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Modelling Chronic Exposure of Larval and Adult Fish to Releases from Offshore Petroleum Platforms

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PROVANN: Model System for Chronic Exposure of Larval and Adult Fish to Releases from Offshore Petroleum Platforms

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INTRODUCTION

Produced water from offshore oil and gas production platforms contains a variety of hydrocarbons, heavy metals, and production chemicals. Vertical and horizontal mixing generally brings concentrations in discharge plumes below levels associated with acute effects within 500 or 1000 m of the source (Rye et al., 1996). Chronic effects outside this region, on the other hand, remain a potential problem.

The purpose of PROVANN, the system of models described here, is to assess the potential for chronic effects from produced water. The preliminary focus is on potential bioaccumulation and biomagnification of produced water constituents in the marine food web. Other possible types of chronic effects, such as reduced fecundity, or pheromone response interference, can also be assessed with the model described here to the extent that such effects may be correlated with exposure.

PROVANN simulates 3-dimensional transport, dilution, and degradation of chemicals released into the water, from one or more simultaneous sources. The resulting time series of concentration fields is saved in a file, which then serves as input to a simulation of fish movement (swimming) and fish egg and larval transport.

The PROVANN model system described here consists of four components:

- a near-field release model,
- a far-field transport model,
- a biological exposure model, and
- a bioaccumulation and biomagnification model.

The near-field and far-field models are integrated into one system component and the biological processes into a second, as depicted schematically in Figure 1. Potential effects at the population level could be incorporated through linkage to population dynamics models for selected species of interest.

The near-field release model is based on the buoyant plume equations developed by Koh and Chang (1973) and Brandsma et al., (1980, 1992). As the plume forms, water is entrained, the plume increases in cross section, and its density approaches that of the surrounding water. In the presence of a density gradient or thermocline, the plume may reach an equilibrium level in the water column. Otherwise, the plume will eventually arrive at the sea floor or the sea surface, depending on its initial buoyancy, depth, strength and orientation.

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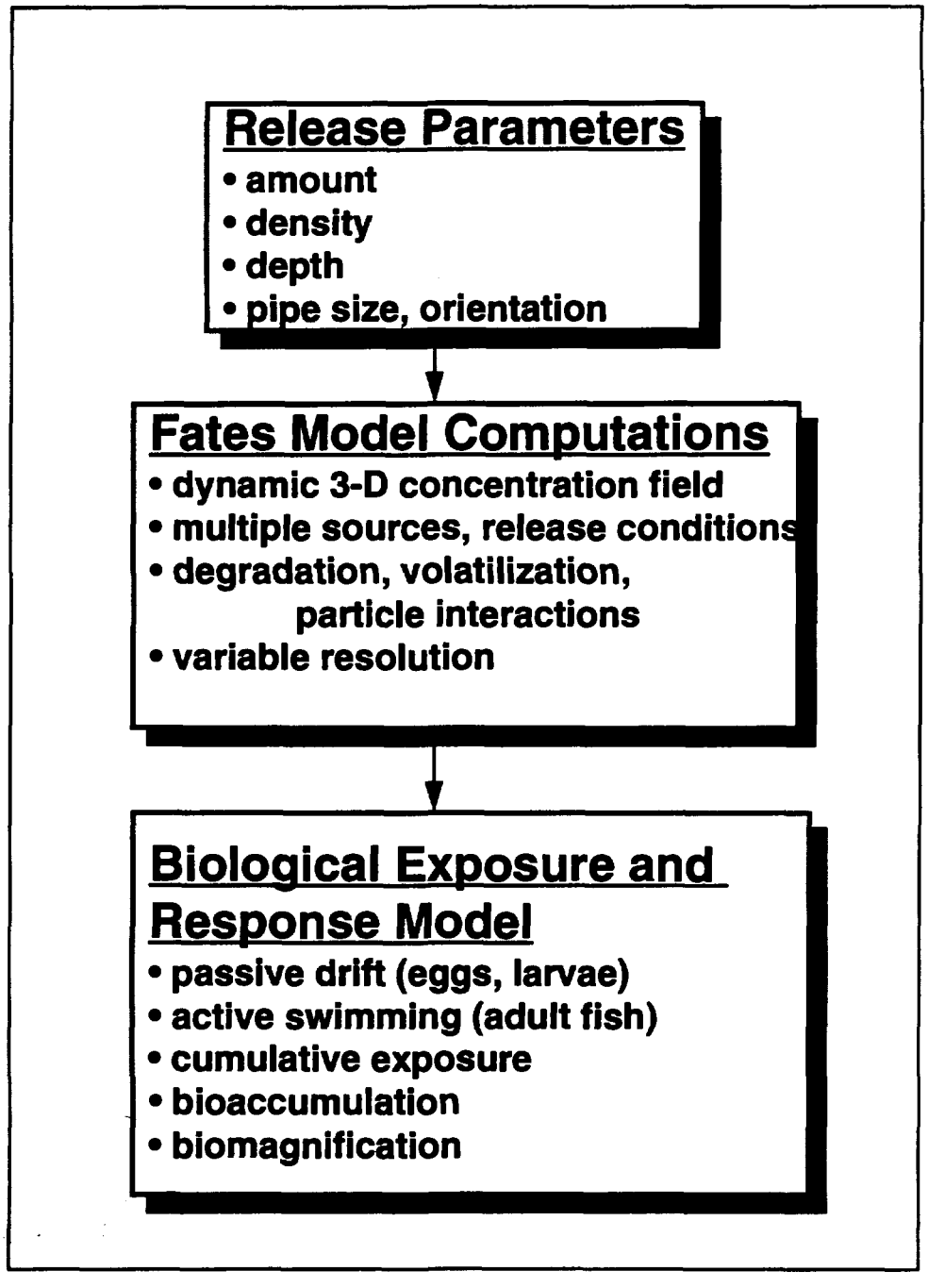


Figure 1. Schematic overview of the PROVANN model system

The far-field model uses individual particles released from the near-field plume to simulate the further transport and fate of contaminants in the water column. A fraction of the contaminant mass is associated with each particle. These particles are Lagrangian in the sense that they move with the surrounding water, unless buoyant oil droplets are being simulated. The use of Lagrangian particles in the contaminant transport calculations effectively eliminates numerical diffusion problems associated with finite difference calculations in the presence of steep

gradients (e.g. at the edge of contaminant plumes), and also provides a versatile modeling framework. Both the near-field and far-field models are described in detail in Reed et al. (1995).

The far-field model solves the generalized transport equation in three physical dimensions and time:

$$\frac{\partial C}{\partial t} + \vec{V} \bullet \vec{\nabla} C = \vec{\nabla} \bullet D \vec{\nabla} C + \sum_{i=1}^{n} r_i C \qquad (1)$$

Relevant processes (r_i) included in the physical fates component are:

- adsorption/dissolution kinetics,
- entrainment and dissolution of oil droplets into the water column,
- volatilization from water column,
- degradation,
- addition of mass from continuous releases, multiple sources,
- dissolution from sediments to water column,
- deposition from water column to sediments.

These process rates (r_i) result in mass transfers from one model state to another.

The biological exposure model simulates exposure pathways of planktonic organisms and fish (Figure 2). Phytoplankton, fish eggs and larvae, as well as other zooplankton upon which fish may feed, are simulated as passive drifters. Swimming by pelagic and demersal fish is modeled as a random walk process, with the speed being a function of fish size and type (Figure 3). Some fish within the geographical region being modeled will swim through the plume, which in the present version is assumed not to affect their behavior. Contaminated food organisms which they consume while within the plume, as well as direct uptake from dissolved contaminants in the water will contribute to their body burden.

For screening purposes a relatively simple food chain model has been incorporated into PROVANN. Bacteria and phytoplankton are assumed to adsorb pollutants in accordance with simple equilibrium partitioning between adsorption and dissolution. Calanus copepods, krill, and pelagic fish, which form the higher trophic levels of this simple food chain, are then potentially exposed to pollutants through absorption across gill membranes, as well as through ingestion of lower trophic organisms.

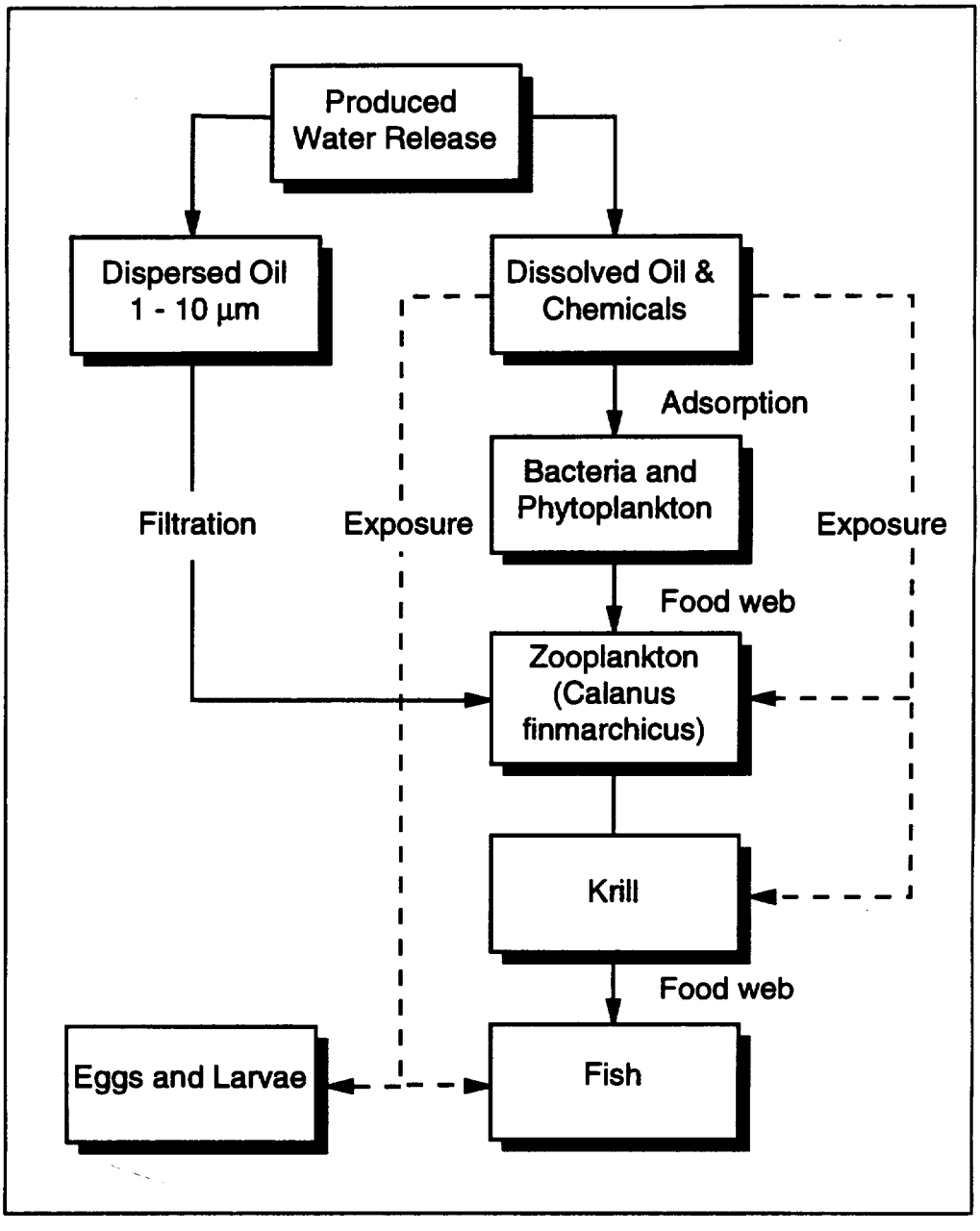


Figure 2. *Exposure pathways in the bioaccumulation/biomagnification model. (The uptake of oil droplets by Calanus is not yet included.)*

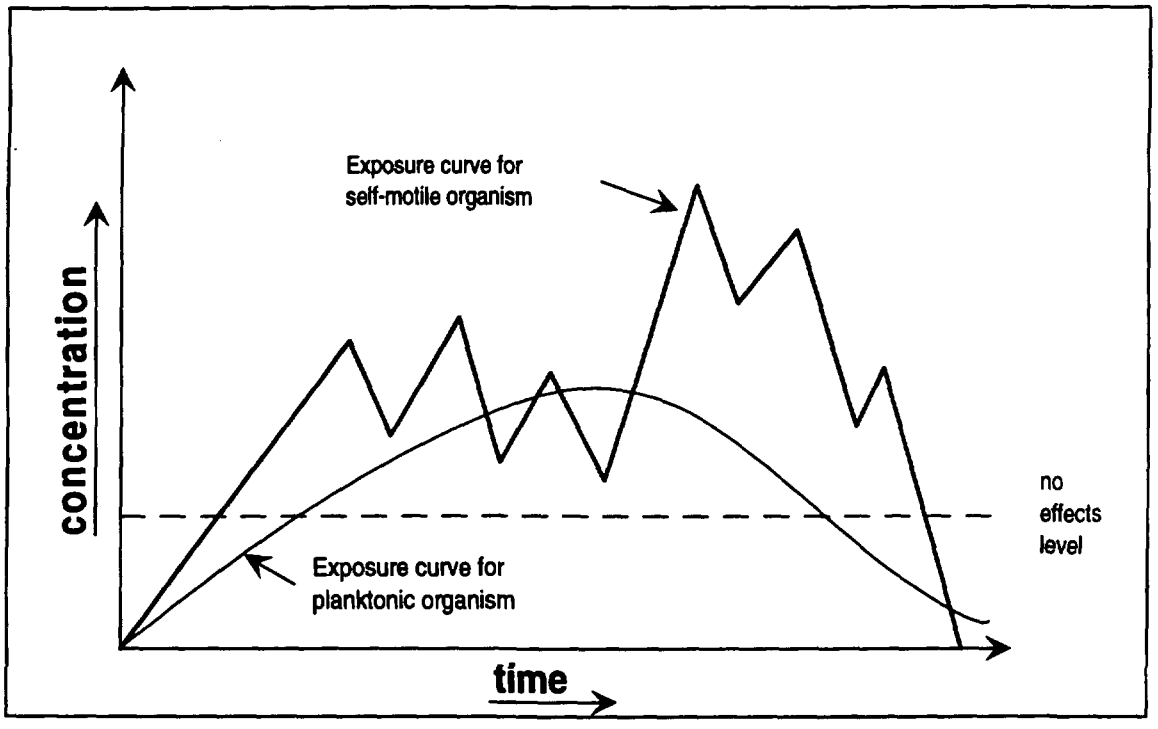


Figure 3 *Conceptional comparison of exposure patterns for freely swiming and passively drifting organisms in the vicinity of a contaminated release plume.*

If it is assumed that equilibrium partitioning kinetics are sufficient to estimate concentrations in the phytoplankton, then the ratio of the adsorbed to the dissolved concentration is given by:

$$C_p/C_d = K_p\, C_{phyto} \qquad (1)$$

where

C_p = adsorbed concentration on phytoplankton
C_d = dissolved concentration in the water column
K_p = equilibrium partition coefficient for phytoplankton
C_{phyto} = concentration of phytoplankton in water column.

The partition coefficient K_p has units "per unit concentration (e.g. mg/l) adsorbing material". If phytoplankton represent the major adsorptive particles present, then the total concentration is the sum of $C_p + C_d$, and the concentration on the phytoplankton can be calculated from

$$C_p = K_p\, C_{phyto}\, C_{total} / (1 + K_p\, C_{phyto}). \qquad (2)$$

In the case of a system with phytoplankton, herbivorous zooplankton, krill, and fish present, the total concentration of a substance averaged over a given volume of water is distributed according to

$$C_{total} = C_d + C_p + C_z + C_k + C_f\,, \qquad (3)$$

where the meaning of the subscripts are:

d = dissolved
p = phytoplankton
z = herbivorous zooplankton (e.g. *Calanus finmarchicus*)
k = krill
f = planktivorous fish (e.g. herring).

The concentrations in (3) are values averaged over a given volume of water, and need to be divided by the mass density per unit mass water of each organism class to compute typical concentrations in individual organisms.

Within a given volume of water, the following equations, in conjunction with (3), govern the distribution of the chemical substance being modeled:

concentration adsorbed to phytoplankton, present in concentration C_{phyto}:

$$C_p = K_p C_{phyto} C_d \tag{4}$$

concentration adsorbed to herbivorous zooplankton, present in concentration C_{zoo}:

$$C_z = K_z C_{zoo} C_d \tag{5}$$

concentration internal to herbivorous zooplankton:

$$dC_{zi}/dt = k_z C_d - k_{z\text{-}dep} C_{zi} + k_{grazing\ z\text{-}p} C_p \tag{6}$$

concentration internal to krill, assumed to feed primarily on herbivorous zooplankton:

$$dC_k/dt = k_k C_d - k_{k\text{-}dep} C_k + k_{grazing\ k\text{-}z} C_z \tag{7}$$

internal concentration in fish, assumed to feed primarily on krill:

$$dC_f/dt = k_f C_d - k_{f\text{-}dep} C_f + k_{grazing\ f\text{-}k} C_k \tag{8}$$

Note that equations (6) - (8) give body burden concentrations for individuals, and need therefore to be corrected for the mean mass density of individuals per unit mass of water.

For a known value of C_{total}, and given values of the partition coefficients, uptake, and depuration and grazing rate parameters, the set of equations (3) - (8) can be solved. For the simple model postulated here, it is assumed that, since the metabolic processes in zooplankton occur much more rapidly than in fish, it is reasonable to use the equilibrium solutions to (6) and (7):

$$C_z = (k_z C_d + k_{grazing\ z\text{-}p} C_p) / k_{z\text{-}dep}, \tag{9}$$

and

$$C_k = (k_k C_d + k_{grazing\ k\text{-}z} C_z) / k_{k\text{-}dep}, \tag{10}$$

where the effect of external adsorption is neglected for krill and larger organisms.

The dynamic equation for bioaccumulation and depuration for fish can then be solved analytically as a function of time t as the simulation proceeds:

$$C_f(t) = (-(k_f C_d + k_{grazing\ f\text{-}k}\, C_k) / k_{f\text{-}dep} + C_{f0}) \exp(-k_{f\text{-}dep}\, t) + (k_f C_d + k_{grazing\ f\text{-}k}\, C_k) / k_{f\text{-}dep}. \quad (11)$$

where C_{f0} is the internal concentration in the fish at the beginning of the exposure interval.

EXAMPLE SIMULATIONS

Two pairs of simulations are used to demonstrate model performance and capabilities. Both sets involve releases of produced water from two neighboring platforms offshore Trondheim, Norway.

The first pair of simulations traces the evolution of the concentration fields of C_7-phenol and naphthalene in produced water, and covers the 60-day time period April - May. The total assumed release rate for produced water was 4610 m^3 per day, divided 30% - 70% between two platforms. Assuming a concentration of 0.3 ppm naphthalene in the produced water gave a total release of 83 kg naphthalene over 60 days. For phenol, the release was 332 kg over 60 days. Hydrodynamic input for these first simulations is supplied by a 3D hydrodynamic model covering the region of interest.

The second pair of simulations again traces phenols from two simultaneous sources on Haltenbanken, but compares results with and without degradation, and with a simpler hydrodynamic input. Release rates for total produced water are 22,500 and 13,700 m^3/day, containing concentrations of 16 and 5 mg/l phenols, corresponding to 400 and 70 kg/day respectively. Release depths are 10 and 40 meters for the larger and smaller releases. A pycnocline is assumed to limit vertical mixing below a depth of 20 m. This is a typical stratification depth in early spring, which reduces to some extent the interactions between the two releases. The releases are simulated over a 90 day period, to allow full formation of the combined release field. The background current field used is based on Sætre and Bjørke (1988), as are spawning locations in 1986 for herring off the coast of mid-Norway (Figure 4). A wind record for 1986 supplied by the Norwegian Meteorological Institute was used to drive a time-varying wind-driven current field, averaged over the upper mixed layer.

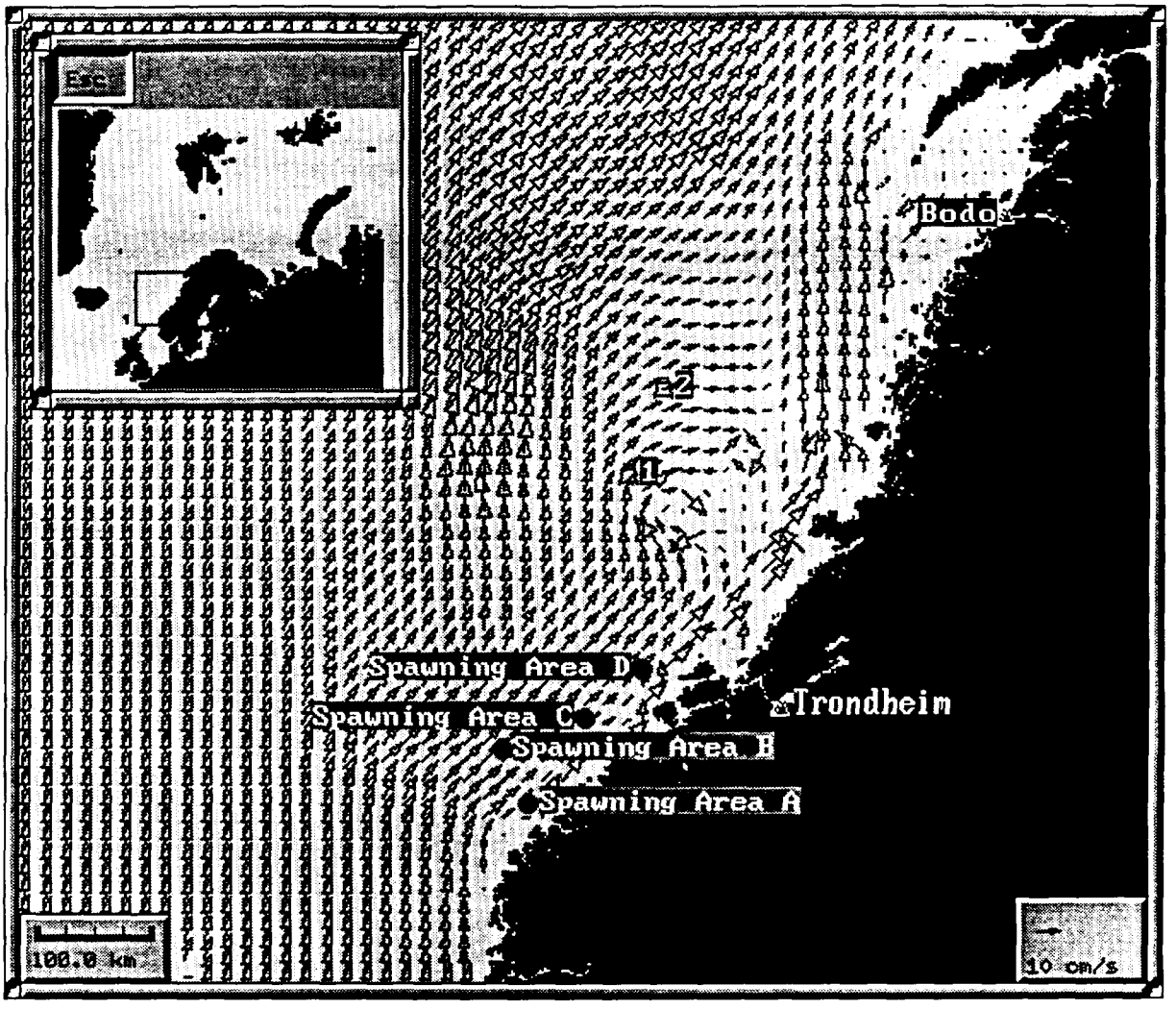


Figure 4. *Background current field used in the second simulation. The figure also shows release areas for spring spawning herring eggs and larvae, and the locations of the produced water releases.*

Biological and chemical input parameters used in the simulations are given in Tables 1 - 3.

Table 1. *Biological uptake, depuration, and predation (grazing) parameters used in the calculations. It is assumed that rates for krill and herbivorous zooplankton are similar.*

	k_z (day^{-1})	$k_{z\text{-dep}}$ (day^{-1})	$k_{gr\ z\text{-}p}$ (day^{-1})	k_k (day^{-1})	$k_{k\text{-dep}}$ (day^{-1})	$k_{gr\ k\text{-}z}$ (day^{-1})	k_f (day^{-1})	$k_{f\text{-dep}}$ (day^{-1})	$k_{gr\ f\text{-}k}$ (day^{-1})
Naphthalene	7200	1.2	1.0	7200	12	0.5	720	0.4	0.1
C_7 Phenol	7200	12	1.0	7200	12	0.5	720	1.2	0.1

Table 2. Mean biological parameters assumed to characterize phytoplankton, herbivorous zooplankton, krill, and small pelagic fish.

	Mean Concentration (mg/l)	Mass/Individual (gm)	Number Individuals per m^3
phytoplankton	5	0.000005	1,000,000
zooplankton	3.5	0.001	3500
krill	0.25	0.5	0.5
fish	0.1	500	0.0002

Table 3. Chemical parameters used in the model calculations.

	Solubility (ppb@25C)	Vapor Pressure (atm@25C)	Adsorbed Dissolved Partition Coeff. K_p	Degradation Rate (day^{-1})	Density (ton/m^3)
Naphthalene	22000	0.0001	1380	0.02	1.16
C_7 Phenol	8.2×10^7	0.0006	140	0.001	1.11

In the simple biological model used here it is assumed that typical spring concentrations of zooplankton and phytoplankton in the Haltenbanken area are on the order of 3.5 and 5 mg/l, respectively. To the extent that these values are on the high side, model output will be weighted towards increased uptake of pollutants in the food chain. The adsorption-dissolution coefficients for phytoplankton and zooplankton are both set equal to the partition coefficient K_p. Faunal organism weights have been estimated by assuming that dry weight is about 1/3 of wet weight, and that carbon content is about 40% of dry weight (Sakshaug et al., 1991).

MODEL RESULTS

PROVANN simulates 3-dimensional transport, dilution, and degradation of chemicals released into the water, from one or more simultaneous sources. The resulting time series of concentration fields is saved in a file, which then serves as input to a simulation of fish movement (swimming) and advective transport of fish eggs and larvae.

First Pair of Simulations

Figures 5a - 5d are snapshots of the evolution of the naphthalene concentrations in the produced water plume from the two platforms. Five days after the start of the simulation (Figure 5a), the two concentration fields remain separated and distinct from each other. After 12 days (Figure 5b), the plumes have joined together, such that the smaller release to the north is revealed simply as an area of higher concentration in the overall concentration field. At 36 days (Figure 5c), the plumes begin to separate again under the influence of a stable weather pattern, and remain nearly separate for the next 2 weeks (Figure 5d).

Note that the concentrations recorded are extremely low, the white areas in Figures 5a - 5d representing a concentration of 6×10^{-14}.

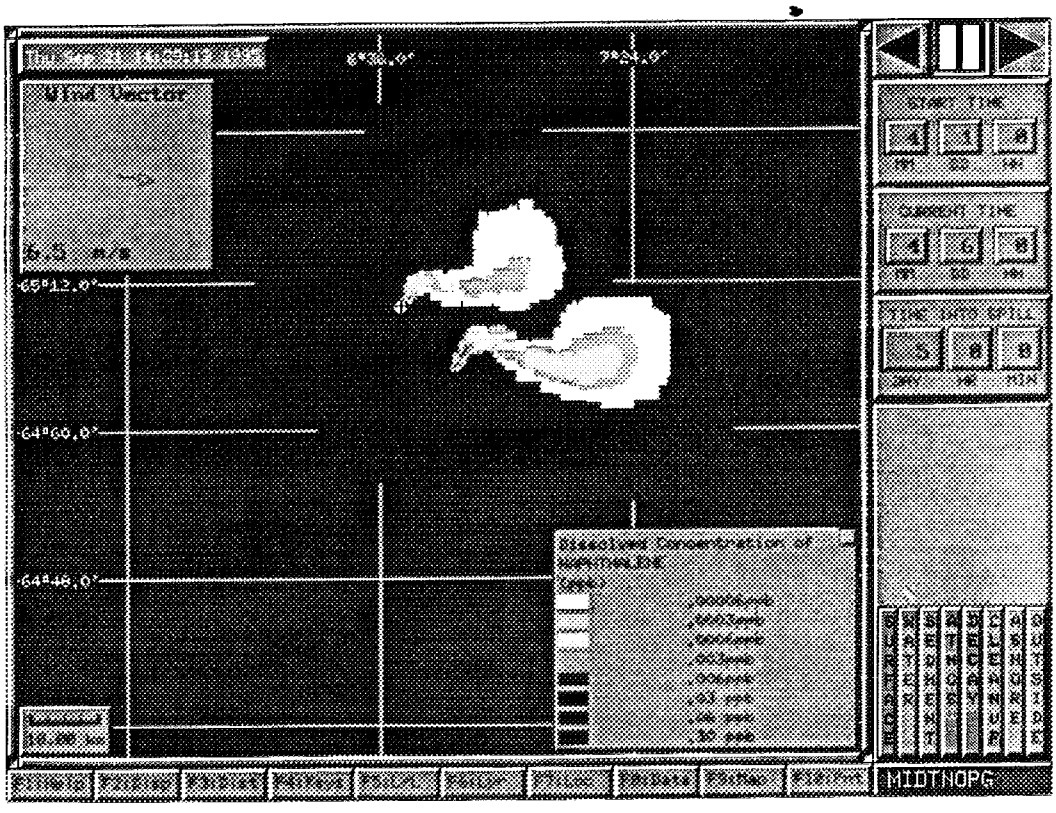


Figure 5a. Concentration field of naphthalene 5 days after beginning of the simulation.

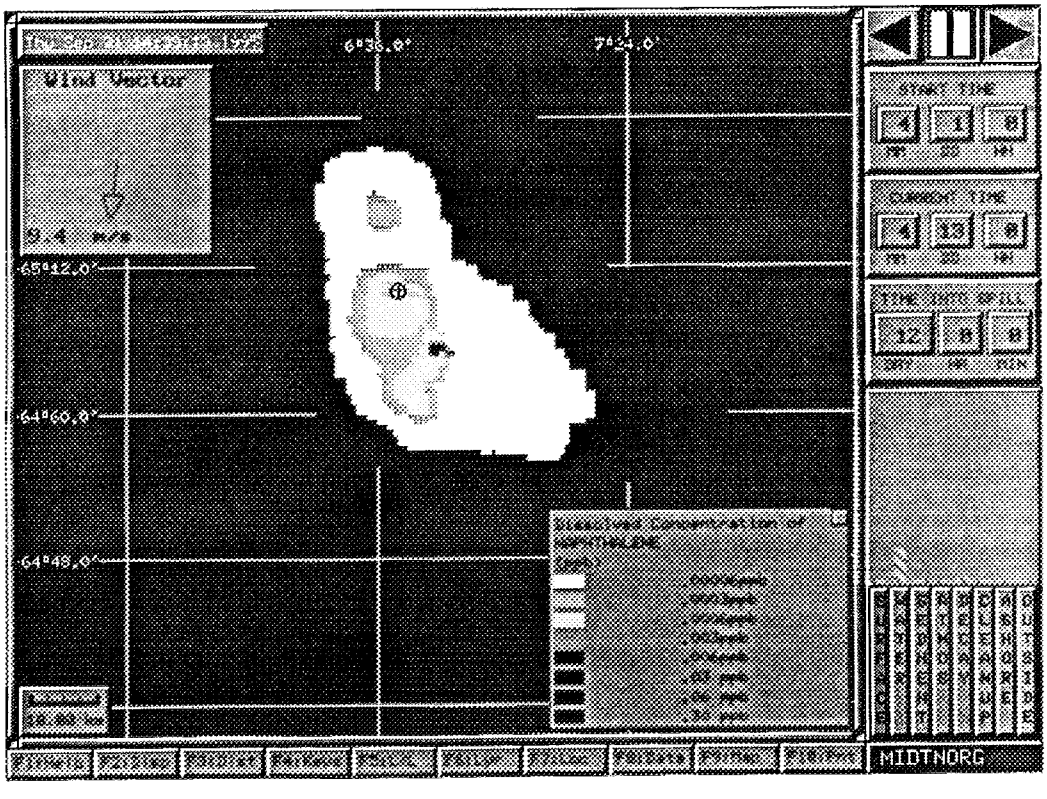


Figure 5b. Concentration field of naphthalene 12 days after beginning of the simulation.

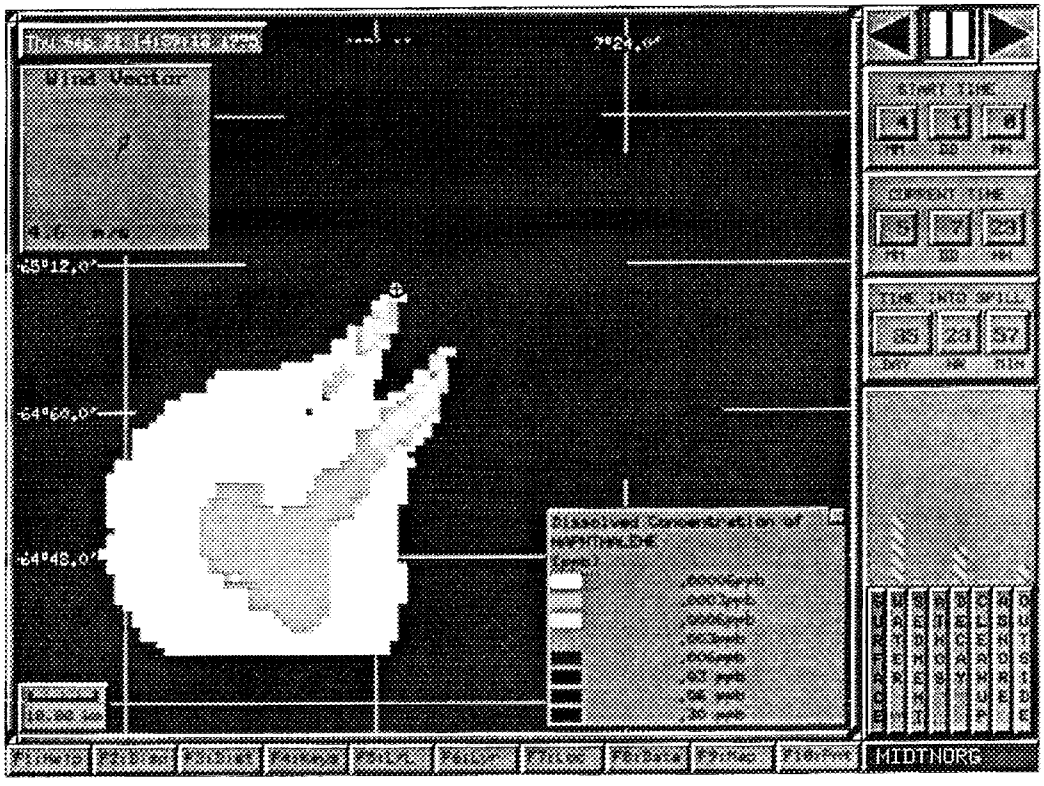


Figure 5c. Concentration field of naphthalene 36 days after beginning of the simulation.

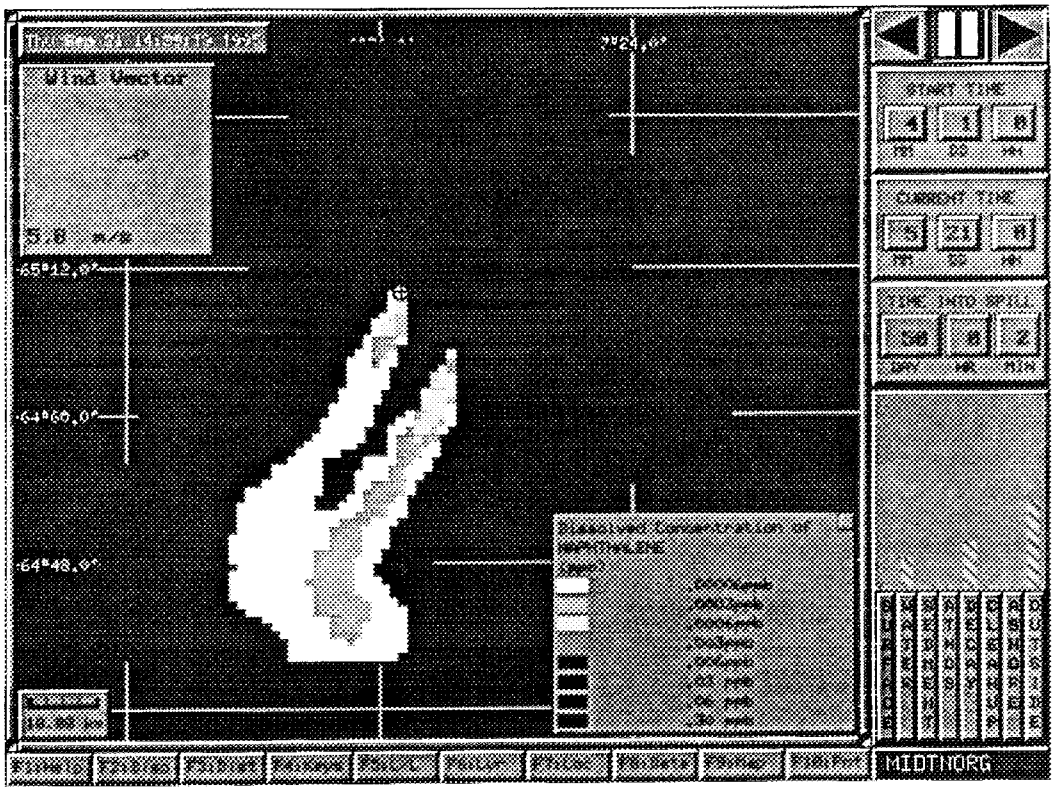


Figure 5d. Concentration field of naphthalene 50 days after beginning of the simulation.

The simulation of fish exposures is carried out within a three-dimensional Eulerian (spatially fixed) grid. Fish are represented by particles which move stochastically within defined speed ranges, depending on fish type. Demersal and pelagic fish swim in the lower and upper water column, respectively. The model checks at each time step whether each fish particle is within the release plume, which is itself resolved on a second expanding, translating three-dimensional grid, independent of the Eulerian grid. Thus each particle accumulates and depurates as the simulation proceeds, depending on its physical location relative to the plume.

The size of the Eulerian grid affects the absolute results of a simulation, in both the fraction of the simulated fish particles which encounter the plume, and the magnitude of exposures. If the fixed grid is very large relative to the size of the plume, relatively fewer fish particles will encounter the plume than if the fixed grid is small. In the extreme, one could create a very small fixed grid very near the source, such that all of the fish were exposed virtually all the time, simulating perhaps fish in a moored cage. Thus the fraction of the fish represented in the model which are exposed to the produced water plume is relative to the selected grid size; what fraction of the total population is exposed depends on the fraction enclosed by the grid.

The small magnitude of the released quantities in this first simulation resulted in very limited areas within which environmental effects occurred. Figure 6 shows time series of whole body concentration for fish encountering naphthalene in the produced water plume. Maximum bodyburdens are on the order of 6 ppb. The distribution of body burdens in the local population during the simulation is shown in Figure 7. The majority of fish remain unaffected, with a maximum of about 1% reflecting an increase in body burden over background at any one time. During the first 25 days of the simulation, when the plume is becoming established, the fraction of fish with non-zero (above background) body burdens increases. This fraction then begins to decrease as stronger winds result in more rapid dilution of the plumes.

Figure 8 depicts time series of C_7-phenol body burdens for selected pelagic fish. Although the release rate for phenol is about 4 times greater than that for naphthalene, maximum body burdens are similar as a result of a higher depuration rate (Table 1). However, Figure 9 shows that individual fish may achieve higher short term body burdens of phenol than naphthalene, since the high concentration core of the plume is larger.

Both C_7-phenol and naphthalene have relatively high solubilities and low adsorbed-dissolved partition coefficients (Table 3), as reflected in the uptake and depuration rates in the food chain (Table 1). As a result, the modelled body burdens discussed above for fish are primarily the result of direct absorbtion of chemical across gill tissues from the water, with only a small percentage coming through feeding.

Second Pair of Simulations

To observe the relative importance of degradation in PROVANN, we follow the advection of spring-spawning coastal herring eggs and larvae into the produced water plumes. Particles representing the ichthyoplankton are released at four spawning areas identified by Sætre and Bjørke (1988), as shown in Figure 4. Advection due to wind and background current carries the larvae northward, and some of them encounter the plume. The model then computes the time-integrated exposure in units of concentration-time, of all particles which enter the plume.

Figure 10a is a histogram of the distribution of exposures for the released particles during the simulation without degradation. About 33% of the released particles never enter the plume. Many particles which do enter the plume are captured within the gyre over Haltenbanken (Figure 4), and experience relatively high exposures.

When degradation is included in the computations (Figure 10b), almost twice the fraction of larvae escapes exposure entirely since the plume is significantly smaller, and those entrapped in the gyre receive much lower net exposures.

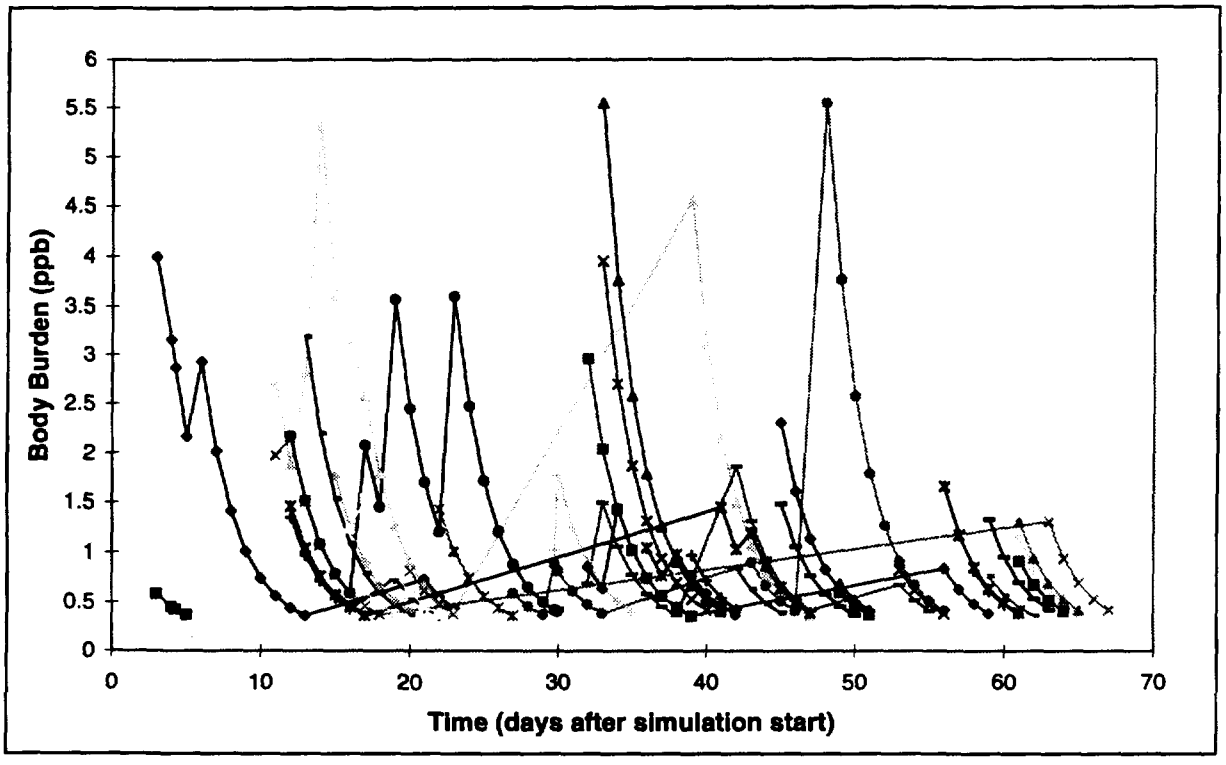


Figure 6. *Time history of body burdens (ppb) in selected fish during simulated release of naphthalene.*

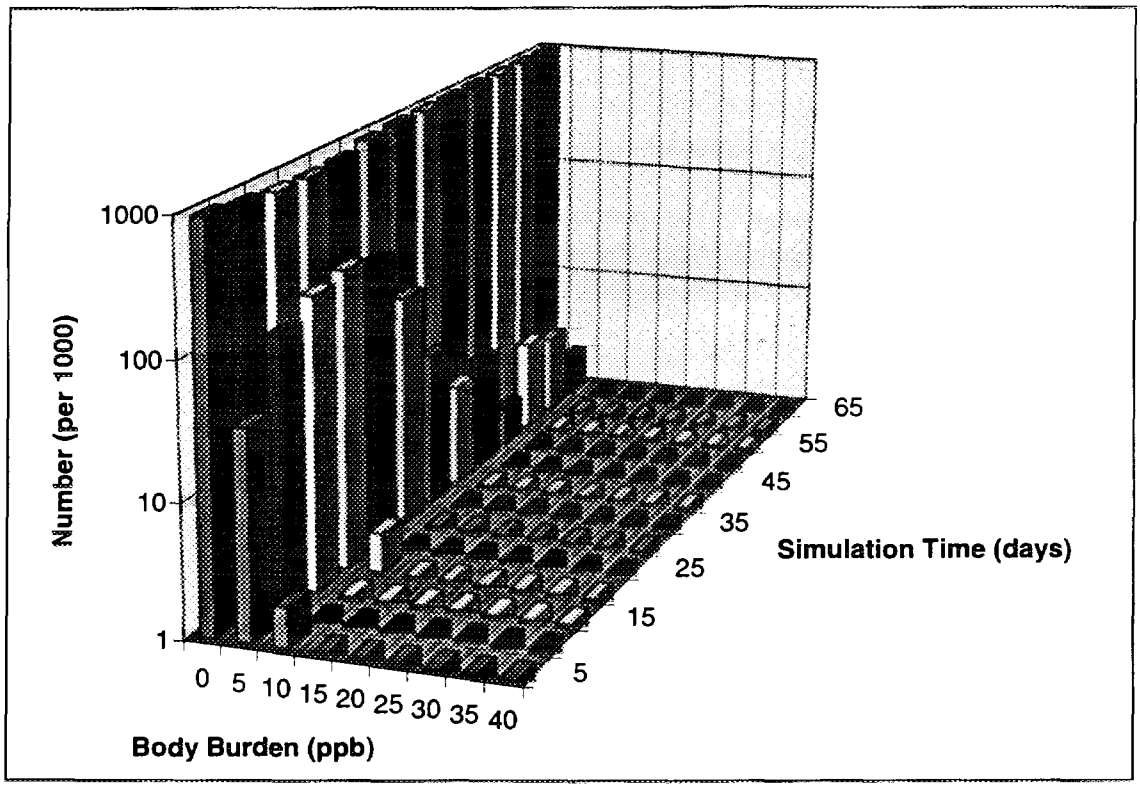


Figure 7. *Distribution of body burdens of naphthalene in small pelagic fish (assumed herring). Swimming speed 1 km/day.*

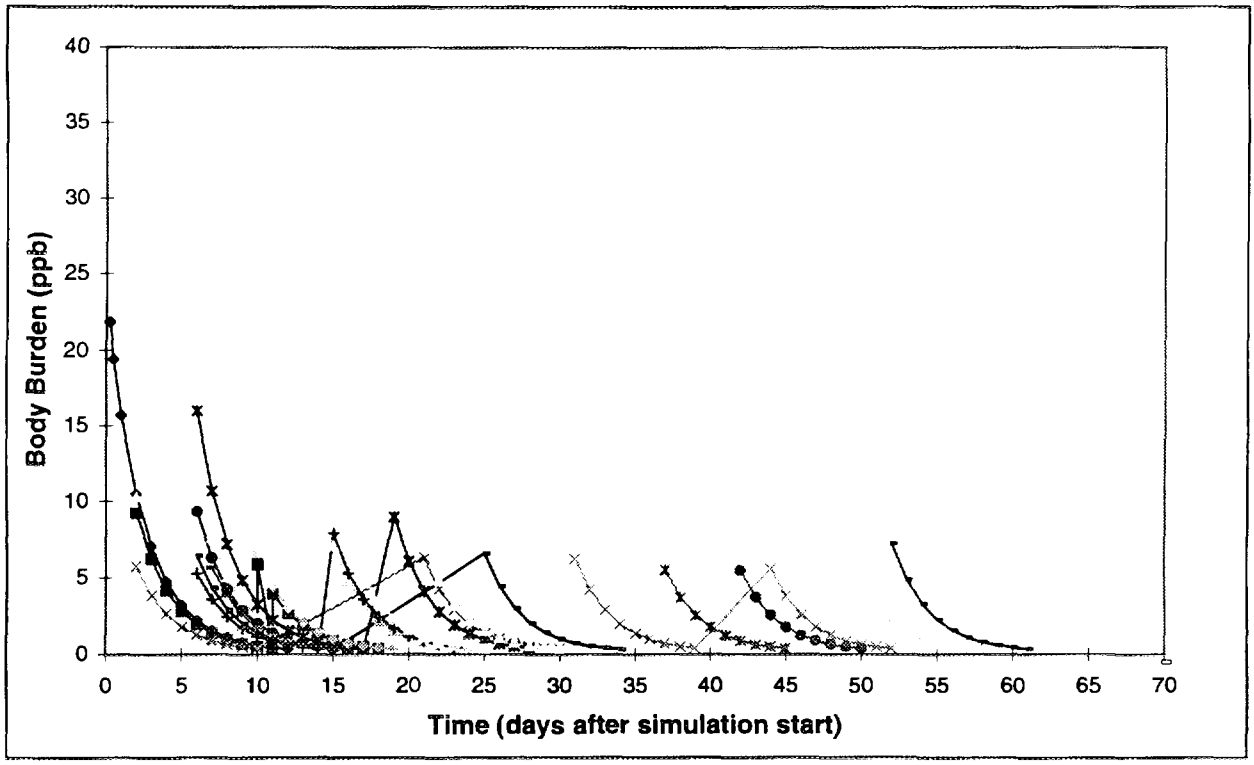


Figure 8. *Time history of body burdens (ppb) in selected fish during simulated release of C_7-phenol.*

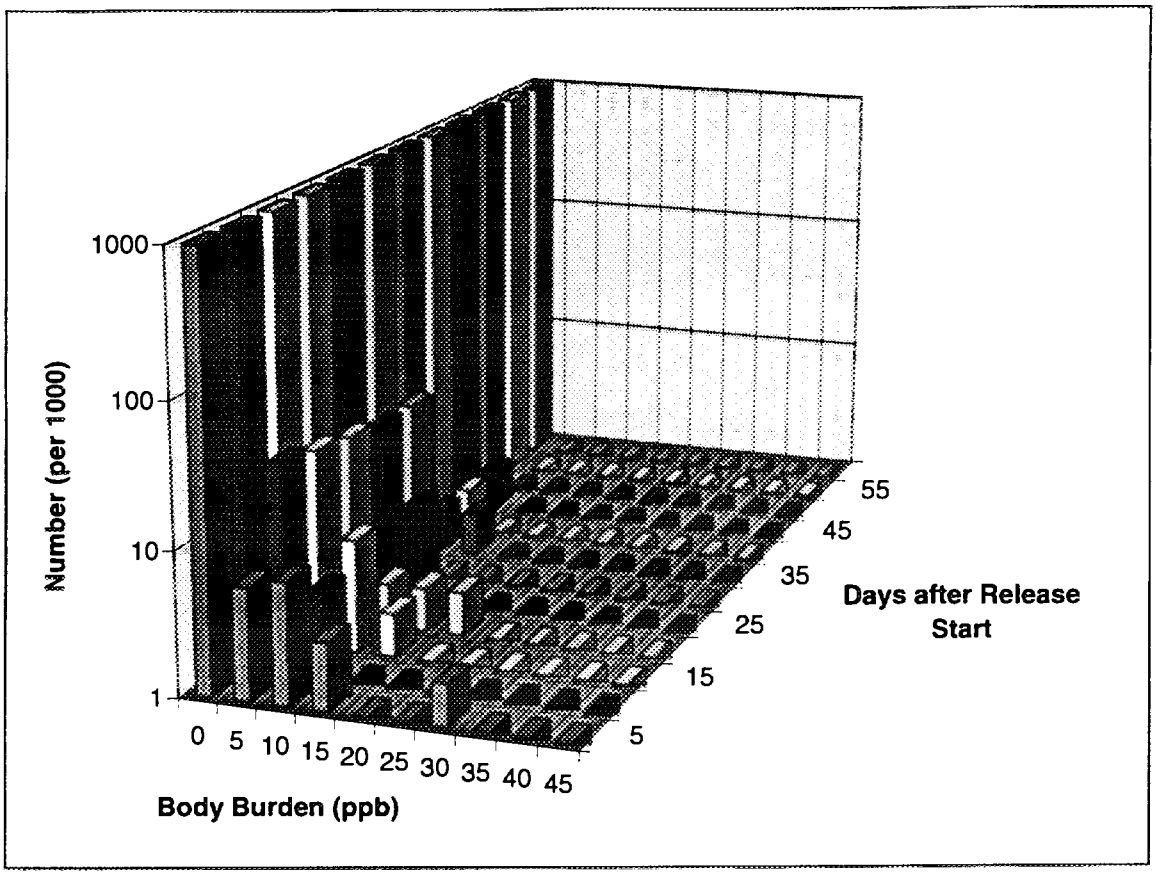
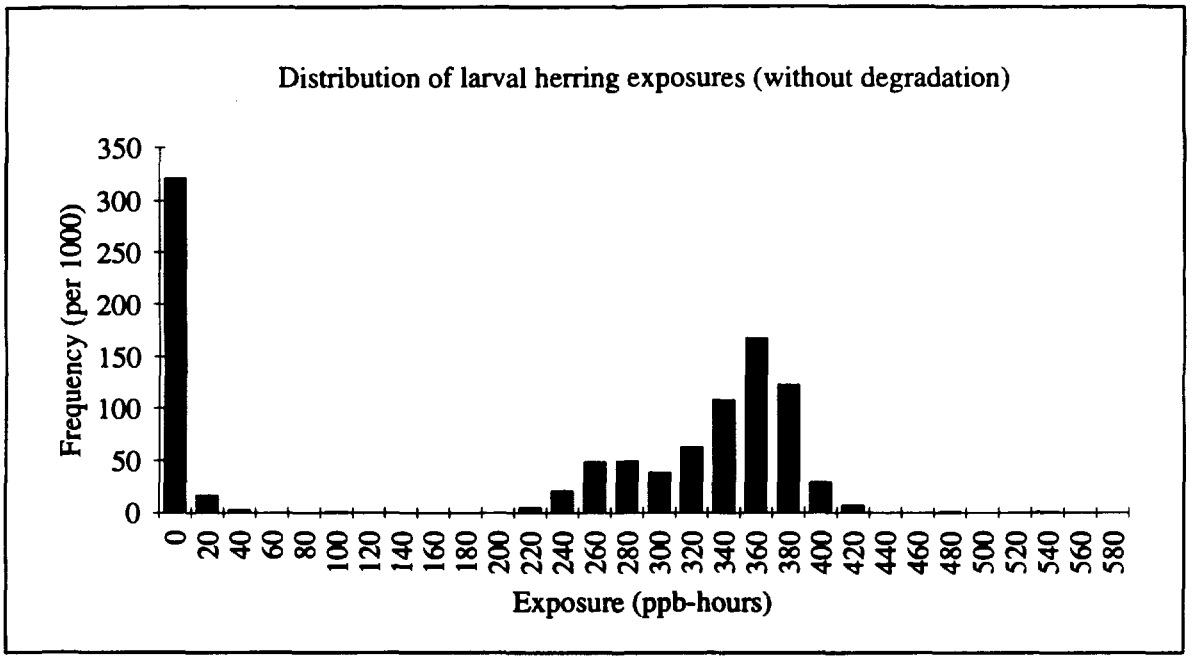
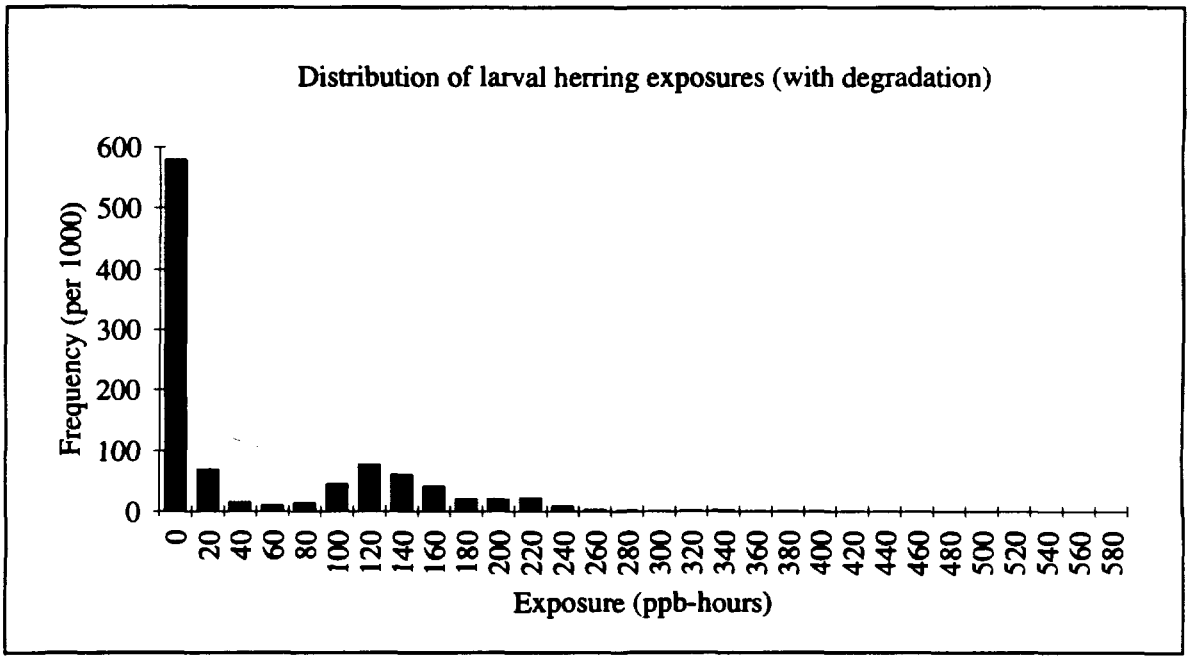


Figure 9. *Distribution of body burdens of C_7-phenol in small pelagic fish (assumed herring). Swimming speed 1 km/day.*



(10a)



(10b)

Figure 10. Exposure histograms computed for larval herring, released at spawning areas observed in 1986 (Sætre and Bjørke, 1988): (a) without degradation, and (b) with degradation included in the simulation.

SUMMARY AND CONCLUSIONS

The PROVANN system of models introduced here is designed to assess the potential for chronic effects from produced water. The preliminary focus is on potential bioaccumulation and biomagnification of produced water constituents in the marine food web. Other possible types of chronic effects, such as reduced fecundity, or pheromone response interference, can also be assessed with the model described here to the extent that such effects may be correlated with exposure. PROVANN simulates 3-dimensional transport, dilution, and degradation of chemicals released into the water, from one or more simultaneous sources. The resulting time series of concentration fields is saved in a file, which then serves as input to a simulation of fish movement (swimming) and fish egg and larval transport.

Two sets of simulations have been discussed, one using a time-dependent 3-dimensional hydrodynamic field computed by a numerical model, the second using a mean background current with a superimposed vertically averaged time-dependent wind-driven current. Although the two sets of simulations are not strictly comparable due to different release rates, it is clear that the full 3-dimensional field results in significantly more mixing than the simpler approximation. This is not surprising, in that vertical and horizontal shears are much weaker or lacking in the simpler case. Compensation through increased dispersion coefficients is a potential and usual remedy, but the correct scaling of these coefficients remains a problem (Rye et al, 1996).

The inclusion of degradation is clearly an important factor in modelling long term exposures. The same is probably true for other slow processes, such as evaporation from the water to the atmosphere, which are often neglected in assessment of acute impacts. Thus it is important to implement relatively comprehensive models for chronic assessment problems.

Simulations of adult fish, eggs, and larvae exposed to two individual components of produced water (C_7 phenol and naphthalene) from multiple sources on Haltenbanken suggest that bioaccumulation and biomagnification of these two substances will be small. There may be components which will have a greater tendency to biomagnify than those evaluated here. Furthermore, the biota are actually exposed to the mixture of chemicals which compose the produced water stream. The possible effects of multiple components therefore remain to be addressed.

Finally, it should be noted that only the physical fates component of PROVANN has in any sense been verified (Rye et al, 1996). No testing, calibration, or verification work has yet been performed on the preliminary biological components of the system.

REFERENCES

BRANDSMA, M.G ., L. DAVIS, R. AYERS, T. SAUER, 1980. A computer model to predict the short term fate of drilling discharges in the marine environment. Proceedings of Symposium on Environmental Fate and Effects of Drilling Fluids and Cuttings. January 21-24, 1980. Lake Buewna vista, Florida. 0.588-610.

BRANDSMA, M.G ., L. DAVIS, R. AYERS, T. SAUER, 1992. Modeling Offshore Discharges of Produced Water. In Produced Water, edited by J.P. Ray and F.R. Engelhart, Plenum Press, New York, USA.

KOH, R. C. AND Y. C. CHANG, 1973. Mathematical model for barged ocean disposal of waste. Report to Office of Research and Development, U. S. Environmental Protection Agency, Wash. DC. circa 400 p.

REED, M., D. FRENCH, H. RINES, AND H. RYE, 1995. A three dimensional oil and chemical spill model for environmental impact assessment. 1995 International Oil Spill Conference Proceedings, p. 61-66.

RYE, H., M. REED, A. MELBYE, S. JOHNSON, 1996. An intercomparison between field measurements and three different calculation models for estimates of dilution factors. In Reed, M. and S. Johnson (eds), 1996. Produced Water: Environmental and Mitigation Issues. Plenum Press, NY.

SAKSHAUG, E., A. BJØRGE, B. GULLIKSEN, H. LOENG, F. MEHLUM, 1992: Økosystem Barentshavet. ISBN 82-90565-17-8, Mesna-Trykk a.s., Lillehammer, Norway, 304 p.

STAPLES, C., K. DICKSON, J. RODGERS, F. SALEH, 1985: A model for predicting the influence of suspended sediments on the bioavailability of neutral organic chemicals in the water compartment. In R. Cardwell, R. Purdy and R. Bahner (eds), Aquatic Toxicology and Hazard Assessment: Seventh Symposium. ASTM Pub. 04-854000-16. p. 417-428.

SÆTRE, R. og BJØRKE, H., 1988: Oljevirksomhet på Norne. Konsekvenser for fiskeressursene. HELP Report no. 19, 1988. Marine Research Institute, Bergen. 87-7461-005-9.