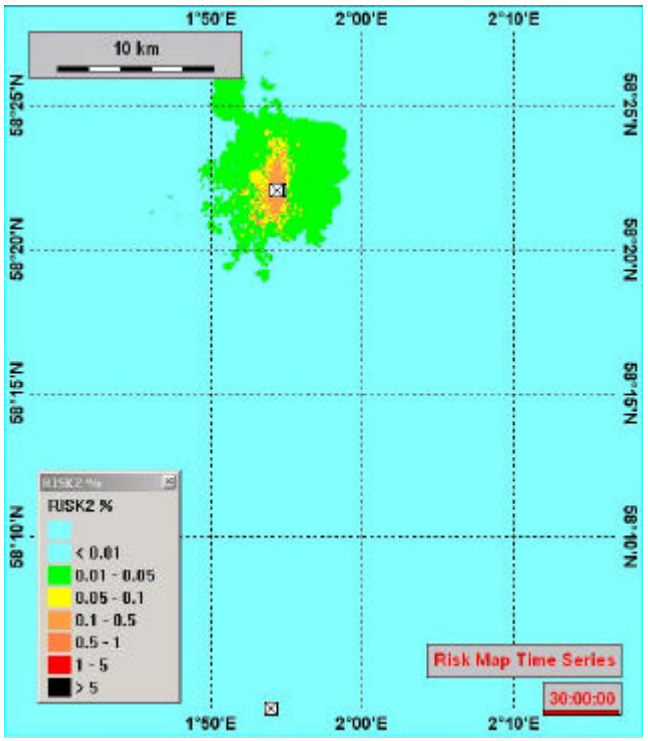


Figure 6.20 PEC/NOEC map of Sleipner and Varg showing the maximum risk area for the simulation.

The time step with the highest contribution to risk was at day 18,75 and as we can see from figure 6.21 there is only a small area south of Sleipner that is visible (PEC /NOEC between 0,01 – 0,01)

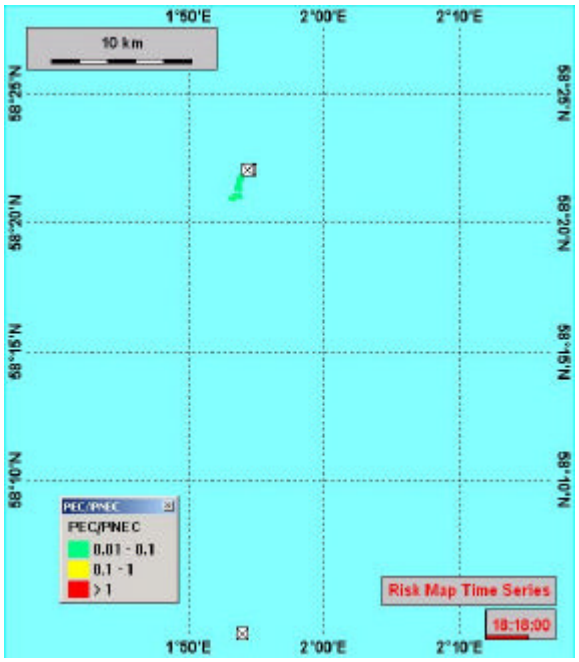


Figure 6.21 PEC/NOEC map of Sleipner and Varg showing the time step with maximum contribution to risk at day 18.75.

6.2.2.8 Region Ekofisk area, NOEC 40 ng/l 2006

The EIF=0 indicating no observable effect. From figure 6.22 we can also see that there are no overlapping plumes from the different installations. Based on the very low concentration of alkyl phenols from the simulations we concluded that further simulations at higher resolutions were not necessary.

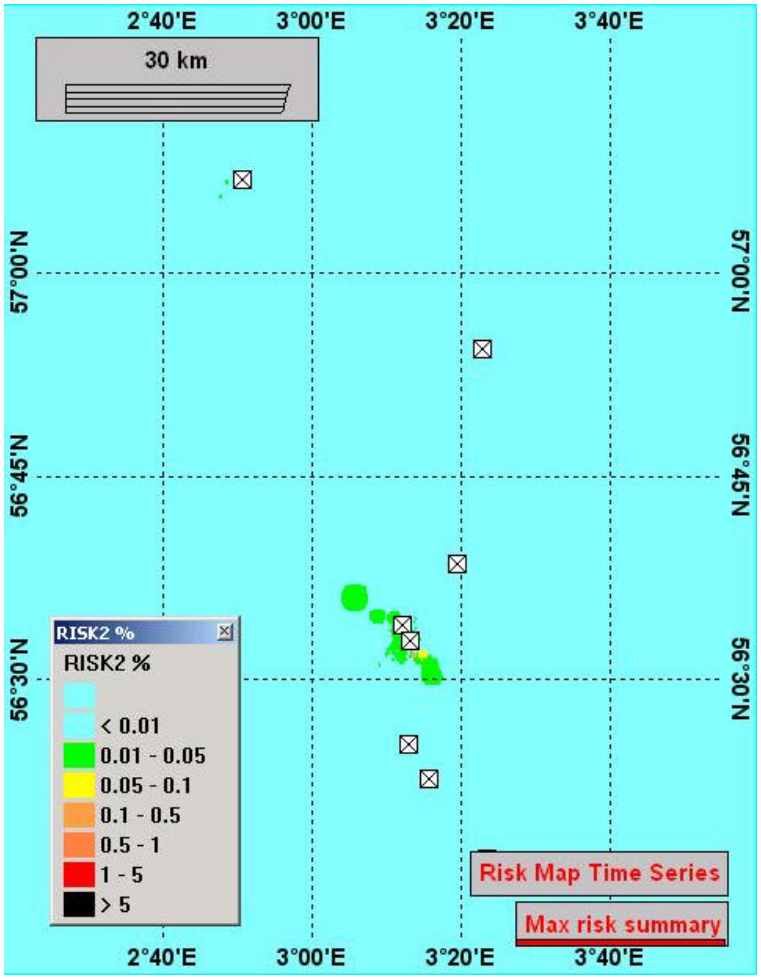


Figure 6.22 PEC/NOEC map for Ekofisk region showing the maximum risk area for the simulation.

6.2.3 Simulations with NOEC 4 ng/l

Moved to appendix.

6.2.4 Sum of the results from Step 1- screening simulations

The details from the simulations with NOEC 4 ng/l are presented in the Appendix. As seen in table 6.11 the highest risk area is from the Tampen area with NOEC 4 ng/l. For the Sleipner area the area of risk is minor and in the Ekofisk area there is no observable risk area.

The method for simulating risk areas is not accurate when the PEC/NOEC value is small. Risk areas of 0,01 km² consist of only one or very few squares where the PEC value is higher than NOEC. When using this simulation tool to run EIF studies, inaccuracies when EIF is close to zero have been addressed previously. By looking at the EIF values for Sleipner and Ekofisk in this project, which is not related to the normal EIF estimations, we can see that the values are very small.

When dealing with low EIF values it is possible to use near field simulations in DREAM but for the risk assessment purpose there was no need to go into further details by trying to estimate the small risk areas around Ekofisk and Sleipner, due to the resolution of the fish stock data.

Table 6.11 Sum of results from the screening simulations.

	Environmental Impact Factor				**Risk area, time step with largest area, km²**			
	2002		2006		2002		2006	
Region	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**	**40 ng/l**	**4 ng/l**
Tampen	8,4	947,9	8,39	662,7	x	x	x	x
Statfjord/Gullfaks	10,5	572,5	2,1	314,6	0,084	4,788	0,021	2,415
Oseberg/Troll	0	195,5	0	134,4	0	1,734	0	1,196
Snorre	2,41	68,3	3,21	131	0,0243	0,632	0,032	1,34
Sum Tampen area	**12,91**	**836,3**	**5,31**	**580**	**0,1083**	**7,154**	**0,053**	**4,951**
Sleipner	0	0	0	0	x	x	x	x
Sleipner zoom	0	0	0	3,254	0	0	0	0,03
Jotun Balder	0	1,03	0	5,127	0	0,01	0	0,05
Sum Sleipner area	**0**	**1,03**		**8,381**	**0**	**0,01**	**0**	**0,08**
Ekofisk	0	0	0	0	0	0	0	0
Ekofisk zoom				0				0

6.3 Simulation with DREAM - risk assessment step 2

Only simulations from the Tampen region were performed due to the low risk areas in screening simulations for the Sleipner and Ekofisk regions. We used the same sub regions giving three simulation regimes:

- Statfjord/Gullfaks
- Snorre
- Oseberg/Troll.

6.3.1 Statfjord/Gullfaks

Figure 6.23 shows an example of fish particle density around Statfjord installations with the concentration plumes of C4 - C5 alkyl phenols. We attempted to run both C4-C5 and C6 + together but the simulation tool gave inconsistent results. We therefore ran the simulations with C4 - C5 and attempted to simulate C6+, but the concentrations of C6+ are too low to run simulations of fates. The model was manipulated by increasing the concentrations 50 fold. It was then possible to run the simulations, but it produced no body burden in any of the fish particles. This corresponds well to the results from the screening simulations where the C6+ only represented 0.67 % of the total contribution to risk (example Statfjord/Gullfaks 2002). Even though the model will not produce a risk value for C6 + alkyl phenols it gives a strong indication that the risk is very small.

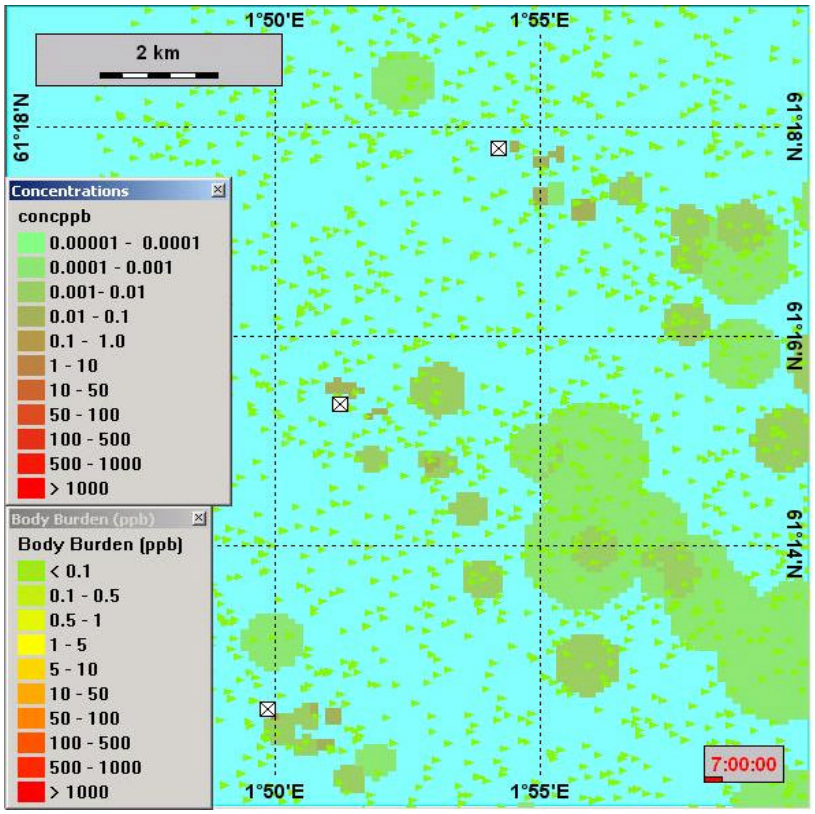


Figure 6.23 Fish particle density around the Statfjord installations combined with the concentration grid of C4 -C5 alkyl phenols.

During the simulations the body burden of the fish particles increase according to k1 when they are exposed in the concentration grid and decrease in body burden according to the elimination rate k2. If a fish particle had been in a constant exposure regime it would have established a steady state relationship with the surrounding water giving a bio concentration factor of k1 divided by k2. But this is not the case for these simulations.

The result of simulations with Statfjord and Gullfaks installations is illustrated in figure 6.24 where the cumulative body burden over the simulation period is shown. The highest accumulated body burden observed was 0.09 ppb in particle nr. 5246. As we can see from figure 6.24 the body burden varies considerably. This is logical since the fish particles have their own movement pattern and the plumes shift in direction according to currents (tidal). It is not reasonable to assume that the fish follows the plume and it is more likely that the fish have more of a discontinuous rather than a constant exposure regime.

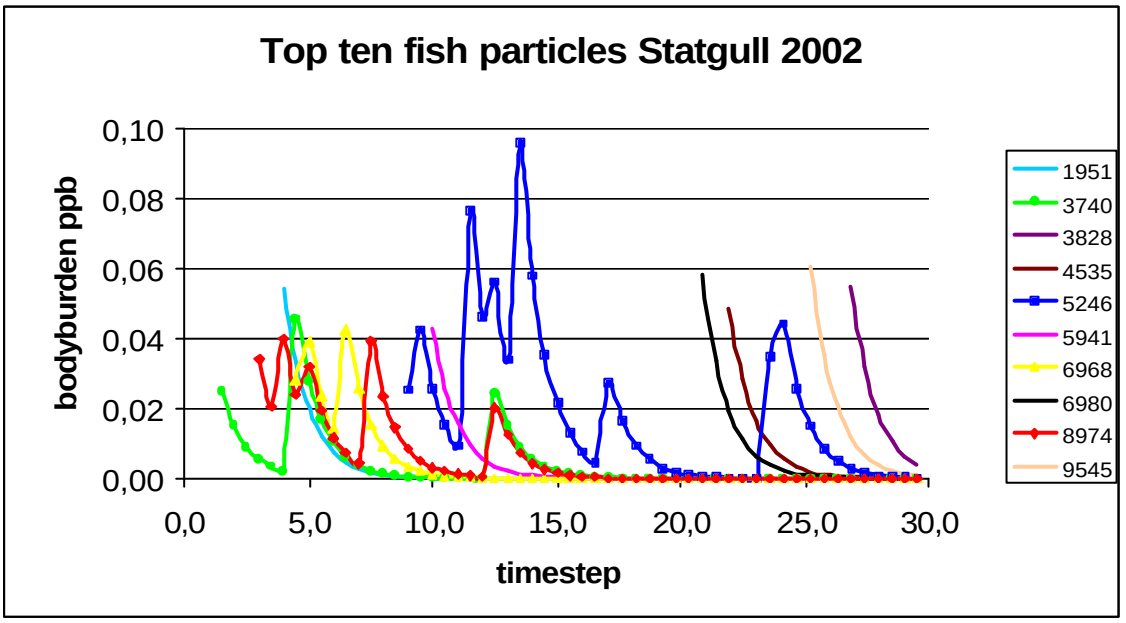


Figure 6.24 Cumulative body burden in fish particles simulated for the sub-region Statfjord/Gullfaks with the discharge data from 2002.

As we can see from figure 6.25 the fish particles in the simulations for Statfjord Gullfaks 2002 move from 10 meters depth to 65 meters depth through the simulation periode

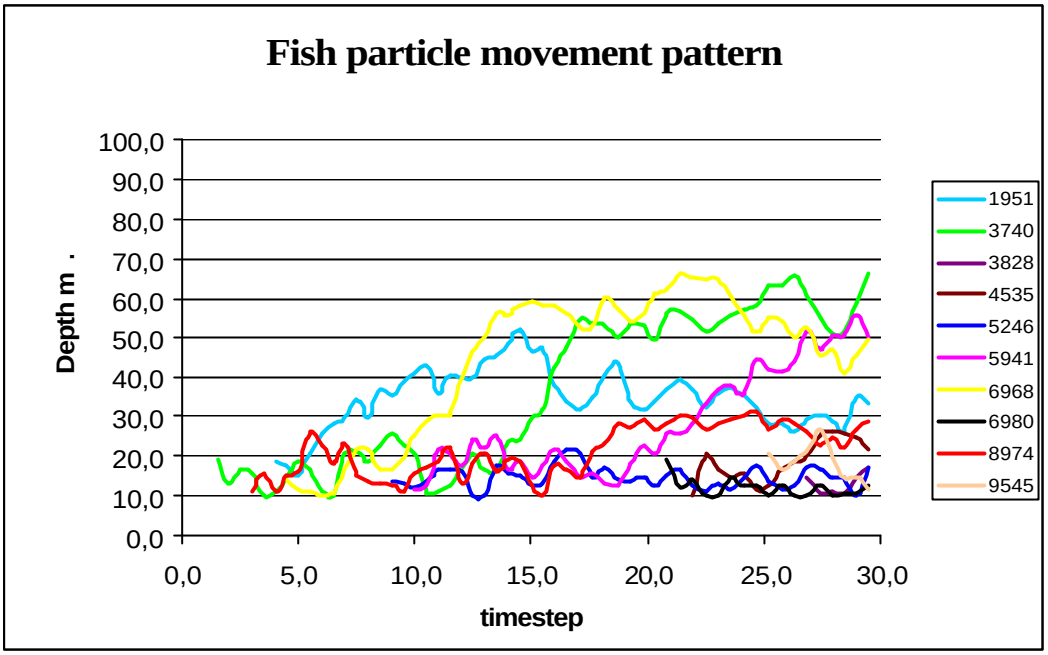


Figure 6.25 Fish particle movement pattern in depth during the simulation for Statfjord Gullfaks 2002.

For discharge data from 2006 (after measures have been implemented to reduce the produced water discharge) there are only a few fish particles that accumulate levels of alkyl phenols, and this level is low. Figure 6.26 shows the top four particles and the highest accumulated body burden is 0.02 ppb.

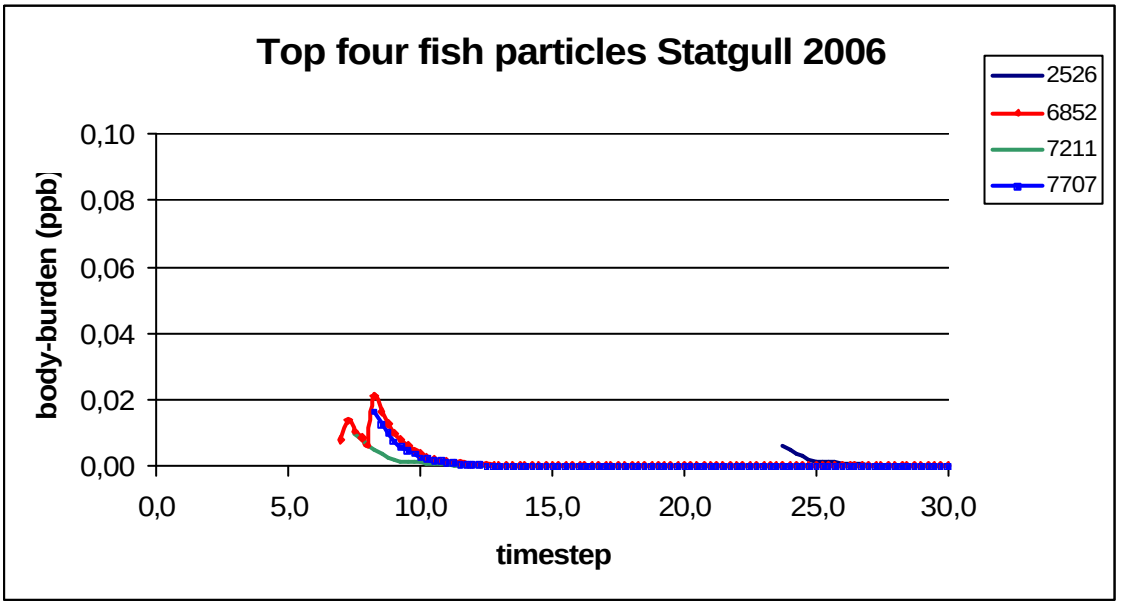


Figure 6.26 Cumulative body burden in fish particles simulated for the sub-region Statfjord/Gullfaks with the discharge data from 2006.

6.3.2 Snorre

Figure 6.27 shows an example of fish particle density around Snorre TLP and Snorre B. The amount of fish particles per cubic meter is greater than in the Statfjord/Gullfaks simulation. The higher density of fish particles has no implication on the results as long as we use the percentage of particles which have a body burden over the effect level. It must be ensured that there are enough particles so that they actually move through the plume. As shown in figure 6.27 it is more than sufficient.

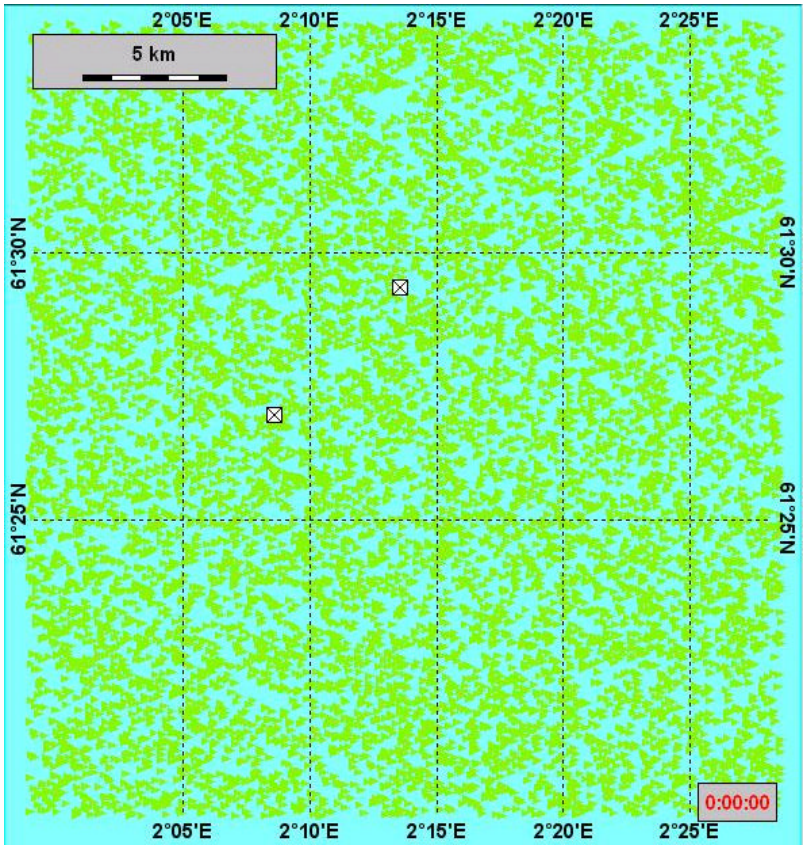


Figure 6.27 Fish particle density around Snorre TLP and Snorre B

The highest cumulative body burden observed was 0,037 ppb in particle nr. 9060. As we can see from figure 6.28 the body burden for the top ten particles is between 0.005 and 0.03 ppb, which is much lower than the level of observed effect in IMR's studies.

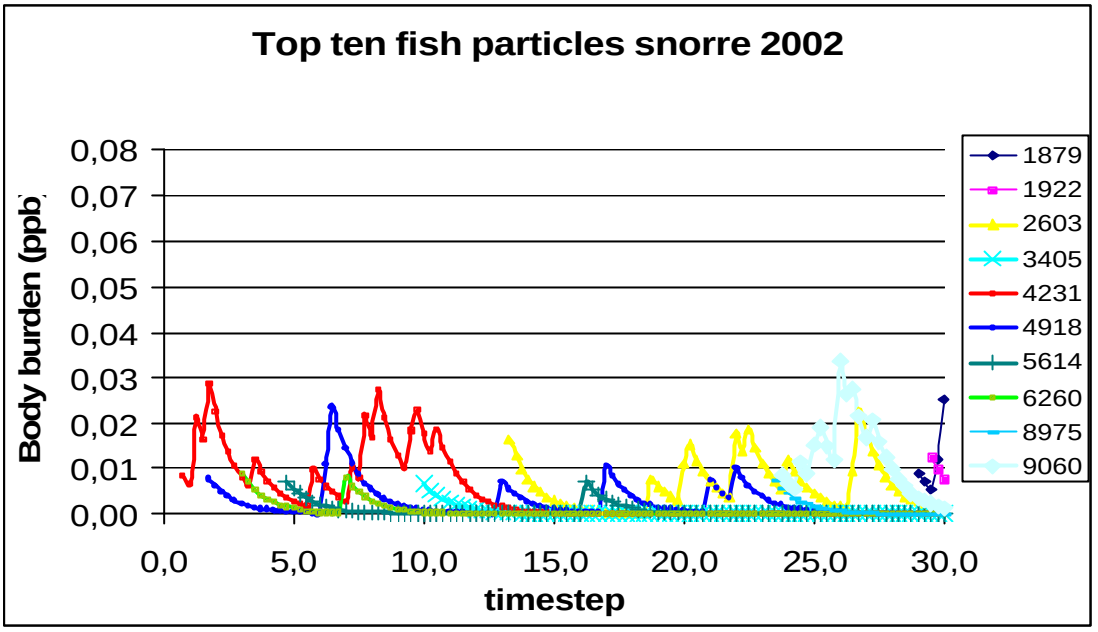


Figure 6.28 Cumulative body burden in fish particles simulated for the sub-region Snorre with the discharge data from 2002.

For discharge data from 2006 (after measures have been implemented to reduce the produced water discharge) the top ten fish particles have a higher level of alkyl phenols than in 2002. This is a result of the fact that the discharges are estimated to increase towards 2006. The highest accumulated body burden observed was 0,071 in particle nr 4755 (figure 6.29).

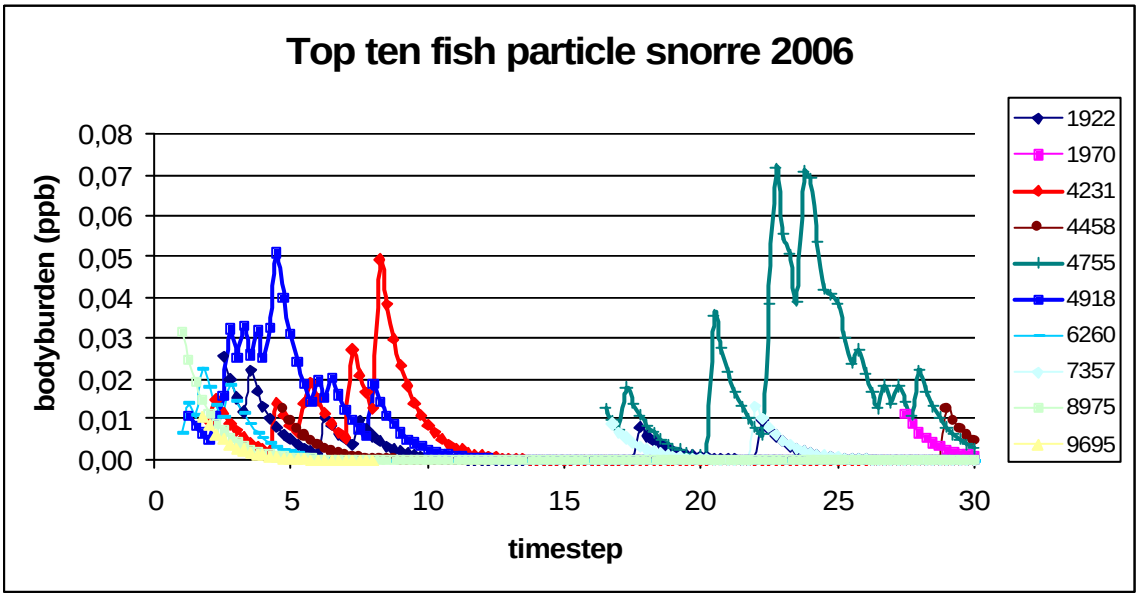


Figure 6.29 Cumulative body burden in fish particles simulated for the sub-region Snorre with the discharge data from 2006.

6.3.3 Oseberg and Troll area

When using the same sub-region as in the screening simulations there were no particles that had accumulated a body burden.

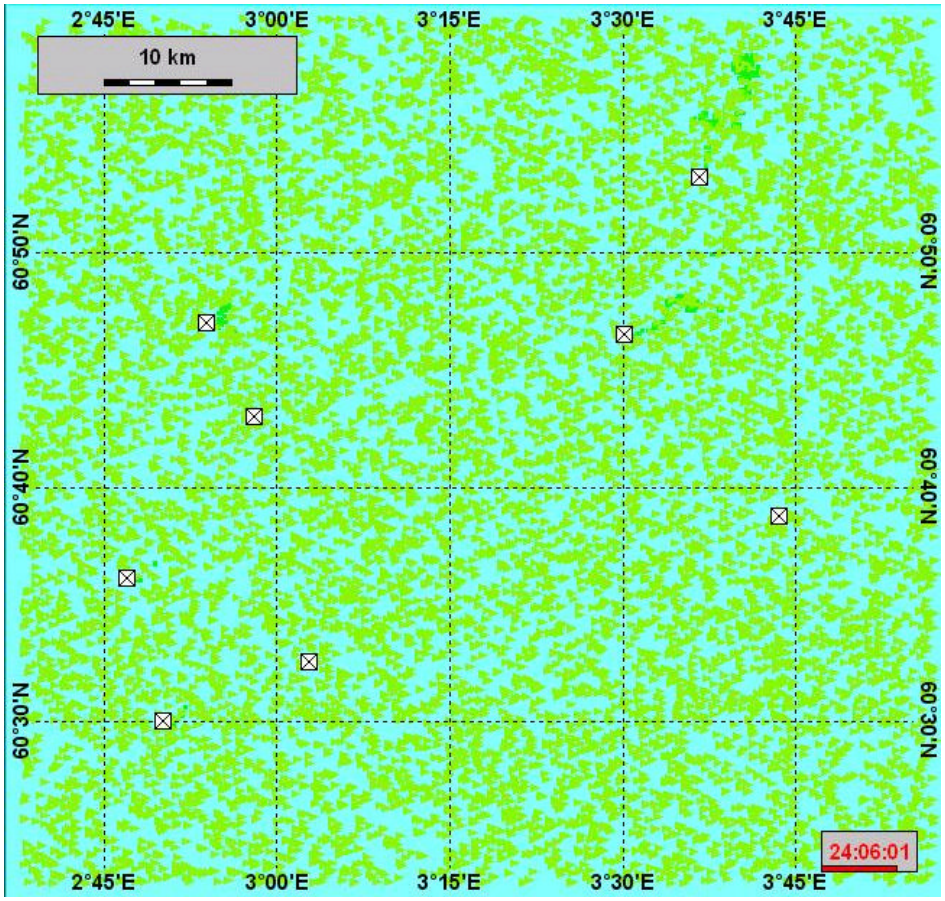


Figure 6.30 Sub-region Oseberg Troll with fish particles and concentration grid.

Since the simulation tool has limitations to the amount of fish particles in a simulation, we had to simulate smaller regions. We simulated the Troll installations since these installations represent 80 % of the discharge of produced water in that sub-region.

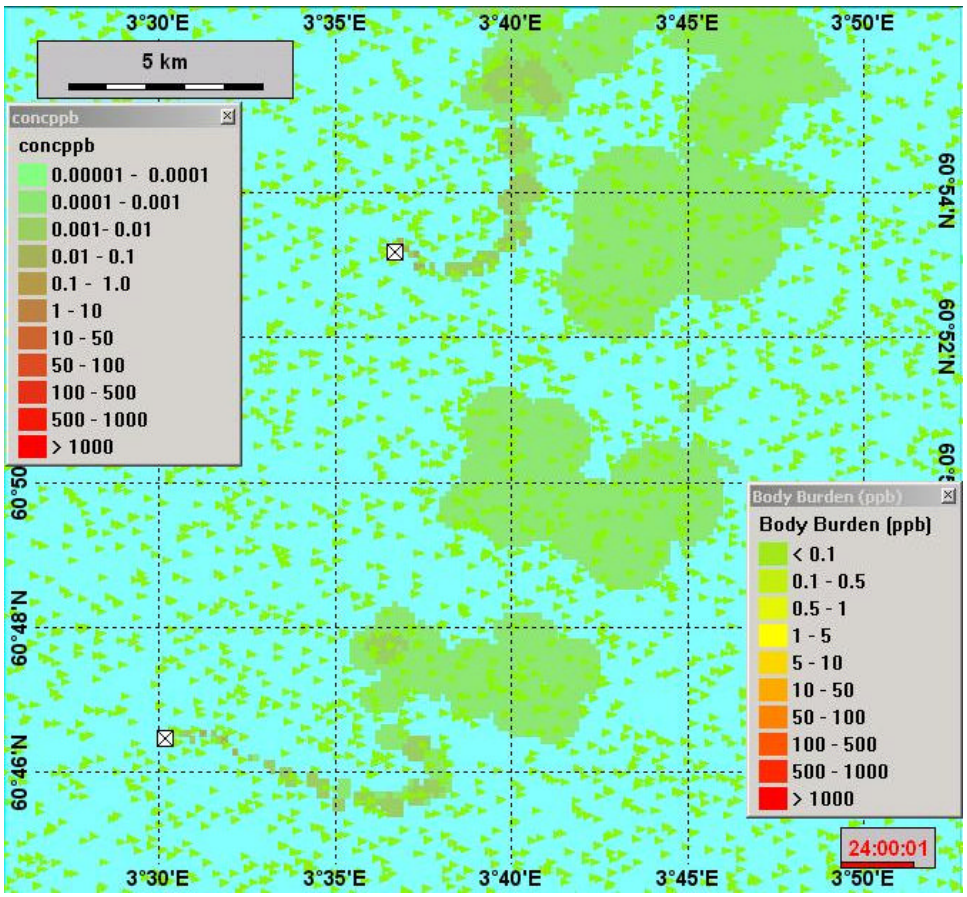


Figure 6.31 Troll area with concentration plumes and fish particles

Even at this density of fish particles there were only two particles which accumulated a body burden over zero, where the highest had 0,007 ppb.

6.3.4 Results from Simulation with DREAM- risk assessment step 2

The input to the risk assessment should have been the percentages of fish particles in the simulations which had an accumulated body burden of more than 2 ppb (critical body burden). The highest level of accumulated body burden we found was 100 folds lower than the critical body burden (table 6.12).

Table 6.12 number of fish particles with accumulated body burden of 2, 0,2 and 0,02 ppb

Region	**# fish particles Body burden > 2 ppb**		**# fish particles Body burden > 0,2 ppb**		**# fish particles Body burden > 0,02 ppb**	
Year	**2002**	**2006**	**2002**	**2006**	**2002**	**2006**
Statfjord/Gullfaks	0	0	0	0	16	1
Snorre	0	0	0	0	4	6
Oseberg/Troll	0	0	0	0	0	0

6.4 Calculations of fish distributions within the North Sea

6.4.1 Results

Results for the different oil production areas are given in tables 6,13, 6,14 and 6,15. In appendix 3 the distributions of cod, saithe and haddock are illustrated for each quarter. Figure 6.32 and 6.33 are examples of selected years. The average and standard deviation of the different years and quarters is given for each species. The estimated value given for each year and quarter should be read as approximate values and depend slightly on the extrapolation method and grid resolution used. The variation as a function of grid resolution and extrapolation method is not calculated. The average over the different surveys should be interpreted as the general tendency of the distribution of this species. Looking at the distributions of saithe, such tendencies are clearly seen, as the abundance is higher in the northern part of the North sea giving rise to higher values in the Tampen area, whilst almost absent south in the Ekofisk area, appendix 3.

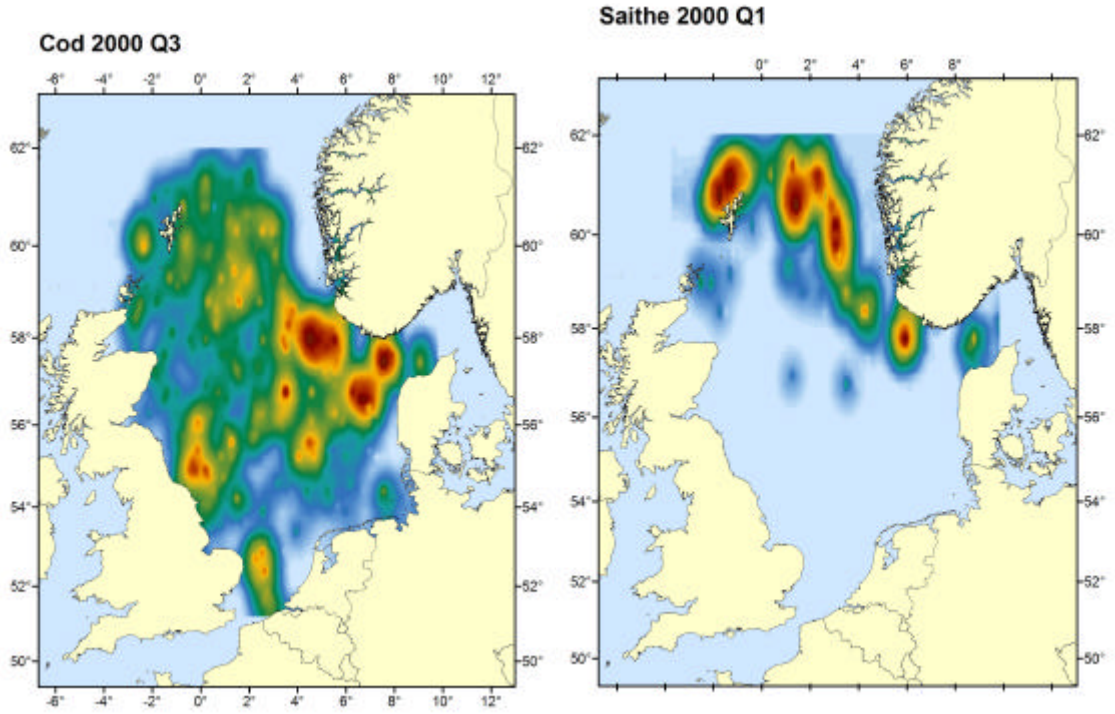


Figure 6.32 Distribution maps for cod 2000 third quarter and saithe 2000 first quarter.

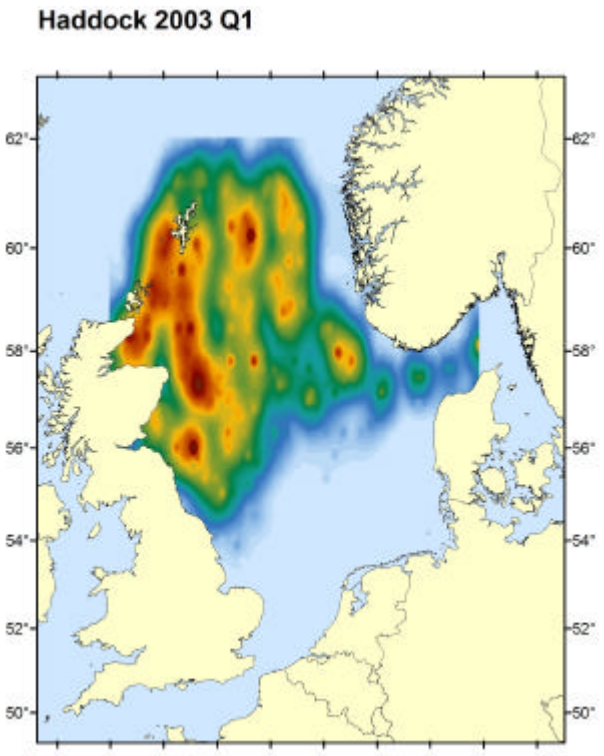


Figure 6.33 Distribution maps for cod haddock 2003 first quarter

The North Sea has been defined by the coordinates:

62º 0.0’ N to 50º 9.0’ N ; -4º -0,0’ E to 9º 57.0’ E

Total area = 1138908 km²

6.4.1.1 Tampen

The Tampen area has been defined by the coordinates:

61º 30.0’ N to 60º 25,2’ N ; 1º 42.0’ E to 3º 16.8’ E

Total area =10260 km²

Table 6.13 Summary of abundance indexes for three different species within the Tampen region. Index 2 is based on an extrapolated North Sea grid with resolution 0.15°, calculated as the sum of all grid cells covering the Tampen area defined with a resolution of 0.05° (5.6×2.7 km).

Species	Year	Quarter	# North Sea Stations	Index (%)
Cod	1999	1	363	2.8
Cod	1999	3	370	0.8
Cod	2000	1	384	3.2
Cod	2000	3	323	1.0
Cod	2001	1	436	2.6
Cod	2001	3	351	0.7
Cod	2002	1	435	0.8
Cod	2002	3	347	0.6
Cod	2003	1	355	4.4
Cod	2003	3	278	0.1
Average				1.7± 1.43
Saithe	1999	1	363	7.6
Saithe	1999	3	370	4.1
Saithe	2000	1	384	13.4
Saithe	2000	3	323	9.7
Saithe	2001	1	436	34.7
Saithe	2001	3	351	7.6
Saithe	2002	1	435	14.6
Saithe	2002	3	347	14.7
Saithe	2003	1	355	5.8
Saithe	2003	3	278	10.6
Average				12.3± 8.67
Haddock	1999	1	363	4.0
Haddock	1999	3	370	4.4
Haddock	2000	1	384	2.9
Haddock	2000	3	323	1.0
Haddock	2001	1	436	1.3
Haddock	2001	3	351	0.9
Haddock	2002	1	435	1.1
Haddock	2002	3	347	0.7
Haddock	2003	1	355	2.4
Haddock	2003	3	278	1.0
Average				1.9± 1.37

6.4.1.2 Ekofisk

Area= 11313 km^2

Table 6.14 Summary of abundance indexes for three different species within the Ekofisk region. For haddock, year 2003 third-quarter is omitted for the calculation of the average value. Three decimal places are included for saithe, since the density values are very low in this area.

Species	Year	Quarter	# North Sea Stations	Index (%)
Cod	1999	1	363	1.7
Cod	1999	3	370	2.2
Cod	2000	1	384	1.7
Cod	2000	3	323	2.7
Cod	2001	1	436	1.2
Cod	2001	3	351	1.2
Cod	2002	1	435	0.4
Cod	2002	3	347	1.1
Cod	2003	1	355	1.6
Cod	2003	3	278	1.6
Average				1.5 ± 0.63
Saithe	1999	1	363	0.010
Saithe	1999	3	370	0.003
Saithe	2000	1	384	0.100
Saithe	2000	3	323	0.004
Saithe	2001	1	436	0.002
Saithe	2001	3	351	0.060
Saithe	2002	1	435	0.002
Saithe	2002	3	347	0.020
Saithe	2003	1	355	0.020
Saithe	2003	3	278	0.150
Average				0.037 ± 0.051
Haddock	1999	1	363	0.9
Haddock	1999	3	370	1.0
Haddock	2000	1	384	1.6
Haddock	2000	3	323	1.5
Haddock	2001	1	436	1.0
Haddock	2001	3	351	2.5
Haddock	2002	1	435	0.4
Haddock	2002	3	347	1.3
Haddock	2003	1	355	0.7
Haddock	2003	3	278	9.0
Average				1.2 ± 0.61

6.4.1.3 Sleipner

Area= 24511 km^2

Table 6.15. Summary of abundance indexes for three different species within the Sleipner region.

Species	Year	Quarter	# North Sea Stations	Index (%)
Cod	1999	1	363	5.6
Cod	1999	3	370	4.2
Cod	2000	1	384	2.4
Cod	2000	3	323	4.6
Cod	2001	1	436	4.8
Cod	2001	3	351	5.5
Cod	2002	1	435	3.1
Cod	2002	3	347	1.7
Cod	2003	1	355	3.0
Cod	2003	3	278	1.5
Average				3.6 ± 1.50
Saithe	1999	1	363	3.1
Saithe	1999	3	370	8.2
Saithe	2000	1	384	1.8
Saithe	2000	3	323	5.3
Saithe	2001	1	436	3.7
Saithe	2001	3	351	12.7
Saithe	2002	1	435	1.3
Saithe	2002	3	347	7.9
Saithe	2003	1	355	2.6
Saithe	2003	3	278	1.7
Average				4.8 ± 3.71
Haddock	1999	1	363	12.5
Haddock	1999	3	370	16.2
Haddock	2000	1	384	10.7
Haddock	2000	3	323	7.7
Haddock	2001	1	436	10.5
Haddock	2001	3	351	7.3
Haddock	2002	1	435	13.2
Haddock	2002	3	347	7.9
Haddock	2003	1	355	6.9
Haddock	2003	3	278	5.9
Average				9.9 ± 3.32

6.4.1.4 Values for further use in the risk assessments

There are some variations in the abundance indexes between the different years and quarters. For example Saithe in the Ekofisk area have a larger index in the first quarter than in the third quarter. Since the risk assessment must be valid for more than one quarter in a particular year, we have used the mean values over the years. This gives an index that is valid for more than one year, but will in some years be an underestimation and in other year an over-estimation.

Table 6.16 Mean values from fish distribution data for the selected areas in the North sea

	Tampen	**Ekofisk**	**Sleipner**
Area, km²	10 260	11 313	24 511
% of total area	0,9	0,99	2,15
Cod, %	1,70	1,50	3,60
Saithe, %	12,30	0,04	4,80
Haddock, %	1,90	1,20	9,90

The total area of the North Sea considered corresponds to about 1138 908 km^2.

7 Risk Assessment

The risk assessments have been carried out in two steps. The first step was the screening simulation where the Predicted Effect Concentration grid (PEC) was compared with the Predicted No Effect Concentration grid giving the area of risk for two different concentrations with no effect, namely 40 and 4 ng/l (chapter 4.3.2 and 4.4.1). The risk areas from these simulations were compared with fish distribution data for Cod, Saithe and Haddock giving a risk potential for each fish population. The next step is to take the risk assessment one step further and compare risk area with fish particles in movement in the concentration grid. This semi-random walk around in the three dimensional concentration grid gives a more realistic perspective of the potential exposure regime. The percentage of fish particles which have a body burden over the level where IMR found effects was compared with the fish distribution data. Step 2 of the risk assessment was only carried out for the Tampen region since the other regions had almost no risk in step 1.

7.1 Assumptions

- The discharge data used in the simulations are the sum of alkyl phenols C4 – C5 and C6+. It is only a fraction of these alkyl phenols that have shown reproductive effects, which makes this a conservative approach.
- Degradation data is extrapolated from laboratory experiments.

- Fish movement in the 0 – 100 meters of the water column is not realistic for Haddock and Cod populations which tend to have a more demersal distribution pattern. This overestimate the exposure rate for the fish (cod and haddock) particles
- Currents and wind, this are the same files that are used in the standard EIF simulations and they are representative for May 1990. We have no meteorological data to assume whether this is representative.
- Fish particles which in any time step of the simulation period had an accumulated body burden over the critical body burden is assumed to be affected.
- We assume that reduction of overlap gives 100 % mortality for eggs spawned from this fish, further we assume that 35 % of the spawning fish stock that is exposed over the given critical body burden value will not reproduce that year. This is a conservative approach

7.2 Screening simulations (DREAM-EIF)

In this chapter we take the risk areas from the screening simulations (table 6.11) and combine them with distribution data (table 6.16). As we can see from table 6.11 the simulations gave some areas with a potential for risk in the Tampen region. For Sleipner and Ekofisk the risk areas were negligible.

The simulation for Tampen region was divided into three sub regions to improve the resolution. The fish distribution data did not have good enough resolution to use these small areas. The risk areas for each sub-area were added together to give the total risk area in the region.

To perform a comparison between risk area and fish we have to assume that the fish (F) is evenly distributed in the Tampen region. By looking at the percentage of risk area (A_{risk}) compared to the region area (A_{tampen}) we get the percentage of area with concentrations over the NOEC ($A_{\%risk}$).

$$(A_{risk} * 100) / A_{tampen} = A_{\%risk}$$

The next step is to correlate $A_{\%risk}$ to the fish abundance index (F_{tampen}) to give the percentage of fish populations in the North Sea with potential to be exposed to alkyl phenols (F_{risk}) for the chosen NOEC and simulation year.

$$(F_{tampen} * A_{\%risk}) / 100 = F_{risk}$$

Table 7.1 Percentage of fish populations in the North Sea with a potential to be exposed to alkyl phenols over the given NOEC values (F_{risk}).

Tampen	NOEC	A_{risk}	A_{tampen}	A_{OE}	F_{risk} Cod	F_{risk} Saithe	F_{risk} Haddock
F_{tampen}					1,7	12,3	1,9
2002	40 ng/l	0,1083	10260	0,0011	0,00002	0,00013	0,00002
	4 ng/l	7,154	10260	0,0697	0,00119	0,00858	0,00132
2006	40 ng/l	0,053	10260	0,0005	0,00001	0,00006	0,00001
	4 ng/l	4,951	10260	0,0483	0,00082	0,00594	0,00092

The screening simulations are very conservative and its main purpose was to pinpoint the areas of main concerns for the DREAM-risk assessment simulations which is also conservative but takes into account fish movement, uptake and elimination of alkyl phenols and by that give a more realistic risk assessment.

As seen in table 7.1 the F_{risk} is very low for all simulation regimes.

7.3 Simulations with DREAM-risk assessment, step 2

The methodology for estimating risk on the fish stocks in the North Sea from simulations with DREAM is described below.

The number of fish particles that exceeded 2 ppb (P_{risk}) compared to the total number of particles (P_{total}) in the simulation gives the risk of effect on fish in that sub-region ($P_{\%risk}$).

$(P_{total} * P_{risk}) / 100 = P_{\%risk}$

The simulation for the Tampen region was divided into three sub-regions to improve the resolution. The fish distribution data did not have high enough resolution to use these small areas. If we assume that the habitat grid used in the three sub-regions is more or less the same area as the region used for the fish abundance index, then we can sum the $P_{\%risk}$ for each sub area for further use in the risk assessment.

This value is then correlated to the fish abundance index (F_{tampen}) to give a risk assessment for the fish stocks in the North Sea.

$(F_{tampen} * P_{\%risk}) / 100 = F_{risk}$

Neither simulations with discharge data from 2002 nor 2006 gave body burden levels in any fish particles that exceeded the critical body burden (2 ppb; IMR studies). From this result we can conclude that the risk of reproductive effects from alkyl phenols on fish stocks in the North Sea is insignificant.

We can assume that individual fish in the North Sea in the close vicinity of the discharges can be exposed to a level at which the body burden reaches the levels where IMR found effects. The resolution of the risk assessment does not permit use to evaluate such a detailed level. This project's objective was to assess the risk of endocrine disruption from discharges of alkyl phenols in produced water on fish stocks in the North Sea. The data available for discharges of alkyl phenols and fish stock distributions is only detailed enough to make an overall risk assessment of the fish stocks in the North Sea as a whole. In order to make a risk assessment with higher resolution following aspects are needed:

- Fish distribution data from the actual region (sub-region) with higher resolution
- Discharge data where it is possible to extract the compounds with potential for endocrine disruption
- Use of the near field mode of the simulation tool with fish particles.

7.4 Risk of effect on fish exposed to alkyl phenols

In the IMR study they found that an oral exposure of alkyl phenols corresponding to 20 ppb body burden gave a 20 days delayed spawning time for cod. Studies show that the absorption efficiency of the AP compounds over the gut wall is only about 10% (Pickford *et al.* 2003; Sundt and Baussant 2003). This suggests that Meier *et al.* 2002 could have overestimated the actual body burden in their study. Since approximately 10% of what is ingested is actually absorbed, the estimated body burden of fish fed 20 ppb would be 2,0 ppb. If we assume that the effect of being exposed to 2 ppb of alkyl phenols is 20 days delayed spawning time, we can estimate what effect this would have on the survival of larvae.

7.4.1 Fish recruitment and effects of changes in spawning time

Most commercial fish species with large populations have a reproduction regime where they lay a high number of eggs, typically of the order of one million. The eggs are spawned in the water column and/or the newly hatched larvae are released into the water. This reproductive biology can be seen as an ecological adaptation to a life history with a passive drift of eggs or larvae as plankton with the ocean currents. This secures transport and spread of the juveniles over a large nursery area from which the juveniles and adults can migrate on seasonal feeding and spawning migrations. They spatially close the life cycle by having spawning migrations back to their spawning areas from where the larvae originated (Skjoldal, 2002).

The price for having a high number of eggs and larvae is inevitably a high mortality because on average only two individuals out of the high number of larvae produced by a spawning pair of fish need to reach mature age and spawn in order to maintain the population. Therefore the accumulated mortality is very high (typically more than 99.9%) and the fraction that survives to become adults is very small. Johan Hjort

introduced the concept of a critical stage in the development of fish larvae and a hypothesis that recruitment variability was due to a high but variable mass mortality at the stage when the larvae changed from using the yolk sac reserves to starting their first feeding on small plankton organisms (Hjort 1914). There is little evidence to support the hypothesis of mass mortality in a very limited time. Instead there seems to be a relatively high mortality rate sustained over a long time period during the development of the larvae and juveniles (Skjoldal and Melle 1989).

Mortality rates of small fish larvae are typically of the order of 10% per day (McGurk 1986). The reason for such high mortality is likely to be predation from a variety of predators, both invertebrates (jellyfishes, amphipods) and planktivorous pelagic fish. The number of individuals is rapidly reduced at such mortality rates. To illustrate this, with about 10% mortality per day (exponential coefficient of 0.1) and starting with one million individuals, about 50 000 would survive after one month, about 2 500 after two months, and about 120 after three months. Small changes in the mortality rate would be translated into large variability (orders of magnitude) in the small fraction of survivors (Skjoldal and Melle 1989).

The place and time for spawning is likely to be strongly selected for in the ecological and evolutionary adaptation of fish populations. The place must be right in terms of larval drift to suitable nursery areas and the time must be right in terms of suitable feeding conditions and low abundance of predators. It is the combination of these factors that finally determines the outcome and success of recruitment in any given year (Skjoldal and Melle 1989). In this way the effects of food and predators on the survival of fish larvae interact. Good growth due to favourable feeding conditions lowers the duration of a given segment of the larval development, thereby lowering the accumulated mortality and increasing the fraction of survivors.

Many fish stocks spawn in spring around the time of the initiation of the seasonal plankton development. This is also the case for the North Sea cod stock. The copepod *Calanus finmarchicus* is a key zooplankton species in Norwegian waters, and early development stages (nauplius larvae) of this species are the main prey for fish larvae (Sundby 2000). The spawning of *Calanus finmarchicus* depends on the supply of phytoplankton food and typically occurs in the early phase of the spring phytoplankton bloom (Melle and Skjoldal 1998, Melle *et al*. 2004). It is a fair assumption that fish spawn in spring so that the fish larvae can benefit from the seasonal occurrence of suitable prey, notably *Calanus* nauplii. These spring events with the phytoplankton bloom and *Calanus* spawning are of relatively short duration and lead to marked temporal changes in the conditions for feeding and growth of the fish larvae. Variation in the timing of the plankton development and the spawning and larval development of fish has been considered in the match-mismatch hypothesis to be a major cause for variable recruitment of fish (Cushing 1972, 1990).

To document the effect of timing on recruitment success requires detailed and extensive studies including time series of spawning or hatching of larvae. There are therefore a limited number of studies that actually provide such documentation. Use of otholith microstructure (daily growth zones) to determine the age of fish larvae and juveniles in principle allows a comparison between the back-calculated hatching date distribution for the survivors and the distribution of hatching dates as determined on the spawning grounds.

The hatching curves of larvae of Norwegian spring spawning herring were determined from high frequency sampling of newly hatched larvae at the main spawning grounds at Møre during the spawning seasons in 1988-1993 (Fossum 1996). The peak hatching varieded by about one month among the years. The hatching date distribution of the surviving post-larvae, sampled in the drift route further north about 2 months later, differed in some years from the hatching time distribution observed at the spawning ground. In 1990, the hatching time distribution for the survivors came from the latter part of the hatching curve at the spawning grounds, indicating that the larvae that hatched early did not survive. This corresponded to low abundance of prey organisms at that time (Fossum and Moksness 1993). In contrast, in 1991 the abundance of prey (copepod eggs and nauplii) was high from the period of early hatching, and survivors that year came from both the early and late part of the hatching curve at the spawning ground (Fossum and Moksness 1995). The 1991 yearclass became very strong.

Similar evidence has also been found for timing effects on recruitment of Barents Sea cod (Northeast Arctic cod stock) (Solemdal 1997).

7.4.2 The match and mismatch of larval production compared with their larval food.

Based on (Eilertsen, et al., 1989) the match and mismatch of the distribution of first feeding larvae in relation to the distribution of nauplii production in April/May is estimated. The data points are assumed to resemble normal distributions for both distributions. Based on the graphs reported, the following distributions have been approximated for the distribution of first feeding larvae and the nauplii production (table 7.2). There are great differences in the extensions and overlap of these distributions between different years and no clear general conclusion or precise number can be given regarding the effect of the delayed egg production. The calculation multiplies the distributions with each other resulting in a product representing the normal situation. When the first feeding larvae production is shifted right 20 days, a new product is calculated, and the rate between the new and old product gives reduced matching.

Table 7.2 Reduction in overlap between distributions with 20 days delay for four years.

Year	First feeding larvae	Nauplii	Reduction in overlap between distributions with 20 days delay
1983	N(130,10)	N(100,20)	30,0 %
1984	N(118,12)	N(130,18)	71,0 %
1985	N(130,10)	N(115,15)	21.5 %
1960	N(110,12)	N(90,15)	20,0 %
average			35.0 %

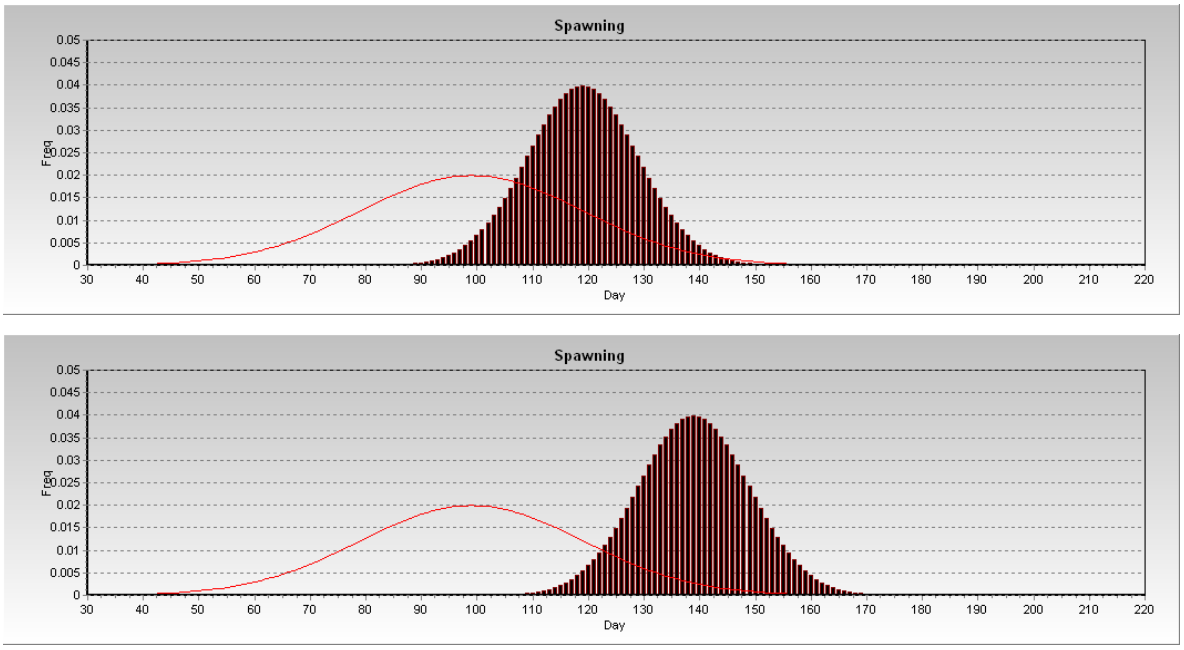


Figure 7.1. Distribution of first feeding larvae of cod in 1983 in relation to production of copepod nauplii (red line). Lower image: 20 days delay in egg production reduces the overlap to about 30% of that of the normal situation.

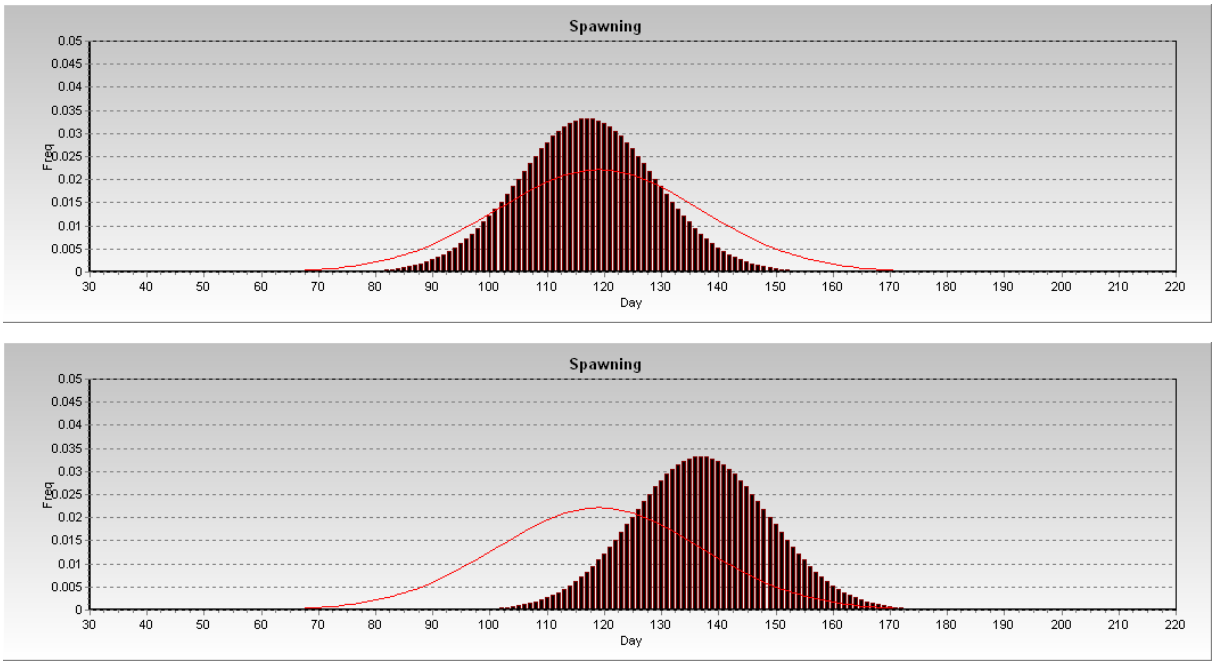


Figure 7.2. Distribution of first feeding larvae of cod in 1984 in relation to production of copepod nauplii (red line). Lower image: a 20 day delay in egg production reduces the overlap to about 71% of that of the normal situation.

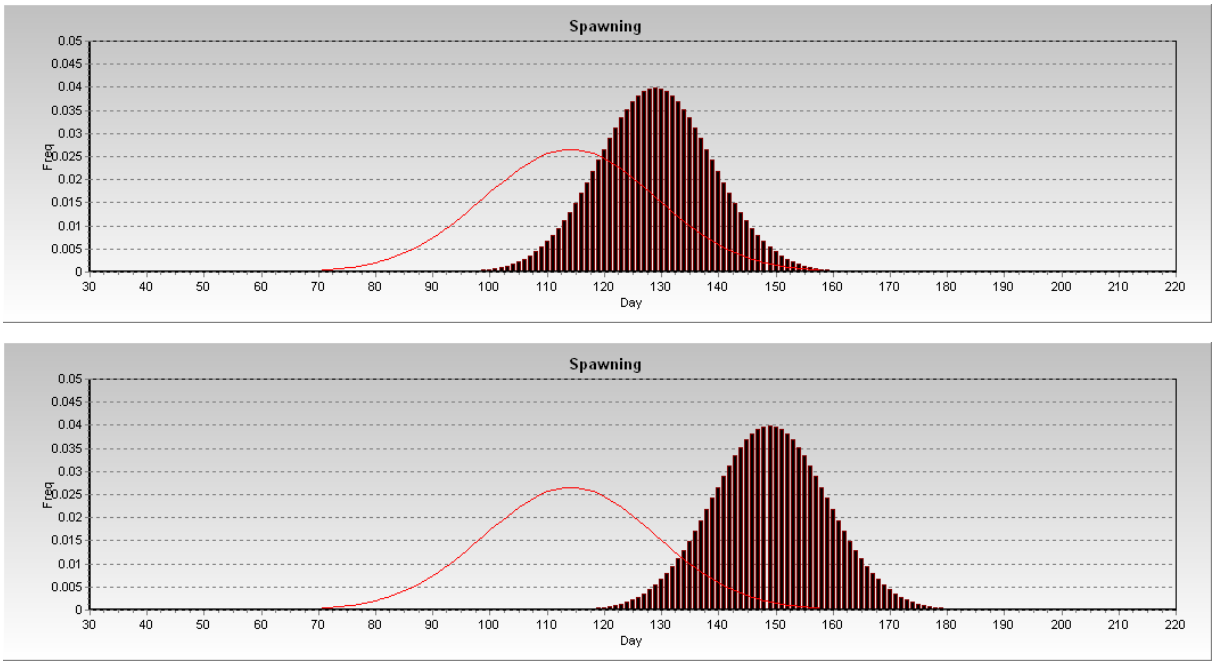


Figure 7.3. Distribution of first feeding larvae of cod in 1985 in relation to production of copepod nauplii (red line). Lower image: a 20 day delay in egg production reduces the overlap to about 21.5% of that of the normal situation.

7.5 Overall risk assessment

- The overall results of the simulations with DREAM show that there is no significant risk potential. In other words there were no fish particles which accumulated alkyl phenols above the critical body burden of 2 ppb in any of the simulations. The highest accumulated body burden in any of the fish particles was 0.09 ppb.
- The next step in the risk assessment was correlation to effect in the reproduction success, but since we have no risk potential this step is unnecessary.

In appendix 4 we have an example on how we intended to assess the overall risk. In that example we have used the results from the screening simulations to illustrate the methodology (Note that this is not a formal Risk assessment, and will not contribute to the overall conclusions stated above).

In this project we have done a conservative risk assessment of the reproductive effects from alkyl phenols on the fish stocks in the North Sea and have not found any risk potential. Even with a simplified and conservative approach (screening simulations, appendix 4) the percentages of fish that would have unsuccessful spawning are insignificant compared to other factors that influence spawning success.

Our conclusion is similar to the conclusions in the unpublished report from Matthiessen (Matthiessen, P. 2003). The report evaluated the environmental implications of alkyl phenols and estrogenic activity found in produced water at UK offshore productions platforms. They state that alkyl phenols do not make significant contributions to the oestrogenicity of the discharges. Furthermore they state that the alkyl phenols are not present in produced water at concentrations which would be expected to cause non-oestrogenic environmental effects at distances from the installations of more than 1 km in the worst case.

8 Conclusion

The best of currently available methods and data have been used. For this risk assessment 40 ng/L and 4 ng/l have been used as No Observable Effect Concentrations (NOEC) based on the findings of IMR and RF-akvamiljø. The critical body burden used was 2 ppb of alkyl phenols which correspond to 4 ng/l water exposure.

The simulations show that there is no significant risk of reproductive effects on the population levels of cod, saithe and haddock in the North Sea as a result of alkyl phenol discharges in produced water.

In our judgement the overall assumptions made for the assessment seems sound and reasonable.

It is still important that the alkyl phenols discharges will be followed up with monitoring as soon as the methods for this are sufficiently developed.

In the simulations no significant effects on fish in the close vicinity of the discharges were calculated. However, low resolution in the fish stock data forced an assumption of even distributions of fish in these areas. This is not necessarily a valid assumption.

At sub-risk level the alkyl phenols in the concentration grid for 2002 are higher than for the 2006 discharge regime, except for Snorre were it was slightly elevated.

This study has assessed the reproductive effects of alkyl phenols grouped in C4-C5 and C6+. Other compounds of produced water have not been included in this assessment.

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Appendix 1: Selected references to biological experiments with alkylphenols

Appendix 2: Results from the screening simulations with NOEC 4 ng/l