MODELLING THE EFFECTS AND UNCERTAINTIES OF DIFFERENT SEDIMENT REMEDIATION SCENARIOS IN THE GRENLAND FJORDS, NORWAY.

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Introduction

The Grenland fjords (Fig. 1), situated in the south-eastern Norway, have some of the highest concentrations of polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in sediments of any fjord system in Norway. The main load of PCDD/Fs has come from a magnesium plant on Herøya in the Frierfjorden in the period 1951-2002. Since the 1960s dietary health advisories have been in place and since the 1980s commercialisation bans on all seafood caught within the Frierfjorden area, as well as health advisories on selected commercial species such as cod and crab in the outer fjord areas. Contaminated sediments currently constitute the only known significant source of PCDD/Fs causing concentrations in biota above the dietary limit value of 4 ng/kg wet weight (sum of PCDD/Fs in 2378-TCDD toxicity equivalents) recommended by EU. As part of the national initiative to remediate the most contaminated sites for marine sediments in Norway, the county administrations have been charged with developing remediation plans for their contaminated sites. In the following, we introduce an integrated multimedia modelling tool called SF-tool and then present some model application examples from simulations on the effects of planned contaminated sediment remediation alternatives on the future PCDD/F levels in cod and crab in the Grenland fjords. The Telemark County (enclosing the Grenland fjords) was the first in Norway to use the SF-tool as part of its evaluation of the effectiveness of large scale sediment capping. SF-tool has also been applied in the Sunndalsfjorden and Ranfjorden in the western and northern Norway.[1,2]

Materials and Methods

The modelling package SF-tool applied in our study consists of 1) a water-sediment fugacity model code for simulating the sources, sinks and transports of persistent organic pollutants (POPs) in a fjord, estuary or lake system, and 2) a bioaccumulation rate constant model code for simulating the intake and bioaccumulation of POPs in a food web. In addition, the SF-tool contains tools for uncertainty and sensitivity analysis of the model results. The models can be executed both in dynamic and steady state mode. The major advantages of the SF-tool include: 1) use of professional and efficient modelling platform (MATLAB; www.mathworks.com), 2) the possibility to easily analyze the models with powerful uncertainty and sensitivity analysis techniques, 3) the built-in flexibility allowing the user to easily change the model setup (e.g. compartment division) or to build a new (or transfer already existing) model application onto a new site. The biotic and abiotic model codes were based on features from several published models.[3, 4, 5, 6, 7]

For the Grenland fjords model application, the fjords were divided horizontally to five areas (Fig. 1) and vertically to 2-3 layers which resulted in totally 13 water compartments. As each water compartment is associated with a sediment compartment, defined by the corresponding water-sediment interface area, the total number of model compartments was 13+13 = 26. In addition, the atmosphere over the Grenland fjords, as well as the upper river Skienselva and open ocean at Skagerrak acted as a source or sink for the PCDD/Fs at the model boundaries. Data and values for the abiotic model parameters, background concentrations, emission time series, and water flow were mostly adopted from Persson et al.[3]

In order to transfer the simulated abiotic concentration time series to concentration levels in cod and crab we used the methodology and model results described in Saloranta et al.[5] They simulated the intake and bioaccumulation of PCDD/Fs in the Frierfjorden food web (consisting of 12 species or species groups) with a similar model code as contained in the SF-tool. This abiotic-to-biotic transformation is based on the linearity of the models which means that, e.g., a 20 % reduction in the water and sediment pore water levels of the dissolved phase will lead to a similar reduction in the simulated concentrations of all the organisms in the food web (taking into account the response time of the biotic system, of course). This method gives us a rather robust modelling strategy for the biotic system, in which we use the biotic model only to calculate the ultimate source (sediment pore water and/or water) of the PCDD/Fs for the target organisms, and to estimate the organisms' response times. In addition, we use observed concentrations in the target organisms on a given year as a starting point. After this we can use the simulated reductions of the dissolved PCDD/F levels in water and sediment pore water together with the source information and the estimated response times to derive corresponding reductions in the PCDD/F levels in the target organisms. In this way we can eliminate the propagation of the possible bias of the (truly dissolved) concentration levels from the abiotic model output into the biotic predictions.

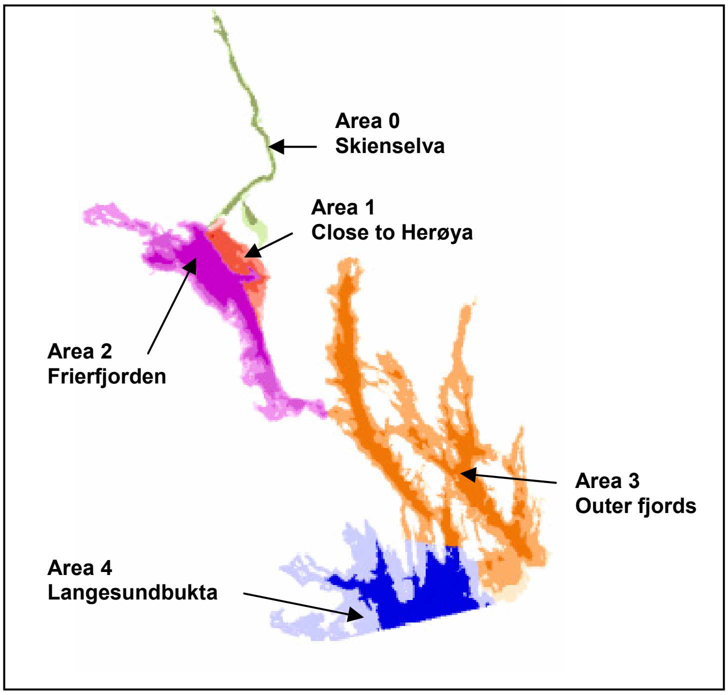

Figure 1. A bathymetric map showing the basis for horizontal compartment division in the model application for the Grenland fjords. The different colours show the horizontal division to five compartments, while the shading within a colour indicates the different bottom depth intervals used in the vertical compartment division.

Table 1. Sediment remediation scenarios in the SF-tool application for the Grenland fjords.

Scenario name	**Description of (incremental) sediment remediation area**	**Remediated area (% of total area of Frierfjorden and Skienselva)**
NoRem	None	0 km^2 (0 %)
R	River Skienselva (Area 0)	~3 km^2 (12 %)
R+Hs	+ Shallow areas (<25 m) close to Herøya (Area 1)	~5 km^2 (19 %)
R+Hs+Fs	+ Shallow areas (<25 m) in Frierfjorden (Area 2)	~11 km^2 (47 %)
R+Hs+Fs+Hd	+ Deep areas (>25 m) close to Herøya (Area 1)	~14 km^2 (57 %)
R+Hs+Fs+Hd+Fd	+ Deep areas (>25 m) in Frierfjorden (Area 2)	~24 km^2 (100 %)

As both cod and crab gain practically their entire PCDD/F load from the sediment (either directly or via food web), we used the simulated time series of sediment pore water between 0-50 m depth in the Frierfjorden (Areas 1 and 2 in Fig. 1) as the PCDD/F source for cod and crab.[5] The response time of the biotic system to changes in their abiotic forcing was set to 2 years for both cod and crab.[5] After *N* response times the system has covered

$(1\text{-}1/e^N)\cdot100\%$ of its way towards the new (quasi) steady state. Both abiotic and biotic model codes and model parameterization are described in more details in Saloranta et al.[8]

The abiotic model was run for 17 PCDD/F congeners for the period 1997-2051 with six remediation scenario alternatives (Table 1). The simulated remediation measures were assumed to take place in August 2006, and consisted of capping the contaminated sediment areas with clean masses (assumed otherwise having the same properties as the contaminated sediment). The assumed (minimum) thickness of the capped layer was the same as the active sediment layer depth (0.5-10 cm).

In order to produce simulation results for the remediation scenarios in terms of probability distributions, rather than single values, an uncertainty analysis of the abiotic model in the SedFlex-tool was carried out. In the uncertainty analysis, the model was run 2500 times with randomly chosen values for the selected 11 parameters sampled from their predefined probability density functions and a rank correlation matrix.[8] The values of the rest of the model parameters, not included in uncertainty analysis, were fixed to their nominal values. Before uncertainty analysis, a detailed sensitivity analysis (FAST technique) for 17 model parameters was done in order to screen the most important parameters for the uncertainty analysis.[9]

Results and Discussion

The sensitivity analysis of the abiotic model showed that when the output variable of interest was the difference in dissolved sediment pore water concentration levels between 2000-2015 and 2000-2050, then the model results were most sensitive for sediment burial and resuspension rates, as well as for the thickness of the active sediment layer and sediment water content.

Fig. 2 shows the results from the uncertainty analysis where the relative reductions in the dissolved sediment pore water concentrations since 2000 are transferred to concentration time series in cod (expressed in 2378-TCDD toxicity equivalent units) by assuming initial median whole body PCDD/F concentration for cod in Frierfjorden in 2000 of 20 ng/kg wet weight, according to observations.[10] We corrected the initial values for the model's initial steady-state assumption, added an additional uncertainty (i.e. standard error of the median) by a 95% confidence factor of 3 (in either direction) on the biotic initial conditions in 2000, and assumed that the co-variation in the abiotic and biotic initial concentrations in 2000 have a rank correlation of 0.95.

The model simulations (Fig. 2) show that a significant reduction in the concentration levels in cod (and crab; not shown) in Frierfjorden around year 2006 can first be seen when larger areas of the Frierfjorden are capped, and thus significant portions of the contaminated feeding and habitat sediment areas of cod and crab are cleaned up. The same type of conclusion applies also for the outer fjords remediation scenarios (not shown). Furthermore, capping of contaminated sediments in Frierfjorden will have no significant effect on the future evolution of the sediment PCDD/F concentrations (and hence on the concentrations in cod and crab) in outer fjords or in Langesundbukta (not shown). This is due to the slowness and ineffectiveness of the transport processes between the sediments of different fjord areas, especially between those separated by shallower sills. The uncertainty analysis reveals the propagation of model parameter uncertainties among others onto the predicted date when the fjord can be considered to be clean again. For example, in Frierfjorden the 5th percentile of the predicted concentration in cod in the "NoRem" scenario falls below the EU dietary limit value of 4 ng/kg wet weight in year 2006, while for the median and 95% percentile estimate not before year 2017 and 2039, respectively.

The simulation results from the uncertainty analysis were also used in a cost-effective analysis of the remediation measures. Effectiveness was defined as the time to biota concentration falling below the EU dietary limit value. The remediation cost model calculated total costs of remediation in each of the model compartments (with uncertainty estimates), differentiating unit costs of capping (and dredging) by contaminant concentration, depth and proximity to disturbance by shipping. This analysis indicates that further data collection is required to reduce parameter uncertainties especially in the abiotic and cost models, as well as in estimates of household benefits of lifting advisories, before large scale remediation efforts can be approved or rejected with requisite confidence. Consistent sensitivity analysis of all model components will allow county planners to determine for which parameters data collection has the greatest information value.

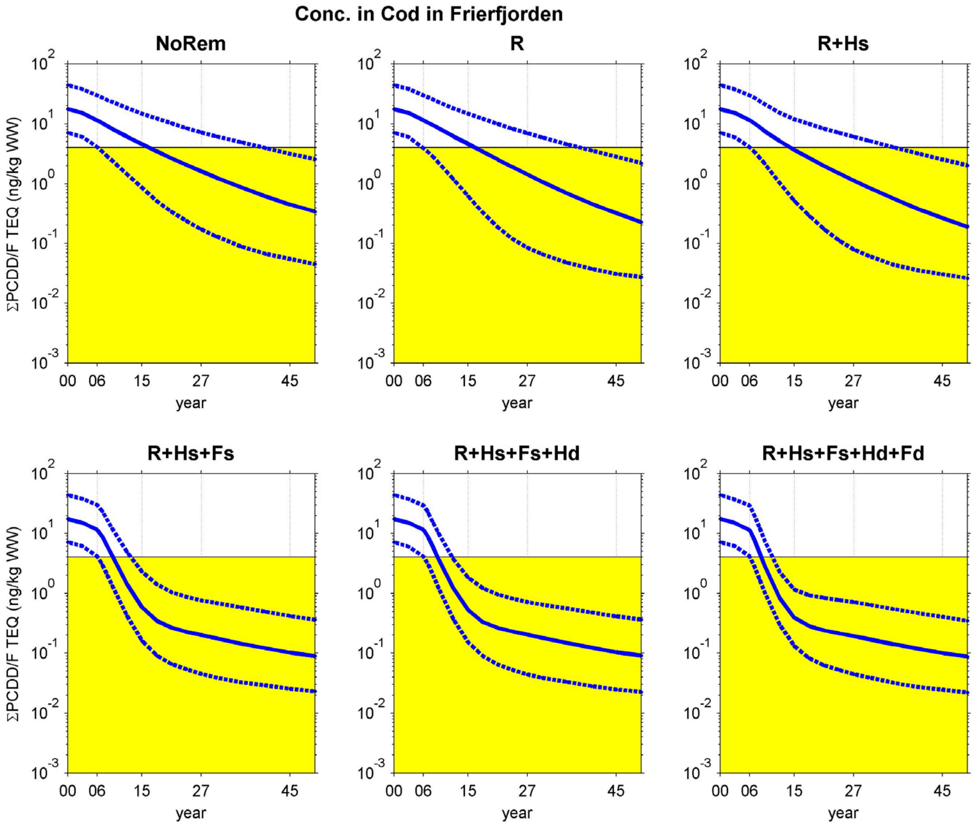

Figure 2. Time evolution of the sum of 17 PCDD/F congeners (concentrations expressed in 2378-TCDD toxicity equivalent units) in cod in the Frierfjorden under six different remediation scenarios (see Table 1). Thick solid lines denote the median, and dashed lines the 5th and 95th percentiles, based on the 2500 model runs executed in the uncertainty analysis. The yellow shaded area denotes concentrations below the EU dietary limit value of 4 ng/kg wet weight.

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