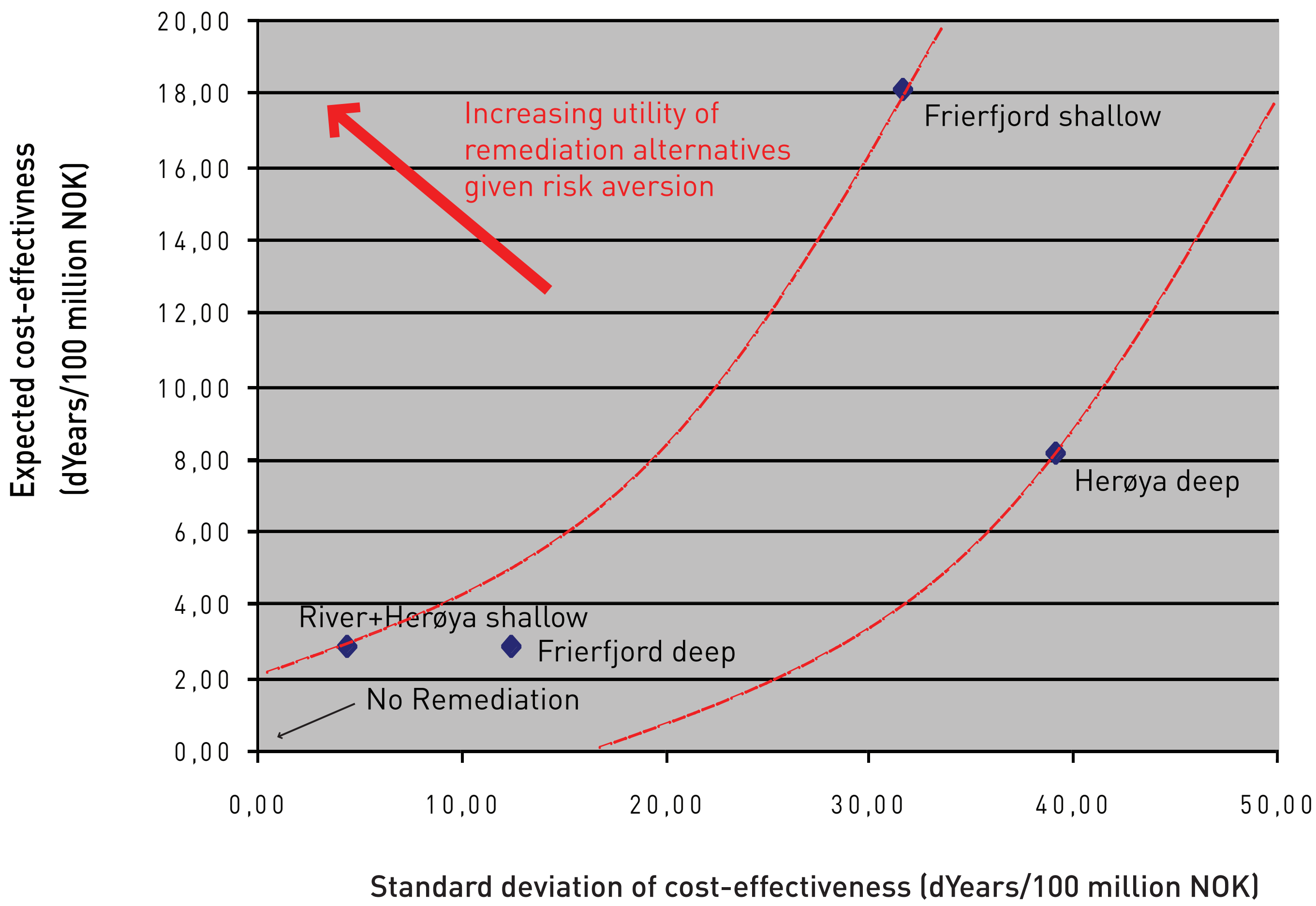
REPORT SNO. 5320-2008

SEDFLEX
- uncertainty analysis of remediation cost for contaminated sediments



Norwegian Institute for Water Research
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REPORT

Main Office	Regional Office, Sørlandet	Regional Office, Østlandet	Regional Office, Vestlandet	Akvaplan-NIVA A/S
Gaustadaléen 21 N-0349 Oslo, Norway Phone (47) 22 18 51 00 Telefax (47) 22 18 52 00 Internet: www.niva.no	Televeien 3 N-4879 Grimstad, Norway Phone (47) 22 18 51 00 Telefax (47) 37 04 45 13	Sandvikaveien 41 N-2312 Ottestad, Norway Phone (47) 22 18 51 00 Telefax (47) 62 57 66 53	P.O.Box 2026 N-5817 Bergen, Norway Phone (47) 22 18 51 00 Telefax (47) 55 23 24 95	N-9005 Tromsø, Norway Phone (47) 77 68 52 80 Telefax (47) 77 68 05 09

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Abstract

This report is one of the technical outputs of the SedFlex project – A flexible, integrated tool for management of contaminated sediments. The report illustrates an approach to combining uncertainty analysis of remediation effects from a dynamic contaminant fate model (SF-tool), with uncertainty analysis of contaminated sediment remediation costs. Various types of cost-effectiveness and cost-risk analysis are illustrated using data from the Grenland fjords, Telemark County, Norway. The analysis of measures are amongst others relevant for the Norwegian EPA (SFT) risk analysis methodology, and economic analysis in coastal water bodies under the EU Water Framework Directive.

4 keywords, Norwegian	4 keywords, English
1. forurensede marine sedimenter	1. contaminated marine sediments
2. Vanndirektivet	2. Water Framework Directive
3. kostnadseffektivitets-analyse	3. cost-effectiveness analysis
4. risiko-analyse	4. Risk analysis

Kristoffer Næs	*Merete Ulstein*	*Jarle Nygard*
Project manager	Research manager	Strategy Director

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SedFlex

Uncertainty analysis of remediation cost for contaminated marine sediments

An application to the Grenland fjords,

Telemark, Norway

Preface

This report is one of the technical outputs of the SedFlex project – A flexible, integrated tool for management of contaminated sediments.

The report would not have been possible without the simulations conducted using the SF-tool and numerous discussions with SedFlex project colleague Tuomo Saloranta. Many thanks also to Espen Eek and Audun Hauge at the Norwegian Geotechnical Institute (NGI) for assistance with grasping technical aspects of remediation measures, and for their expert judgement in determining remediation costs where there was no previous historical data.

The SedFlex project was financed by the Norwegian Research Council.

Oslo, April 2008

David N. Barton

Contents

Summary

This report illustrates an approach to combining uncertainty analysis of remediation effects from the Sedflex SF tool with uncertainty analysis of remediation costs. Data from SF tool simulations are combined with historical cost data from previous remediation actions in Norway to evaluate uncerainty in the cost-effectiveness of large-scale remediation measures (
Figure 1). The report illustrates how this integration can be used in risk management of large scale sediment remediation measures. Previous studies of sediment remediation costing in Norway (DNV 2000) have not conducted simulation-based uncertainty analysis, nor evaluated the uncertainty of remediation costs against uncertainty of remediation effects.

The approach was tested in the Grenland fjords, Telemark County, Norway. The Grenland fjords have some of the highest concentrations of dioxins, i.e. polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in sediments of any fjord system in Norway. Since the mid 1980s dietary health advisories and commercialisation bans have been in place on all seafood caught within the Frierfjord 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 'active' source of dioxin causing concentrations in biota above the toxicity equivalent limit value recommended for dietary health advisories in seafood. As part of a national initiative to remediate the most contaminated sites for marine sediments in Norway,

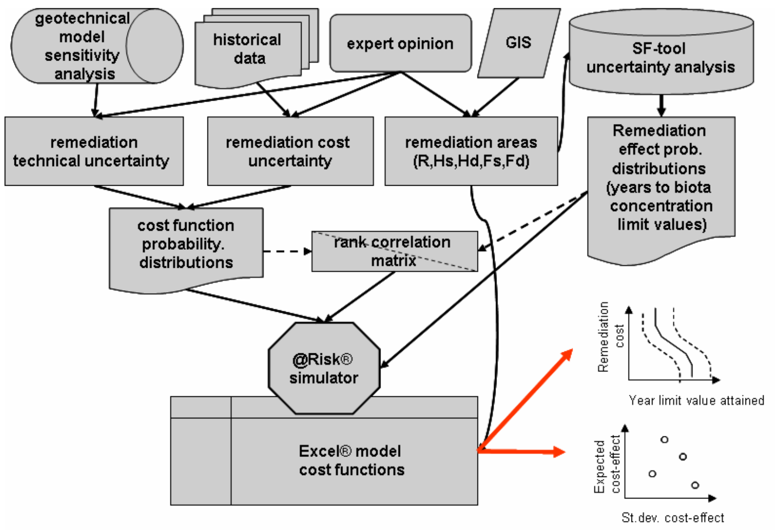


Figure 1. *Structure of data input and modelling of remediation measures' cost-effectiveness*

Table 1. Sediment remediation scenarios used by the SedFlex model

Scenario name	**Description of incremental remediation area by scenario**	**Sediment compartments**	**Remediation methods**	**Remediated area (% of Frierfjord)**
NoRem		none	none/monitoring	
R	Skien River (Area 0)	SS0, IS0	dredging&disposal	~3 km^2 (12 %)
R+Hs	Herøya shallow (Area 1)	above + SS1,IS1	+ ord. capping	~5 km^2 (19 %)
R+Hs+Fs	Frierfjord shallow (Area 2)	above + SS2,IS2	+ thin capping	~11 km^2 (47 %)
R+Hs+Fs+Hd	Herøya deep (Area 1)	above + DS1	as above	~14 km^2 (57 %)
R+Hs+Fs+Hd+Fd	Frierfjord deep (Area 2)	above + DS2	as above	~24 km^2 (100 %)

Note: see ***Figure 5*** for definitions of remediation areas evaluated

Telemark county administrations have been charged with developing remediation plans for their contaminated sites. The remediation scenarios evaluated in this report are listed in **Table 1.** They consisted of capping the contaminated sediment areas with clean sediment mass as well as dredging in active shipping areas. Both types of remediation were designed so as to be 100% effective with regard to stopping contaminant flux to the environment. Telemark County was the first in Norway to use the SedFlex risk analysis toolbox as part of its evaluation of the effectiveness of large scale sediment remediation.

Summary output from joint simulations in the Sedflex risk analysis toolbox may take the form illustrated in the **Figure 2** below. Monte Carlo simulations in the SF tool and the remediation cost model produce probability density distributions for effect ("years to threshold value") and cost ("remediation cost"), respectively, from which confidence levels can be determined (for example 5%, 50%, 95% confidence).

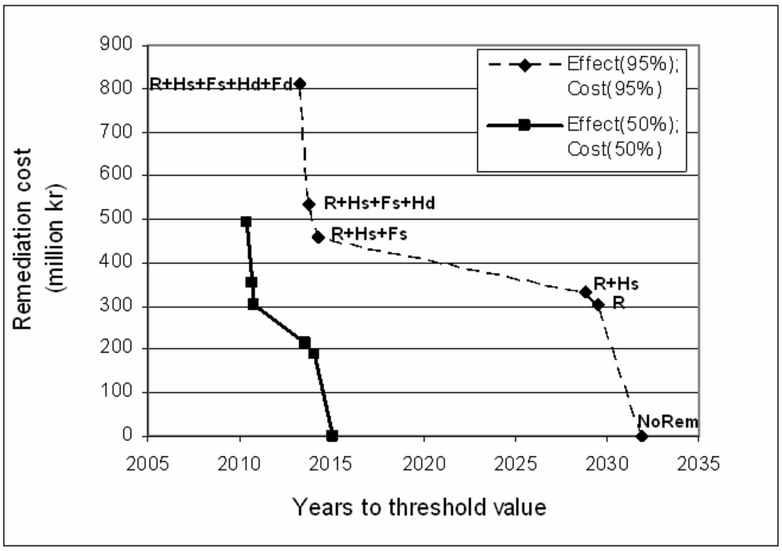


Figure 2. *Cost-effectiveness of remediation measures in Frierfjorden on dioxins in crab*
Note: Line segments between data points reflect incremental remediation of boxes in SF tool (Hs-Herøya shallow, Fs-Frierfjorden shallow, Hd-Herøya deep, Fd-Frierfjorden deep, respectively reading from cost=0 (NoRemediation) upwards).

In **Figure 2**, the 95% and 50% confidence levels for cost and effect are shown for the six different remediation scenarios, from no remediation (NoRem) to full remediation of all areas modeled by Sedflex within the Frierfjord (R+Hs+Fs+Hd+Fd). This type of aggregated information can be used to determine where measures are most cost-effective (flatter parts of the curve), and to compare with estimates of the economic benefits of remediation.

The uncertainty analysis output from SF tool and the remediation cost model can be presented in other ways which can further assist decision-makers in risk management. Risk control methods often use so-called "expected value – variance curves" to evaluate trade-offs between remediation measure *effect* and *probability* of that effect (Ayyub 2003). One definition of risk is precisely the product of *probability x effect.* **Figure 3** illustrates an application of such risk control approach to sediment remediation using the combined uncertainty analysis output from SF-tool and the remediation cost model. The figure shows on the vertical axis the *expected or mean* cost-effect of each remediation area. On the horisontal axis is the standard deviation of cost-effectiveness of each remediation alternative, which is an expression of the uncertainty.

In **Figure 3** fjord areas R+Hs and Fd are low cost-effectiveness - low uncertainty remediation areas, whereas Fs and Hd are high cost-effectiveness - high uncertainty options. Risk averse managers will prefer options as close to the upper left hand corner of **Figure 3** as possible (high return - low uncertainty). Dotted lines in the figure are an example of so-called indifference curves. An indifference curve indicates all the remediation options where a decision-maker is indifferent to combinations of or trade-offs between the expected cost-effectiveness (CE) and the standard deviation of CE. For a risk averse manager remediation in Fs is a better option than Hd (lower standard deviation of cost effectiveness). But depending on *the level of* risk aversion of a manager, remediation in R+Hs, and even Fd, may be preferred to Fs. Very risk averse managers may be willing to trade large reductions in expected cost-effectiveness against large reductions in uncertainty of cost-effectiveness. I.e. "I'd rather do something with small stakes that I'm more certain about, than something with big stakes which I am more uncertain about". Such managers may be inclined to conduct remediation in e.g. R+Hs, before Fs. This is also the case if such an abatement alternative also implies smaller absolute budget commitments (i.e. if the uncertainty of financing of the abatement measure is correlated to the size of the measure).

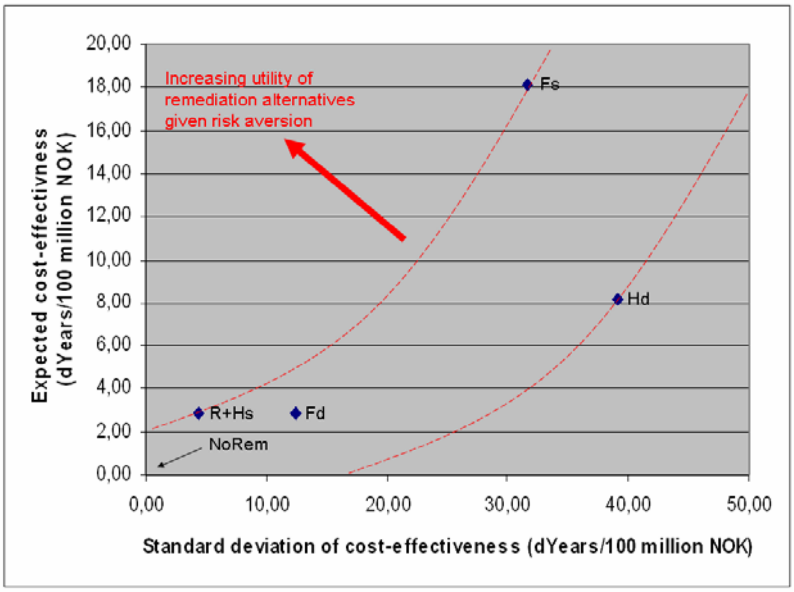


Figure 3 *Risk control trade-offs in the expected value – standard deviation approach to cost- effectiveness analysis of remediation measures.*

Note:" dYears" refers to the reduced time to achieving contaminant limit values of the different remediation scenarios (R, Hs, Hd, Fs, Fd) relative to the baselin or natural recovery scenario (NoRem). NOK refers to thepresent value of remediation cost in Norwegian kroner.

Given the large expected cost-effectiveness of Fs, a solution to the management dilemma between R+Hs (small cost-effect, small uncertainty) and Fs (large cost-effect, large uncertainty) would be to carry out pilot measures that reduced uncertainty about thin capping remediation costs and effects in the Frierfjord shallow alternative (Fs).

Uncertainty analysis can be updated as new information is made available. This was also the case in the Sedflex project. We have included documentation of the first phase of uncertainty analysis in appendix. The second phase presented in the main body of this report represents the state of knowledge uncertainty after quality controlling input data and results with remediation expertise (NGI) per 2005. The great advantage of the SEDFLEX fjord model and remediation cost modelling package is that cost-effectiveness analyses can be continually updated as new monitoring and remediation data become available. The "expected values –variance " framework can then be an active and practical tool in prioritising remediation alternatives under uncertainty.

Finally, this cost-risk analysis is very well suited as input to full benefit-cost analysis of remediation measures where remediation effect or risk is also given a monetary value. This is another aspect of the Sedflex project which is reported elsewhere (FMT 2006).

1. Introduction

This report reviews current (as of 2005) knowledge about remediation costs of contaminated marine sediments in Norway and applies / transfers these historical data, together with expert knowledge, to the Grenlandsfjord case. Table 1A in Appendix gives an overview of the historical data available. The combination of historical cost data and expert knowledge is used to define cost probability distributions. The uncertainty analysis of costs is coupled to the uncertainty analysis conducted using the SF tool (Saloranta, Armitage et al. 2006). The remediation cost model (***Figure 4***) calculates total costs of remediation in each of the abiotic model boxes, differentiating unit costs of dredging and capping by contaminant concentration, depth and proximity to disturbance by shipping.

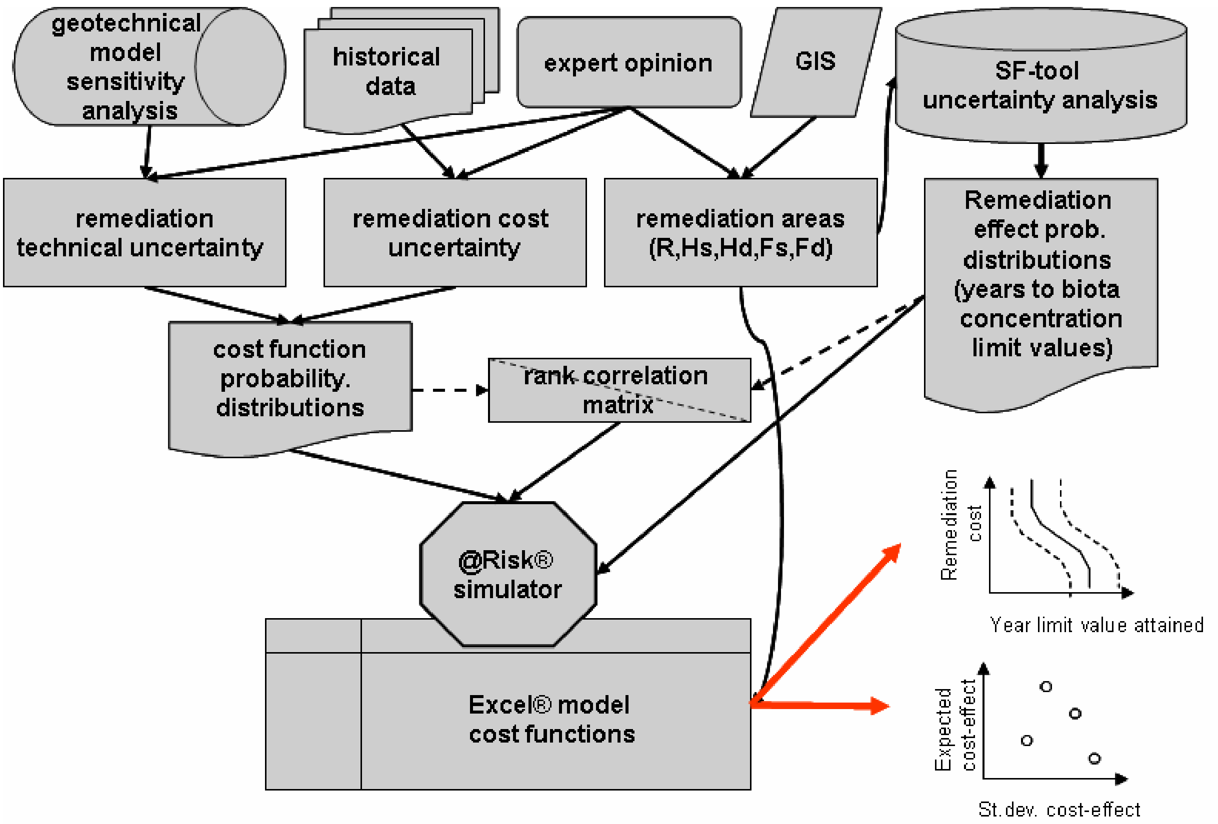


Figure 4. *Structure of data input and modelling of remediation measures' cost-effectiveness*

Similarly to the SF-tool, probability density functions are specified for all uncertain parameters in the remediation cost model using published sources and expert opinion (more detail on this ahead). These are then used to run Monte Carlo simulations of the joint distribution of total remediation costs. The Monte Carlo simulation are carried out using @Risk® software coupled to an Excel® spreadsheet model of remediation costs.

SedNet (www.sednet.org) identifies three levels in selection of treatment chains:

1. identification of possible treatment chains (not site specific)
2. selection of technically feasible treatment chains, based on performance of techniques for type of sediment, level and type of contaminant, and commercial requirements of the remediation measure[1] (site specific)
3. selection of preferred treatment chain(s) based on economic, environmental and social criteria (site specific)

The remediation cost analysis carried out here fits into the second tier in the SedNet approach, a the level of a feasibility analysis. This is mainly given the nature of the data available on remediation costs. The uncertainty analysis method outlined in ***Figure 4*** is however general and can be done at any level.

Relating this characterisation to the Norwegian EPA (SFT) methodology for 3-tiered risk assesment (Breedveld, Bakke et al. 2005), we can summarise the type of decisions and cost data needed at successive levels of analysis (**Table 2**).

Table 2. *Relationship between risk analysis guidance and cost data*

SFT Risk analysis level	Type of decision	Cost data required	Data type	Data source
Level 1. Potential risks and costs	Total budget allocation across sites	Average total project cost per m3 or m2	secondary	DNV(2000), SEDNET, Total cost estimations from Norwegian pilot studies
Level 2. Relevant on-site risk and costs	Pre-feasibility; Total budget allocation on-site	Average unit costs for individual components of treatment chain	secondary	Detailed data Norwegian pilot studies
Level 3. Real risk and projected costs	Feasibility; Cost-effectiveness ranking of measures	Incremental unit costs for individual components of treatment chain	Primary, on-site	On-site feasibility study by entrepreneur

Previous studies of remediation costing Norway (DNV 2000) were aimed at a Level 1 analysis across multiple contaminated sites. The evaluation of cost uncertainty in this report is equivalent to a level 2 type analysis, given that we have no site-specific cost data available. However, the approach to uncertainty analysis is generic and can be applied at any level. It is the the decision context, and even more importantly, the data available (secondary or primary) and which determine the relevant risk analysis level. The analysis of measures performed here is also of relevance for economic analysis of programme of measures in coastal areas under the Water Framework Directive(WFD), and particularly for disproportionate cost analysis under art.4 (WFD).

The treatment chains (scenarios) evaluated in this report have not been selected based on a full assessment of technical feasibility. Particularly, no detailed geotechnical information on local variation in sediment type, contamination level, and bottom topography was available from the Grenland fjords for this study. Because this information is needed for local differentiation of measures

[1] E.g. use of contaminated materials in land-fills, land harvesting etc.

in sediment (e.g. varying cap thickness, dredging depth) optimisation of each measure within the fjord area is not considered here, and costs are probably over-estimated on purely technical grounds[2]. In terms of the uncertainty regarding remediation cost data the analysis is probably similar to those used in pre-feasibility budgetting by contractors, prior to a detailed feasibility study and design of the chosen treatment chain for a specific site.

Previous remediation projects in Norway have mainly evaluated sub-aquatic disposal due to fjord characteristics of the Norwegian coastline and large distances to off-site treatment facilities. Remediation chains similar to those tested in these projects (see appendix 1) are evaluated here.

[2] On the other hand unforeseen site-specific costs often lead pre-feasibility costing exercises to under-budget

2. Remediation scenarios

The Grenland fjords have some of the highest concentrations of dioxins, i.e. polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in sediments of any fjord system in Norway. Dioxins originate from a magnesium plant on Herøya, in the Frierfjord in the period 1951-2002 (Area 1 and 2, ***Figure 5***) (Næs, Persson et al. 2004). Since the 1960s dietary health advisories have been in place and since the 1980s commercialisation bans on all seafood caught within the Frierfjord area, as well as health advisories on selected commercial species such as cod and crab in the outer fjord areas (area 3 and 4) (Økland 2005).

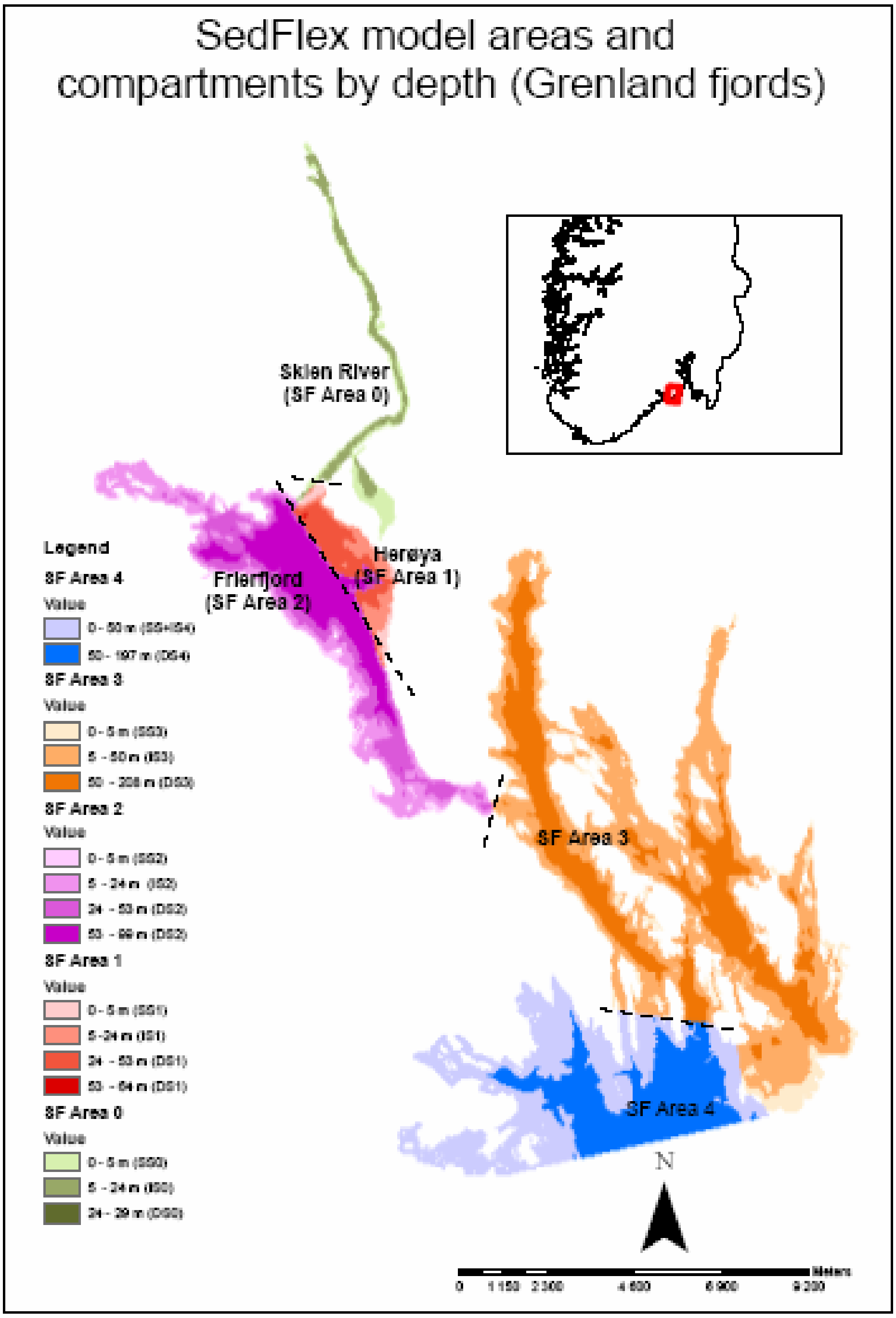


Figure 5. *Area definitions in the SF model*

Contaminated sediments currently constitute the only 'active' source of dioxin causing concentrations in biota above the toxicity equivalent limit value of 4 ng /kg wet weight recommended for dietary health advisories in seafood (VKM 2004). As part of a national initiative to remediate the most contaminated sites for marine sediments in Norway (St.meld.nr.12 2001-2002), county administrations have been charged with developing remediation plans for their contaminated sites. Telemark County was the first in Norway to use the SedFlex risk analysis toolbox as part of its evaluation of the effectiveness of large scale sediment *in situ* capping. The SedFlex toolbox includes the SedFlex abiotic and biotic contaminant fate models (hereafter called the "SF tool"), remediation cost model, cost-effectiveness and cost-benefit analysis.

The uncertainty analysis of costs is to a large degree given by the resolution of the remediation scenarios simulated in SF tool. The abiotic model in SF tool was run for the 17 PCDD/F congeners for the period 1997-2051 with six remediation scenario alternatives (Saloranta, Armitage et al. 2006). The simulated remediation measures were assumed to reach full effect in August 2006, and consisted of capping the contaminated sediment areas with clean sediment mass. The assumed (minimum) thickness of the capped layer was the same as the active sediment layer depth. In calculating remediation costs, dredging was also assumed in active shipping areas near Herøya, designed such that the measure was 100% effective for contaminant flux.

Table 3 outlines the boxes used in SF tool to simulate remediation measures. Boxes in Areas 0-2 (see ***Figure 5***) in the SF tool where successively remediated by setting sediment concentrations to 0 in the year 2006. These scenarios are illustrated in ***Figure 6***. In addition, we have made some additional assumptions on which of the boxes would need to be dredged and capped, as well as proposing some sites for disposal of dredged material (***Figure 6***, last two maps).

2.1 Assumptions remediation costs

Total cost data from 11 Norwegian sediment remediation projects per 2004 were collected and evaluated to find variation in fixed costs and variable costs (Laugesen, Møskeland et al. 2001; Myhre 2002; Brånås 2003; Eek 2003; Forsvarsbygg 2003; Hydro 2003; NCC 2003; Soldal 2004; Evenset, Larsen et al. 2005; Fylkesmannen_Vest-Agder 2005; Hauge 2005; Hauge and Skei 2005). Fixed costs do not vary with the area of the remedial measure, while variable costs do. Variable costs where found by calculating the m2 or m3 average unit cost from each remediation site. Average unit costs from each site where then used to construct simple cost distributions for each type of remedial measure. The cost distributions for any one category of remediation measure are generally valid for 'pre-feasibility' level costing, i.e. prior to any on-site geotechnical studies and detailed design of measures.

In the following justification is provided for the uncertainty distributions used for remediation costs. Although in many cases, there is insufficient empirical data for large sample probability distirbutions we illustrate how probabilistic information about remediation costs can be specified. This is the same approach to the handling of 'technical uncertainty' as in the SF tool. This also illustrates how a remediation database could be used in future as more cases become available.

This uncertainty analysis approach diverges somewhat from the standard approach to accounting for cost uncertainty, where all costs are multiplied by a contingency factor (DNV 2000). In sediment remediation projects this factor has usually been 20% of total costs (pers.com. A. Hauge, NGI). One of the aims of the uncertainty analysis is to evaluate whether such standard factors over or under estimate technical uncertainty for which we have information.

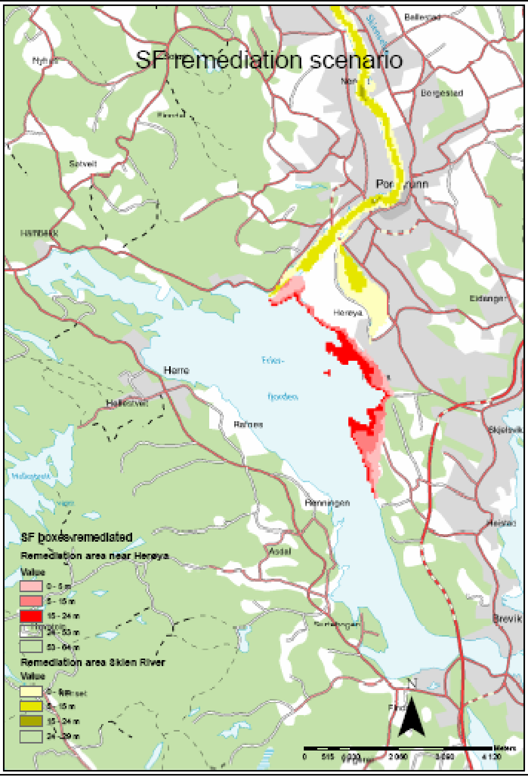
Table 3. Summary of remediation measure scenarios to be evaluated in SF tool

Remediation areas	Method/comment	Depth(m)	SF model map area	SF boxes	% of SF boxes	% effective-ness	Area (m2)	Area (%)
0. Natural recovery	Grenlandsfjords		Areas 0-4	all			88 481 000	
	Frierfjord	all	Areas 0-2	SS0,IS0,DS0, SS1,IS1,DS1, SS2,IS2,DS2	100 %		24 133 764	100 %
1. Skien River (R)	Dredging and capping (mechanical/hydraulic)	0-24	Area 0 (Porsgrunn)	SS0+IS0	23 %	100 %	665 000	3 %
	Dredging and capping (mechanical/hydraulic)	0-24	Area 0 (to Skien locks)	SS0+IS0	93 %	100 %	2 045 193	8 %
Gunnekleiv (R)	Capping ordinary	0-10	Area 0 (Gunnekleiv)	SS0	28 %	100 %	799 930	3 %
2. Heroya Shallow (Hs)	Dredging and capping (mechanical/hydraulic)	0-15	Area 1 (Herøya	SS1+ IS1(<15m)	10 %	100 %	160 778	1 %
	Capping (ordinary)	0-15	Area 1 (outside docks	SS1+ IS1(<15m)	52 %	100 %	857 000	4 %
	Capping ordinary	15-24	Area 1	IS1	38 %	100 %	635 272	3 %
3. Heroya Deep (Hd)	Capping thin	24-62	Area 1	DS1	100 %	100 %	3 849 938	16 %
4. Frierfjord shallow (Fs)	Capping thin	0-24	Area 2	SS2	100 %	100 %	6 796 813	28 %
5. Frierfjord deep (Fd)	Capping thin	24-100	Area 2	DS2	100 %	100 %	10 481 110	43 %
6. Ytre Fjordområde	Capping thin	0-50	Area 3	SS3+IS3	100 %	100 %	28 600 000	100 %

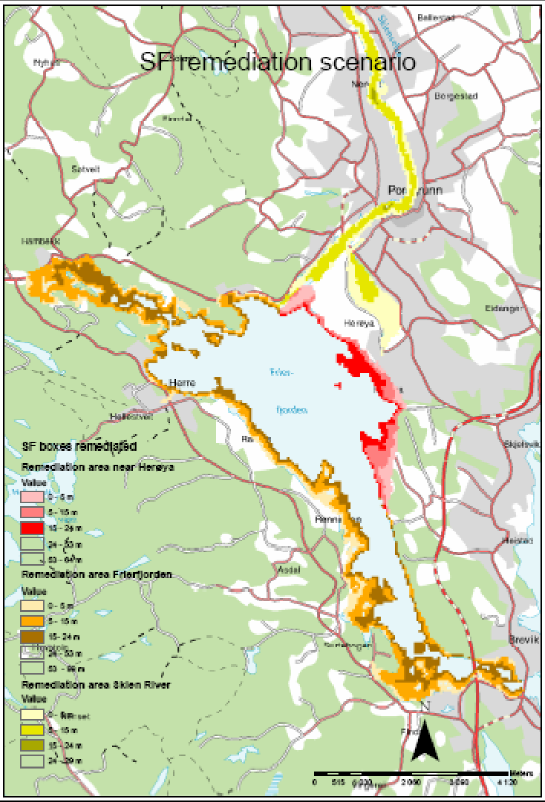
Note: Area(%) expressed as % of Frierfjorden except for area 6. Outer/Ytre Fjordområde

Scenario 0 (baseline, NoRem)

Scenario Rs+Hs (7% Frierfj.+Skien R.)



Scenario Rs+Hs+Fs (43% Frierfj.+Skien R.)



Scenario R+Hs+Fs+Hd (55% Frierfj.+Skien R.)

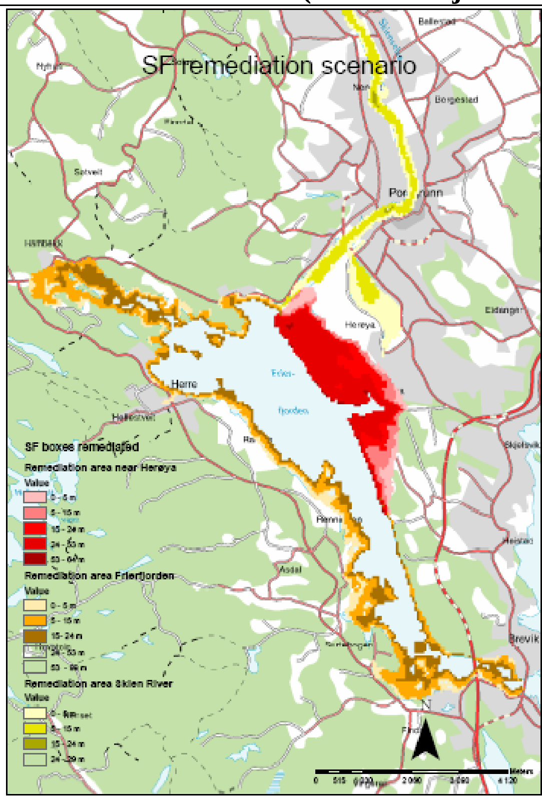
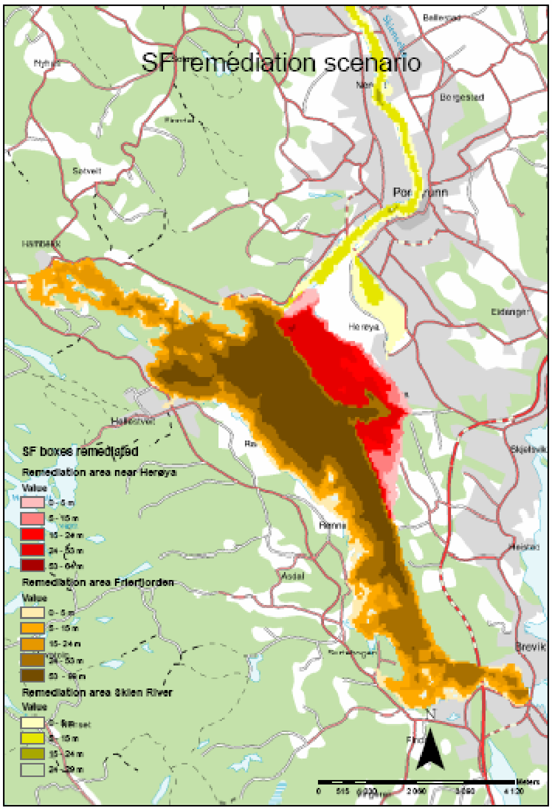
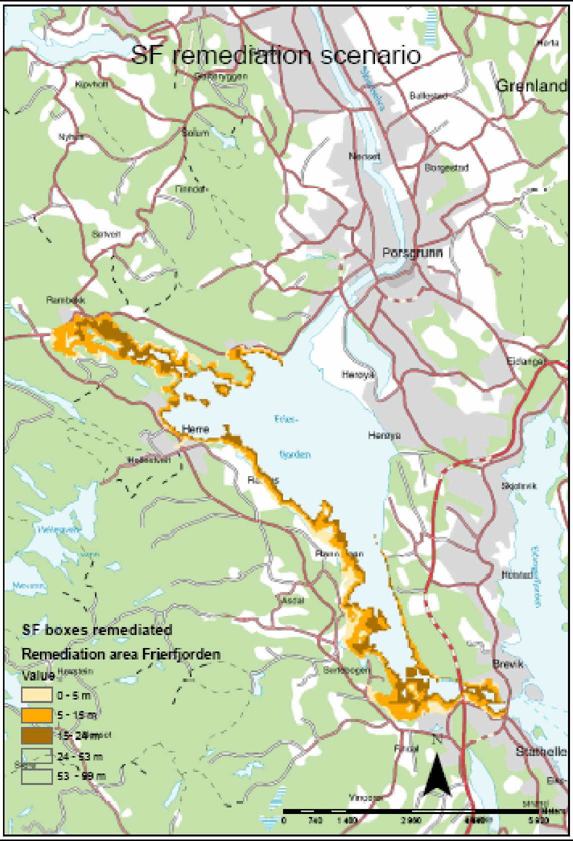


Figure 6. *Remediation scenarios simulated in SF tool (Saloranta 2005)*

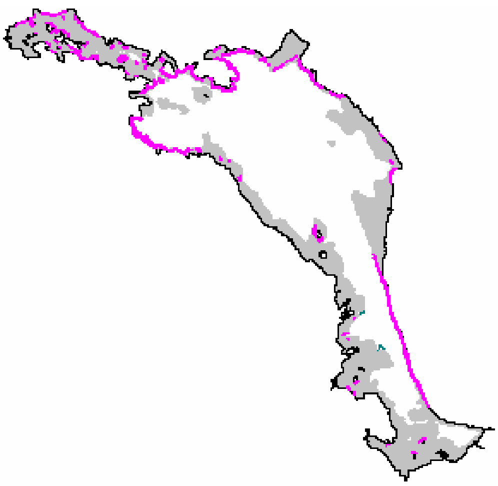
Scenario R+Hs+Fs+Hd+Fd (100% Frierfj.+Skien R.)



Scenario Fs(20%-40%-60%-80%-100%)



Feasible capping area Frierfjorden and Herøya shallow (<20 degree slopes in grey, <24 m)



Scenario Outer Fjords(0-50m, 100%)

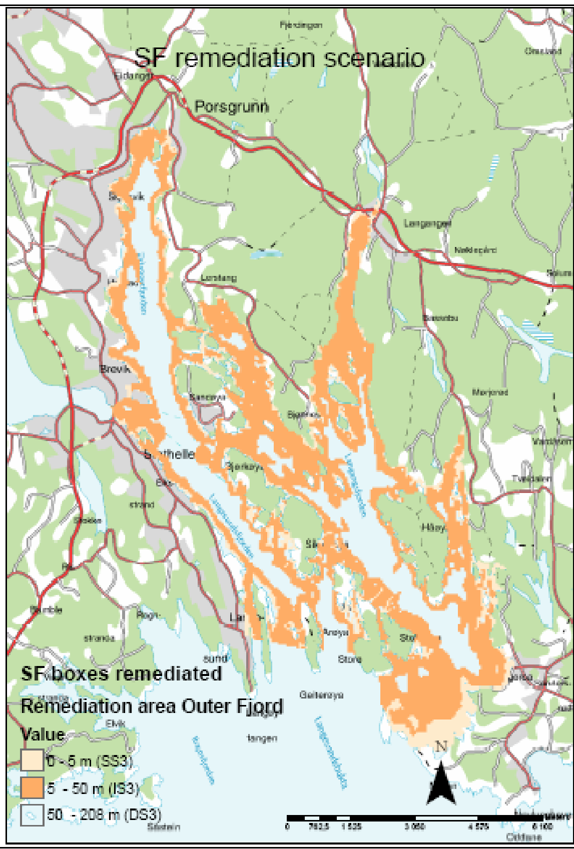


Figure 6 continued

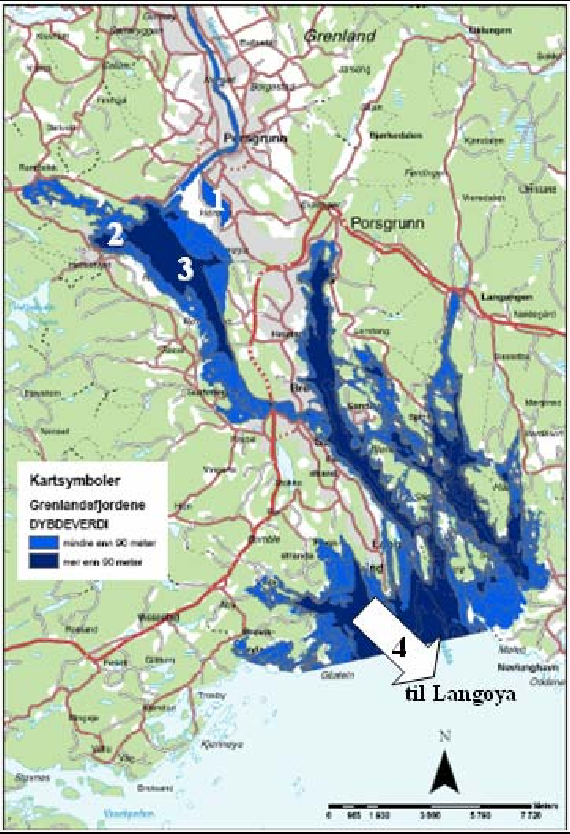
Disposal alternatives in Frierfjord	**Disposal alternative (Langøya)**
	

Figure 6 continued

2.2 Probability distributions

In the following we specify uncertainty in the model using probability density functions (pdf). The underlying idea is that the pdf should not attribute more information to the model than can be documented with data or expert opinion.

- **Estimated**: where sufficient observations are available a PDF can be fitted to the data. FO illustrative purposes this was done for 8 observations of dredging costs. Examples of fitted distributions are exponential, normal, lognormal etc.

- **Triangular**: where data on min, mode, max are available, but with insufficient observations to fit a PDF. With more than 3 observations and/or where expert wants to include max and min values in confidence interval, a triangular distribution with confidence intervals can be used.

- **Uniform**: Used when only a min and max value are available with no further information on the mode/median/mean, or when a single.

Many sediment remediation methods have only one data point and further judgement is required on the choice of distribution. When a single observed/historical cost is available (e.g. shoreline deposition Herøya) a triangular distribution is used with spread of +/- % of that value. When a single estimate is available a uniform distribution is used with expectation equal to the estimate and spread of

+/- %. The difference between the two PDFs having the same expected value and spread is that uncertainty is greater in the uniform than the traingular distribution.

2.2.1 Fixed costs

Reporting of fixed costs in various sediment projects conducted in Norway is highly variable as can be seen from the summary **Table 4** below. The 5 projects which have reported and disaggregated fixed costs report an average 11% of total costs.

Table 4. *Fixed costs reported in (5) selected Norwegian sediment remediation projects*

	min	median	max
FIXED COST COMPONENTS (Total)	10 %	18,8 %	47 %
Sediment status evaluation costs	4,6 %	6,1 %	7,2 %
Mobilisation and demobilisation costs	0,3 %	0,3 %	0,3 %
Diffusion control measures costs	9,4 %	9,4 %	9,4 %
Monitoring and evaluation costs	0,2 %	3,3 %	20,0 %
Consulting costs	1,5 %	1,5 %	1,5 %
Project administration costs	2,2 %	5,6 %	8,9 %
Reporting costs	10,4 %	10,4 %	10,4 %
Other costs (unspecified)	0,9 %	0,9 %	0,9 %

Note: max reported fixed costs come from Oslo Port feasibility study (NGI/NIVA, 2005).

Due to large differences in accounting and reporting between projects, the variation in fixed costs cannot be expected to accurately reflect uncertainty regarding these costs. However, expert opinion on fixed remediation costs does not diverge much from the minimum and median costs found in the Norwegian studies reported above, i.e. 10-25% of total costs (pers. com. Audun Hauge, NGI):

1. Planning and detailed design (5-10% of total costs)
    a. Detailed design
    b. Permit applications
    c. Tendering
2. Project implementation (5-15% of total costs)
    a. On-site coordination of works
    b. Control and monitoring during works (uncertainty whether included in tender by contractor)
    c. Control and monitoring post completion
    d. Rigging and operation (ca. 10% of total cost)

Based on the information above we therefore use a triangular distribution for fixed costs as a % of total costs (min. 10%, median 19%, max 25%), with a 5% and 95% probability that fixed costs may be lower or higher than min, max values respectively.

2.2.2 Variable costs

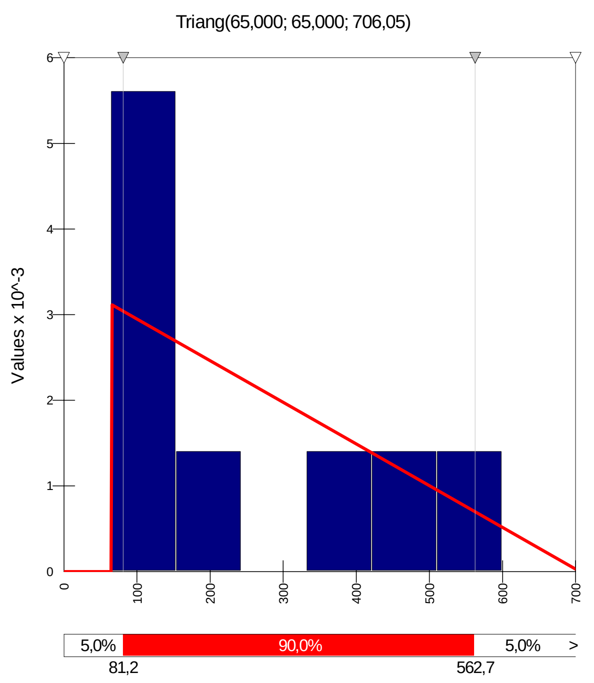
The assumptions regarding types of remediation by area and depth were given in **Table 3** above.

Dredging (0-15 m port area)

In the following we assume that all areas around Herøya 0-15m must be dredged due to ship traffic requirements. In the Frierfjord area we assume that no detailed geotechnical studies have been carried out which would inform us at a ‘pre-feasibility’ stage as to whether mechanical or hydraulic dreding would be preferred around Herøya.

From previous projects we have 4 values for mechanical dredging and 4 values for hydraulic dredging were obtained. Without further information on which site is most similar to a large scale environmental dredging project near Herøya we use a fitted triangular distribution illustrated below.

Table 5. *Historical data on average unit dredging costs and probability distribution assumption*



Case	Type	kr/m3
Bergen Havn (remediation plan)	Mechanical (depth)	65
Oslo Havn (remediation plan)	Mechanical	50-100
Sandefjord (pilot project)	Hydraulic	103
Bergen Havn (remediation plan)	Hydraulic	130
Trondheimsfjord (pilot project)	Mechanical	176
Haakonsvern phase 2-4 (large scale environmental)	Hydraulic	333
Herøya (navigational)	Mechanical	480
Haakonsvern phase 1 (small scale navigational)	Hydraulic	600

As seen in **Table 5** above there is one data point from Frierfjorden/Herøya we can compare the use of a cost distribution to: mechanical grab dredging of an average 1m depth was carried out in a 25 000 m2 area at depths of 6-11 meters near the Herøya docks in 2004 (pers.com. Hydro) at an average cost of 480 kr/m3. Given that pollution levels for the uncovered sediment surface did not vary markedly from the pre-remediation surface there is unceratinty about the required dredging depth in order to uncover uncontaminated sediment. Faced with this uncertainty we assume a dredging strategy whereby 0,5m is dredged and the an ordinary capping of approximately 0,3m is applied (pers. com. A.Hauge, NGI).
Sediments at 1m depth near Herøya) indicated similar sediment contamination levels after dredging (Hydro 2003). In other words, capping after dredging to compensate for navegational depth is assumed to be 100% probable/necessary.

Stage I cost analysis used the uncertainty captured in all the available Norwegian cases summarised in **Table 5**. Stage II cost evaluation narrowed cost uncertainty down to kr. 50-100/m3 dredging (transferred values from Oslo Havn remediation plan).

Capping

Uncertainty about the active sediment layer in shallow water (0-24 m) and deep water (>24m) in Sf tool is given in the following Table 5.

Table 6. *Uncertainty in SF tool regarding thickness of bioactive sediment layer*

		Min (m)	Median (m)	Max (m)
Active sediment layer (shallow , 0-24m)	Uniform	0,02	0,04	0,06
Active sediment layer (deep, >24m)	Uniform	0,001	0,005	0,02

In calculating capping costs per m2 we used the methodology for a "conservative design" capping (Eek 2005). Additional effort was spent on evaluting appropriate cap thickness as sensitivity analysis had shown that cap thickness was a determining variable in the remediation cost model.

Conservative design of capping thickness (h_{total}) includes estimation of operational cap thickness ($h_{operation}$) to account for operational variations; consolidation thickness ($h_{cap\ consolidate}$); erosion protection ($h_{erosion}$); bioturbation ($h_{bioturbation}$) and chemical isolation ($h_{chemical\ isolation}$). For determining "thin" and "ordinary" cap thickness in the greater Grenlandsfjord and shallow areas around Herøya, respectively, we used the recommended values in NGI(2005) for all but $h_{chemical\ isolation}$. We determined $h_{chemical\ isolation}$ based on analytical formulae (Eek 2005) using the dioxin congene in Frierfjorden with the lowest octanol-water partition coefficient (logKow for 2378TCDF) of the 17 congenes found there. Furthermore, we set required "time to contaminant breakthrough" to 100 years for the cap, which includes the 95th (and 99th?) percentile of SF-tool predictions for time to natural recovery. These criteria ensures that the cap design is 100% effective for all dioxin congenes, as assumed in the remediation scenarios. The assumptions used in estimating cap thickness are summarised in the table below.

Capping, ordinary (15-24m port area)

For shallow water in the Herøya box (Hs) below depths normally exposed to navigational turbulance we evaluate the costs of ordinary capping. The evaluation of this alternative reflects an alternative to dredging in shallow areas not affected by ship traffic, but with a thickness reflecting a safety margin relative to bioturbation previously used in other pilot cases.

The only prior data we have for capping with sand of 30-50 cm thicnkess is from Kristiansand-Hanneviksbukta at 20 kr/m2 (7-27 meters depths). For the Oslo Port remediation plan a value of 130 kr./m3 of sand (including purchase, transport and placement), equivalent to 39 kr/m2 (30 cm cap). We specify a traingular distribution (mode 130, min -20%, max +20%) for these capping costs. Cost per m2 capped varies according to uncertainty regarding the appropriate thickness of the cap to achieve 100% effectiveness in the reduction of diffusion. This uncertainty is determined using the guidelines mentioned above (Eek 2005).

Due to lack of measurements of sediment concentrations along the Skien River uncertainty exists as to how much of this model box is exposed to a salt water wedge and so transportation of contaminated particles from Gunnekleivfjord and Herøya shallow. At low flow periods a salt water wedge can extend as far as the Skien town locks, while at times of flood the wedge is pressed downstream 8-

10km almost to Porsgrunn town (Persson, Cousins et al. 2006). Skien River area from the mouth to the second bridge in Porsgrunn (from the rivermouth) is about 665 000 m2 whereas the whole Skien River box measures around 2 million m2. We specify a triangular distribution for Rs remediation area with highest probability at 665 000 m2 declining to 2 million m2.

Capping, thin layer (<24 meters outside port areas, all areas >24m)

Thin layer capping is a measure designed to simulate a speeding up of natural sedimentation processes and to cover very large areas. Principle uncertainty is due to achieving an even coverage of a large area given local bottom topography and currents ($h_{operation}$).

Thin layer capping has not previously been tested in Norwegian pilot studies. Oslo Port remediation plan proposes thin layer capping with clay obtained free of charge from a nearby tunneling and construction project. Unit costs have been estimated at 50-130 kr/m3 of clay (Hauge and Skei 2005). We specify a uniform distribution (min 50, max 130). Cost per m2 capped varies according to uncertainty regarding the appropriate thickness of the cap to achieve 100% reduction in diffusion. This uncertainty is determined using the guidelines (Eek 2005).

Figure 2 (last map) shows that the feasible area for capping (<20° slope) is about 90-95% of the sediment area in Fierfjorden at depth of 0-24 meters. Within this area a maximum cap thickness of 0,8 meters is feasible (assuming shear strength of minimum 2 kPa; maximum own-weight of cap of 8 kN/m^3) (Eek 2005). The cap proposed is well within these limits.

Shoreline disposal site (Gunnekleiv-fjorden)

Dredged material from the Herøya box (15-24 m) is assumed stored in shoreline disposal site in Gunnekleivfjord similar to the 12 000 m2 site established in 2004 (Hydro 2003)(18000 m3 distributed within 6700 m2 for an average depth of dredged material of 2,7 meters). Because the shoreline disposal site would cover a large portion of Gunnekleivfjord mean depth of the fjord (4,72m) is used to calculate the surface area of the disposal site given volume, and the remainder of the area of the Gunnekleivfjord to be capped. The disposal site is "simple without dewatering" calculated at a cost of 240 kr/m3 deposited material. Given similar depth conditions (0-6 m) we assume similar costs as the existing site, with some uncertainty regarding possible economies of scale of up to -20% relative to the existing site (triangular distribution max 240, mode 240, min -20%).

The deposition site is assumed to be used for industrial purposes by Porsgrunn Industripark after stabilisation. Benefits of land reclamation are valued at an average land rental price for the rest of the industrial area.

Other values for shoreline deposition from previous remediation cases can be found in Table 1A in appendix 1.

Marine disposal (deep water)

We have four data points for marine disposal, three from remediation plans (Soldal 2004) and one from a pilot study (NCC 2003) (Appendix 1). The Sandefjord case can be characterised as a shallow water deposition involving capping with on-site sediment at 134 kr/m^3, while a value of 140 kr/m^3 was estimated for shallow water disposal in geotextile bags, and 110 kr/m^3 for geotextile cover in Bergen port area. The remaining estimate of the costs of deep water disposal in Oslo is 90 kr/m^3. The distance from dredged areas around Herøya to a deep water deposition site in the middle of Frierfjorden would be similar to Oslo (3-5 km), but somewhat deeper at 90 meters (see map site 2 or 3 disposal alternatives). Due to lack of other estimates we use a uniform distribution with values +/- 20% around 90 kr/m^3.

NOAH landfill disposal

Disposal costs at Langøya are uncertain due to competitive bidding with other disposal alternatives. In the Oslo Port project costs have been estimated to 200-300 kr/tonne for sediment delivered to disposal site (incl. 70km transportation costs) (Oslo Kommune, 2005). Transport costs have been estimated at 20 kr/m3 for 3-5 km transport (4-6,7 kr/m3 km) (Hauge and Skei 2005). NOAH disposal costs on site vary from 40-80 million kr. for deposition of 500 000 m3, or 80-160 kr/m3. For both transport costs and deposition costs we use uniform distributions to reflect this.

Transportation distance from Herøya to NOAH at Langøya is about 125 km.

2.2.3 Price uncertainty

The data available on remediation costs is a mixture of pre-bid costs obtained from contractors (often excluding VAT) and actual costs reported by the different pilot projects (generally including VAT). While VAT are transfers that should be excluded from social economic analysis, there as some uncertainty as to whether a number of the prices in the database are inflated by VAT.

Documentation of price uncertainty due to competitive bidding is relatively scarce. This is uncertainty related to estimates quoted during bidding and actual accounting costs. During bidding for phase 1&2 of remediation at Haakonsvern in 1999, bids varied between kr. 73-272 million exclusive of unforeen costs (including VAT). After completion of phase 2 in 2003 actual costs came out at kr. 134 million including VAT (Forsvarsbygg 2003). Based on this project pre- and post bid prices used may vary by as much as -45% to +100%. Some of this variation is already reflected in the individual PDFs used to describe costs. This uncertainty has been left out of the current analysis. However, given the mixture of quoted and observed prices in the data underlying the PDFs, uncertainty is probably somewhat greater than specified in the cost model.

2.3 Probability density functions of unit costs

Uncertainty in the cost model was evaluated in two stages (I & II), whereby experts were called on to re-evaluate the uncertainty distributions specified in stage I. **Table 7** provides a summary of the probability density functions (PDFs) used in the "final" or Stage II remediation cost calculation model. Expected value is the mean calculated using parameters given in the table. The results of the stage I analysis are summarised in Appendix 2.

Table 7. *Summary of probability density functions (PDFs) describing uncertainty of remediation costs*

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Distributions**												
2	Item	PDF variable	Unit	Probability distribution (PDF)	St.error /st.dev.	Min	Median /mean/ mode	Max	Botto m%	Upper %	Expected (value)	Source	Revised in stage II
3	Fixed costs	*fc*	% of variable costs	Triangular*		10 %	19 %	25 %	5	95	18 %	pilot studies review	no
4	Dredging depth	*dd*	m	Triangular		-20 %	0,5	20 %			0,50	pers.com Hauge,NGI	yes
5	Dredging cost	*c dr*	kr/m3	Triangular(fit)		50	90	100			80,00	pers.com Hauge,NGI	yes
6	Dredging rate capacity	*Rd*	m3/day per unit	Triangular		2000	2000	2000			2 000	Hauge (2005)	new
7	Tidally exposed area Skien River	*Ar*	m2	Triangular		665 000		2 045 193			1 125 064	DIG paper unpublished	new
8	Capping cost (ordinary, sand)	*c oc*	kr/m3	Triangular		-20 %	130	20 %			130,00	Oslo Port Plan,NGI	no
9	Capping cost (thin, clay)	*c tc*	kr/m3	Uniform		50		130			90,00	Oslo Port Plan,NGI	no
10	Capping cost (erosion barrier limestone)	*c e*	kr/m3	Triangular		-20 %	130	20 %			130,00	Oslo Port Plan,NGI	yes
11	Capping thickness (ordinary)	*h o*	m	Uniform		0,18		0,38			0,28	Eek(2005)	new
12	Capping thickness (thin,shallow)	*h ts*	m	Uniform		0,02		0,21			0,12	Eek(2005)	new
13	Capping thickness (thin,deep)	*h td*	m	Uniform		0,00		0,26			0,13	Eek(2005)	new
14	Capping rate capacity	*Rc*	m3/day per unit	Triangular		2000	2000	2000			2 000	Hauge (2005)	new
15	Potential increase in capping capacity		%of current capacity	Triangular		400 %	400 %	400 %			400 %	hypothesis	new
16	Feasible capping area (<20° slope)	*a f*	% of area	Uniform		90,00		95,00			92,50	GIS,NGI	yes
17	Shoreline deposition costs	*c s*	kr/m3	Triangular		192	240	288			240,00	pilot studies review	no
18	Transport costs	*c t*	kr/m3/km	Uniform		4		6,7			5,33	Oslo Port Plan,NGI	no
19	Cost deposition NOAH	*c r*	kr/m3	Uniform		80		160			120,00	pilot studies review	no
20	Cost deep water deposition	*c dw*	kr/m3	Uniform		72		108			90,00	pilot studies review	no
21	Pre/post bid price variation(Haakonsvern1&2)	*b*	kr	triangular		-46 %		103 %			86 %	pilot studies review	no
22	Own weight sediments		tonne/m3	none							1,3	Oslo Port Plan,NGI	no
23	Mean sediment depth deep water diposal site		m										
24	Mean depth Gunnekleivfjord		m	none							4,76	GIS	no
25	Transport distance NOAH	*km*	km								125	GIS	no
26													
27	WTP for maintaining recreational fishing	WTPf	kr	normal	277		886				886	Toivonen et al.(2000)	
28	Expenses recreational fishing	Cr	kr	normal	450		1589				1589	Toivonen et al.(2000)	
29	WTP for lifting dietary health advisories (high)	WTPdha	kr	normal	116		773				773	Magnussen and Bergland (1996)	
30	WTP for lifting dietary health advisories (low)	WTPdha	kr	normal	113		629				629	Magnussen and Bergland (1996) subsample 2	
31	Portion of WTP due to Frierfjord	scope	%	uniform		10 %		36 %			23 %		
32													
33	Time horizon	T	years	none							100	minimum 60 years	
34	Discount rate	r	%	none							7 %		

Note: * triangular with confidence intervals at %.

2.4 Total cost calculation formulae

The simple cost calculation formulae show where uncertainty is considered in the calculations – PDFs are shown in *italics*. Sensitivity analysis will indicate which variables drive aggregate uncertainty in total remediation costs. These variables are candidates for further specification and data collection.

Expected dredging costs

$E(V_{dr}) = dd * A_{ij}$ (1)

$E(VC_{dr}) = c_{dr} * E(V_{dr})$ (2)

$E(TC_{dr}) = (1+fc) * E(VC_{dr})$ (3)

Expected disposal costs

$E(V_{dr}) = E(V_k)$ (4)

$E(VC_k) = (c_{1-4} + c_t) * E(V_k)$ (5)

$E(TC_k) = (1+fc) * E(VC_k)$ (6)

Expected capping costs

$E(V_{ij}) = h_l * a_f * Aij$ (7)

$E(VC_{tc,oc}) = * c_{tc,oc} * E(V_{ij})$ (8)

$E(TC_{tc,oc}) = (1+fc) * E(VC_{ij})$ (9)

Total expected remediation costs

SUM_{ij} [E(TC)]= E(TC_{dr}**)** + E(TC_k**)** + E(TC $_{tc,oc}$) for all i depths and j remediation areas (10)

Time to full implementation of remediation measures

T= E(V_{dr}) / Rd +E(V_{ij}) / Rc (11)

where

i=SF remediation scenario depth; d=deep,s=shallow
j=SF remediation scenario box; R=Skien River and Gunnekleiv,H=Herøya,F=Frierfjord
m=remediation methods; dr=dredging, oc=ordinary cap, tc=thin cap,
k= diposal method; 1=shoreline, 2&3=deep water, 4=landfill (NOAH)
l=capping method; o=ordinary, ts=thin cap shallow, td=thin cap deep
A_{ij}= remediation scenario box area (m)
a_j= % of SF box area remediated
e_{ij}=remediation effectiveness (% active sediment concentration reduction)
E($V_{m,k}$)= Expected volume $(m3)_{dredged, diposed}$
E($VC_{m,k}$) = Expected variable $cost_{remediation\ method}$
E(TC_{ij}) = Expected total $cost_{depth, area}$

Most of the uncertainty in the cost model is additive - in such a case the central limit theorem suggests that the distribution of total costs will approach a normal distribution. Figure 3.1 shows a distribution with similar characteristics to a normal distribution although skewed to the left.

3. Results

3.1 Expected costs

Table 8 below shows the expected costs of remediation scenarios simulated in SF tool.
The alternative including dredging of Skien River and disposal in and capping of Gunnekleiv fjord are excluded both due to (i) lack of effect shown by SF tool and (ii) excessive sediment volume compared to Gunnekleiv fjord. The alternative including disposal at NOAH Langøya is excluded from the analysis due to excessive transport costs. The alternative including deep water disposal (Hs + deep water disposal) is technically most feasible and the cheapest, and is therefore kept in the cost calculations for all scenarios. Expected costs increase incrementally from 200 million kroner to 510 million kroner as additional areas (Hs, Hd, Fs, Fd) are assumed dredged/capped in SF tool. Including Outer Fjord areas down to 50m for capping increases expected costs to over 865 million kroner.

Table 8. *Expected costs of remediation scenarios simulated in SF tool*

SF remediation scenario areas	Method	Area	Expected thickness/ depth	Expected volume	Expected costs	Expected costs (totals)	Time to 100% implementation(months)	Comment
Disposal alternative 1	Disposal (Gunnekleiv)	135 067		642 921	154 301 080			not evaluated further
Disposal alternative 2&3	Transport (deep water)			642 921	13 715 652			4
	Disposal (deep water)			642 921	57 862 905			Sum of dredging Rs and Hs
Disposal alternative 4	Transport (NOAH)			642 921	428 614 111			not evaluated further
	Disposal (NOAH)			642 921	77 150 540			not evaluated further
	Fixed costs (deep water disposal)				12 749 174			
Total cumulative	**Deep water disposal**					**84 327 730**		
	Capping Rs (Gunnekleiv)	799 930	0,12	93 592	12 166 935		2	
	Dredging Rs (Skien River tidal)	1 125 064	0,50	562 532	45 002 573		9	
	Capping Rs (Skien River tidal)	1 125 064	0,28	313 049	40 696 390		5	
	Fixed costs (Rs dredging, capping)				17 431 328			
	Total Rs					115 297 227	16	
Total cumulative	**Rs+deep water disposal**					**199 624 957**		
	Dredging Hs (docks area)	160 778	0,50	80 389	6 431 120		1	
	Capping Hs (docks area)	160 778	0,28	44 736	5 815 742		1	
	Capping Hs (outside docks area)	857 000	0,12	100 269	9 024 210		2	
	Fixed costs (Hs dredging and capping)				3 788 685			
	Total Hs					25 059 757	4	
Total cumulative	**Rs+Hs+deep water disposal**					**224 684 714**	**20**	
	Capping Fs	6 796 813	0,12	795 227	71 570 438		13	
	Fixed costs (capping Hs)				12 747 728			
	Total Fs					84 318 166		
Total cumulative	**Rs+Hs+Fs+deep water disp.**					**309 002 880**	**33**	
	Capping Hd	3 849 938	0,13	509 251	45 832 549		8	
	Fixed costs (capping Hd)				8 163 438			
	Total Hd					53 995 988		
Total cumulative	**Rs+Hs+Fs+Hd+deep water disp.**					**362 998 868**	**42**	
	Capping Fd	10 481 110	0,13	1 386 389	124 774 997		23	
	Fixed costs (capping Fd)				22 224 227			
	Total Fd					146 999 225		
Total cumulative	**Rs+Hs+Fs+Hd+Fd+ deep water disp.**					**509 998 092**	**65**	
	Capping Outer Fjord shallow	28 600 000	0,12	3 346 200	301 158 000		56	
	Fixed costs (capping outer)				53 640 585			
	Total Outer Fjord					354 798 585		
Total cumulative	**Outer Fjord+ Rs+Hs+Fs+Hd+Fd+ deep water disp.**					**864 796 677**	**121**	

3.1.1 Cost uncertainty

Cost uncertainty was simulated in @Risk^{TM} software. The model was run 3000 using Latin Hypercube sampling from the PDFs shown in **Table 8**. Latin Hypercube (LHC) sampling reproduces the input PDFs better than Monte Carlo simulation, particularly for smaller sample sizes, because LHC has 'memory' of where it has sampled previously, whereas Monte Carlo sampling does not (Vose, 1996).

Figure 7 shows that with the uncertainty specified in **Table 8** only 5% of outcomes are less than 270 million kroner, while only 95% are more than 810 million kroner (Frierfjord remediation). The most important variables driving variation in total costs as seen in the Tornado graph are: (i) capping thickness (thin,deep) (0,703), (ii) capping cost (thin, clay) (0,463), (iii) capping thickness (thin, shallow) (0,319), and (iv) tidally exposed area Skien River (0,311) (Figure 3.2).

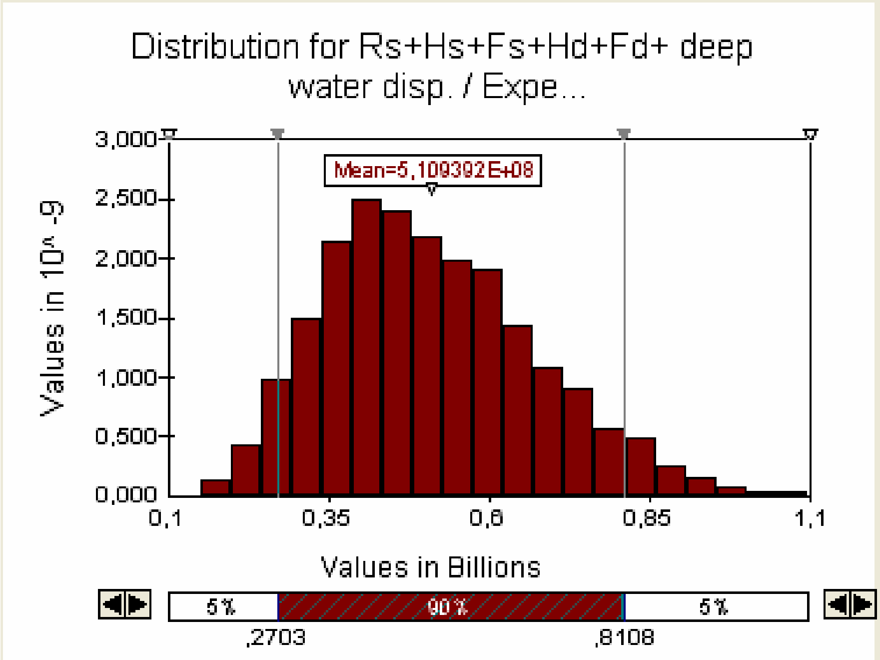


Figure 7. *PDF total remediation costs*

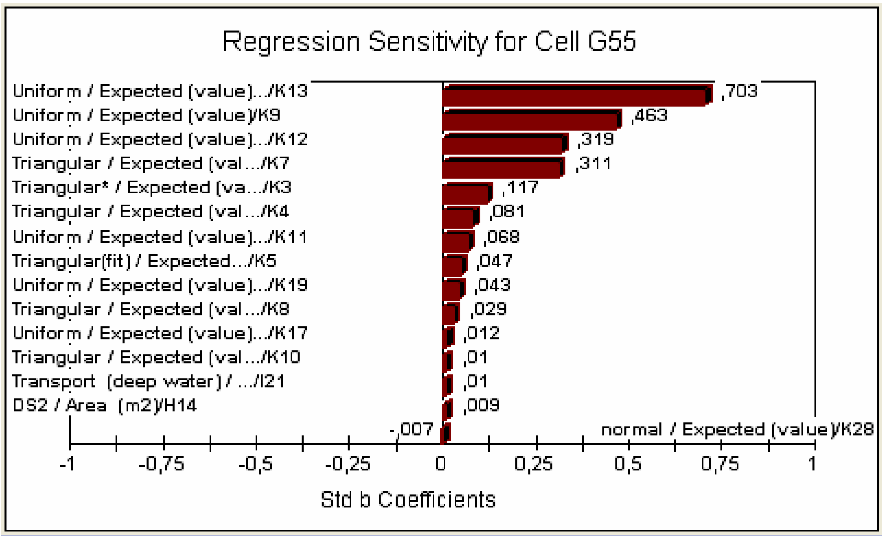


Figure 8. *Tornado graph*

Note: see **Table 8** headings for Excel variable names in **Figure 8**. Cost calculations shown are for remediation of the Frierfjord

A similar PDF for total costs can be output for each of the scenarios modelled in SF tool. See table 8 below for a summary of 5%, 50% and 95% confidence bounds of remediation costs and how these are compared to remediation effectiveness.

3.1.2 Timing of remediation implementation - cost distribution

Calculations thus far have not assumed any technical remediation capacity, nor phasing of the implementation of remediation measures. In order to have a more realistic and discounted value of total costs we make the following assumptions:

- Current available capping capacity of 2000 m3/day, respetively is assumed to be quadrupled(400%) in case of a large remediation project in the area. Current dredging capacity is maintained.
- Dredging and capping are carried out sequentially in Skien River, Gunnekleivfjord and Herøya shallow boxes.
- Capping is carried out simultaneously by 4 capping “units” with 2000 m3/day capacity each in all other boxes.

With these assumptions the cost profile of the remediation plan is as shown in **Table 9**.

Table 9. *Assumed remediation cost time profile*

Remediation area	**Remediation month**	**Expected remediation cost during period**
Dredging and capping in Rs&Hs & deep water disposal	0-13,0	224 684 714
Capping (0-24m) Fs	13,0-16,3	84 318 166
Capping (>24m) Hd	16,3-18,4	53 995 988
Capping (>24m) Fd	18,4-24,2	146 999 225
Capping (0-50m) Outer Fjord	24,3- 38,2	354 798 585
	Total	864 796 677

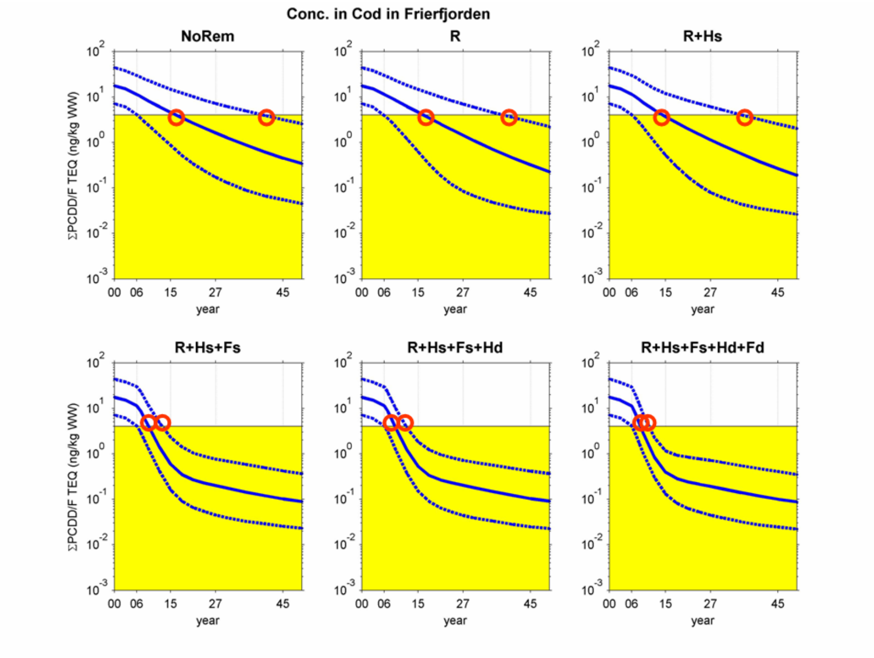
3.2 SF tool input to cost-effectiveness analysis

Remediation effectiveness is calculated in SedFlex tool as years to target threshold, in this case 4 TEQ ng/kg ww in cod, representing a threshold for lifting dietary advisories (VKM 2004). Confidence levels at 50% and 95% are extracted from the SedFlex tool results as shown in **Figure 9-Figure 12**. **Figure 10** demonstrates that measures in Frierfjord and Outer Fjords may be analysed separately as there is little transport of dioxins between the two systems. (At the time of writing the SF-tool for the Outer Fjords was to be recalibrated.). The results shown in this section are therefore for illustrative purposes.

The SF-tool (Saloranta, Armitage et al. 2006)) was used to evaluate the number of years until a dietary health advisory target of 4 ng/kgww, with confidence levels set at 90% and start values in 2000 for cod (17.5 ng/kgww) and crab (23,5 ng/kgww) taking into account a 2 year biota response time (pers.com. T.Saloranta). For the Outer Fjord start values are assumed to be one third of values in Frierfjord based on monitoring data in Bjerkeng and Ruus (pers.com. T.Saloranta).

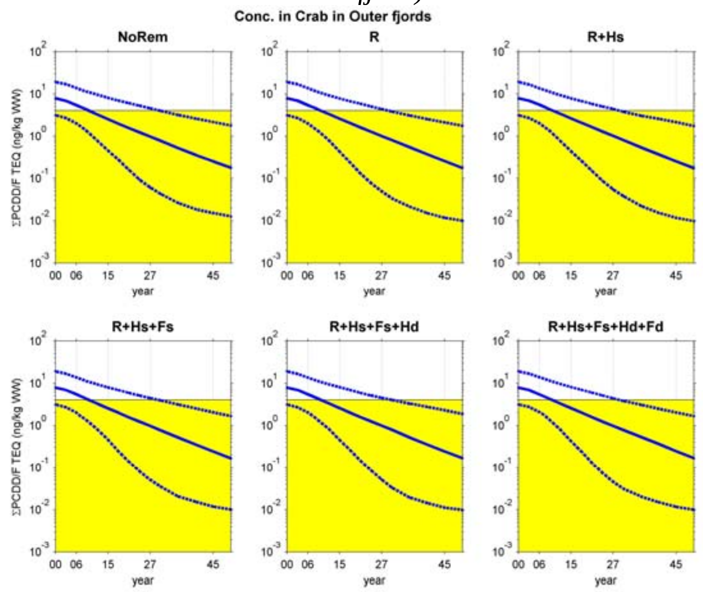
Remediation measures in the SedFlex model are assumed to all take place on 1. August 2006, without any phasing of remediation by area as discussed above. In combining cost-effectiveness data we have conservatively assumed a 2 year lag for SedFlex predicted effects of measures in the Frierfjord assuming all measures take 2 years to implement 100%.

Figure 9. *SedFlex output – concentrations of dioxins in codfish (Frierfjorden due to measures in Frierfjord)*



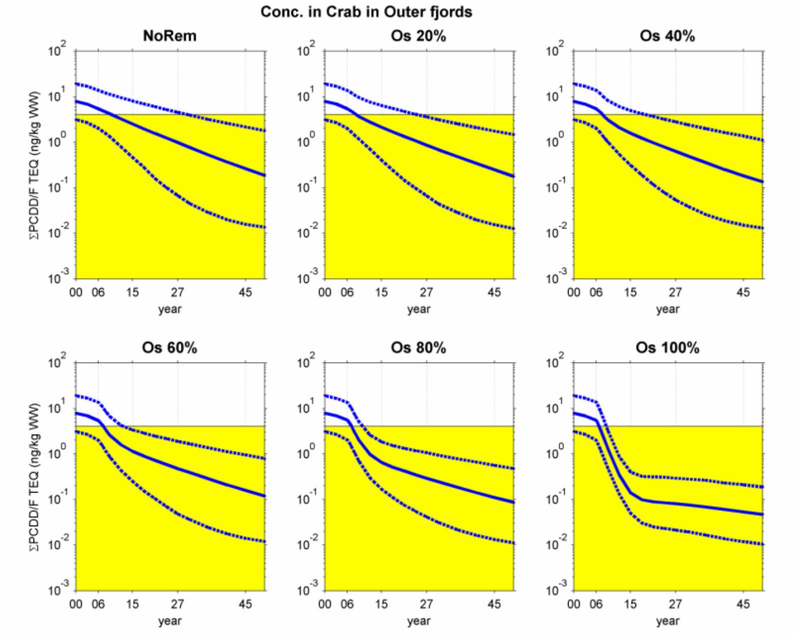
Source: (Saloranta 2005) (draft 6.12.05)

Figure 10. *SedFlex output – concentrations of dioxins in crab (Outer Fjord due to measures in Frierfjord)*



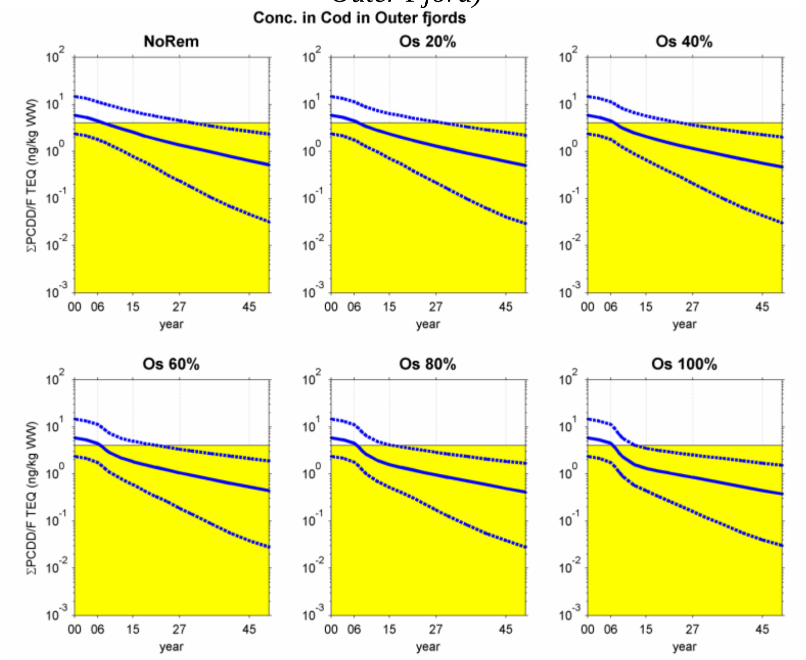
Source: (Saloranta 2005)(draft 6.12.05)

Figure 11. *SedFlex output – concentrations of dioxins in crab (Outer Fjord due to measures in Outer Fjord)*



Source: (Saloranta 2005)

Figure 12. *SedFlex output – concentrations of dioxins in cod fish (Outer Fjord due to measures in Outer Fjord)*



Source: (Saloranta 2005)

3.2.1 Summary of SF-tool simulation results

Table 10. *Remediation of Frierfjorden*

Sedflex calculator simulation output (7.12.05)								
Metamodel version:	Sfmetamodel2							
Start year simulations:	2000							
Startvalue cod (Frierfjorden):	17,5	ng/kg ww	pers. com. Saloranta (2 year lag in biota response)					
Startvalue crab (Fierfjroden):	23,5	ng/kg ww	pers. com. Saloranta (2 year lag in biota response)					
Confidence level	90 %							
Time lag (remediation phasing Frierfjord)	2							
					With remediation time lag			
Frierfjorden (Cod)					Frierfjorden (Cod)			
	5 %	50 %	95 %		%Area	5 %	50 %	95 %
NoRem	2004,2	2011,3	2028,1		0 %	2004,2	2011,3	2028,1
R	2004,2	2010,8	2024,0		8 %	2004,4	2011,0	2024,2
R+Hs	2004,1	2010,2	2023,0		12 %	2004,3	2010,4	2023,2
R+Hs+Fs	2004,1	2008,1	2011,6		40 %	2004,9	2008,9	2012,4
R+Hs+Fs+Hd	2004,3	2007,9	2011,3		56 %	2005,4	2009,0	2012,4
R+Hs+Fs+Hd+Fd	2004,0	2007,8	2010,6		100 %	2006,0	2009,8	2012,6
Frierfjorden (Crab)					Frierfjorden (Crab)			
	5 %	50 %	95 %			5 %	50 %	95 %
NoRem	2005,3	2013,1	2029,9		0 %	2005,3	2013,1	2029,9
R	2005,3	2012,1	2027,5		8 %	2005,5	2012,3	2027,7
R+Hs	2005,3	2011,6	2026,8		12 %	2005,5	2011,8	2027,0
R+Hs+Fs	2005,3	2008,8	2012,3		40 %	2006,1	2009,6	2013,1
R+Hs+Fs+Hd	2005,5	2008,7	2011,8		56 %	2006,6	2009,8	2012,9
R+Hs+Fs+Hd+Fd	2005,3	2008,4	2011,3		100 %	2007,3	2010,4	2013,3

Note: remediation time lag is based on a 2 year implementation time for the whole of Frierfjorden calculated in **Table 9**. Share of implementation time for each scenario is calculated as a fraction of the total remediation area represented by the scenario.

Table 11. *Remediation of Outer Fjord (Sedflex model areas 3)*

Sedflex calculator simulation output (13.12.05)								
Outer Fjord								
Metamodel version:	Sfmetamodel2							
Start year simulations:	2000							
Fraction of startvalues in Frierfjord	0,33	pers. com. Saloranta, Bjerkeng and Ruus data						
Startvalue cod:	5,775	ng/kg ww						
Startvalue crab:	7,755	ng/kg ww						
Confidence level	90 %							
Time lag (remediation phasing Frierfjord)	1				With remediation time lag			
Outer Fjord (cod)					Outer Fjord (cod)			
	5 %	50 %	95 %			5 %	50 %	95 %
NoRem	2000	2007,6	2030,1					
Os 100%	2000	2006,5	2011,9			2001	2007,5	2012,9
Outer Fjord (crab)					Outer Fjord (cod)			
	5 %	50 %	95 %			5 %	50 %	95 %
NoRem	2000	2009,5	2030,3					
Os 100%	2000	2006,8	2008,7			2001	2007,8	2009,7

Note: remediation time lag is based on a 1 year implementation time for the whole of Outer Fjord calculated in **Table 9**.

3.3 Cost effectiveness – combining SF tool output and cost model

Figure 13 below illustrates how SedFlex model simulations are coupled to different sizes of remediation area, which in turn are coupled to remediation costs. **Table 12** also shows in numbers what is suggested by the slope of the curves in Figure 6 – that some areas / boxes are significantly more cost-effective for remediation purposes than others (Hs and Fs).

Table 12 shows how cost-effectiveness comparisons can be made combining Sedflex model data and remediation cost model data. The table illustrates a cost-effectiveness indicator (using predicted concentrations in cod) which makes comparison of remediation areas / SF boxes. The use of other target biota such as crab produce slightly other cost-effectiveness results in absolute terms, but the ranking / relative effectiveness of remediation in the different boxes is unchanged.

Table 12. Cost-effectiveness of remediation measures in Frierfjorden on cod fish in Frierfjorden

SF tool Scenario	Total area remediated	Lower 5%	Median (50%)	Upper 95%	Lower(5%)	Median (50%)	Upper 95%	Cost-effectiveness (50%)(million/ year reduction)	Cost-effectiveness (95%) (million/year reduction)
	m2	kr.	kr.	kr.	Years	Years	Years		
NoRem (Frierfjord)	0	0	0	0	2004,2	2011,3	2028,1		
Rs	1 924 994	127 177 408	189 797 696	301 933 280	2004,2	2010,8	2024	380	74
Rs+Hs	2 942 772	147 707 600	215 413 936	330 142 720	2004,1	2010,2	2023	43	28
Rs+Hs+Fs	9 739 585	185 322 608	303 320 480	456 836 416	2004,1	2008,1	2011,6	42	11
Rs+Hs+Fs+Hd	13 589 523	221 278 768	355 231 744	533 307 104	2004,3	2007,9	2011,3	260	255
Rs+Hs+Fs+Hd+Fd	24 070 633	270 335 936	493 158 080	810 795 264	2004	2007,8	2010,6	1379	396
NoRem (Outer Fjord)	0	0	0	0	2000	2007,6	2030,1		
Os100%	28 600 000	139 885 568	333 542 784	645 367 680	2000	2006,5	2011,9	303	35

Note: effect measured in cod fish in Frierfjorden(Rs+Hs+Fs+Hd+Fd) and OuterFjord (Os),as a result of remediation in those areas respectively. Assumes "instantaneous" remediation (i.e. in 2006). Table 7 indicates that remediation of the whole are may take 3 years or more.

Figure 13 shows how cost-effectiveness can be illustrated graphically (using crab as the target organism). The increments in remediation area leads to reductions in the number of years until the threshold value for dietary health advisory in crab are reached. Each line segment represents and addition sediment box that has been 100% remediated in SF tool (Rs, Hs, Fs, Hd, Fd, respectively reading from bottom to top). If we look at the 95% confidence bounds the SedFlex tool indicates that remediation has an incremental effect mainly for boxes R, Fs and Hs; that the greatest effect is achieved for box Fs; and that marginal effect/area for Hd and Fd is lower than for Fs, i.e. effects are not linear in area remediated.

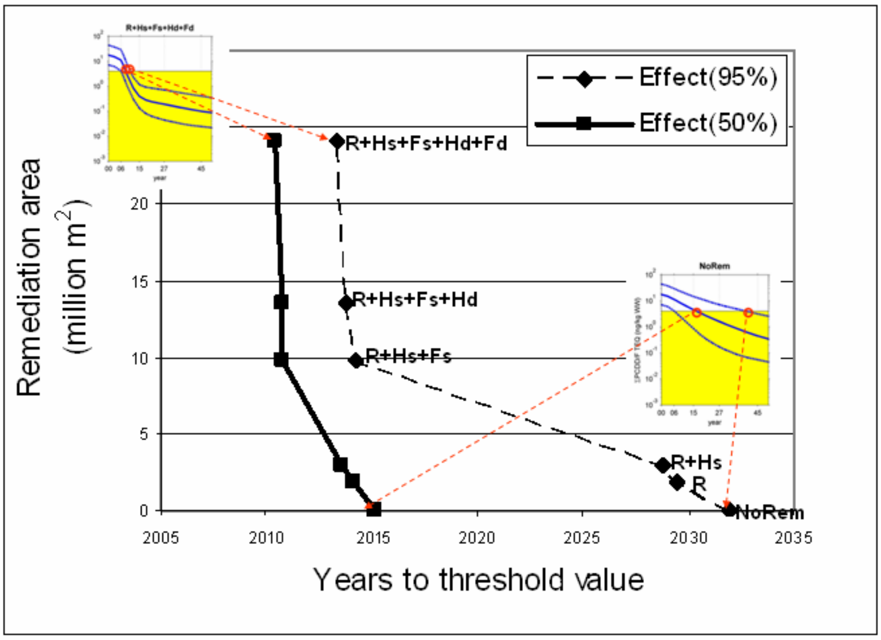


Figure 13. *Combining SedFlex remediation scenario and effect data (example for crab) Note: illustrated for effects measured in crab in Frierfjorden due to remediation measures in Frierfjorden*

Figure 14 shows how areas that are dredged and capped (R and Hs) are more expensive per m2 than areas that are only capped. Differences affect the cost-effectiveness of each remediation area. This is illustrated in **Figure 15**.

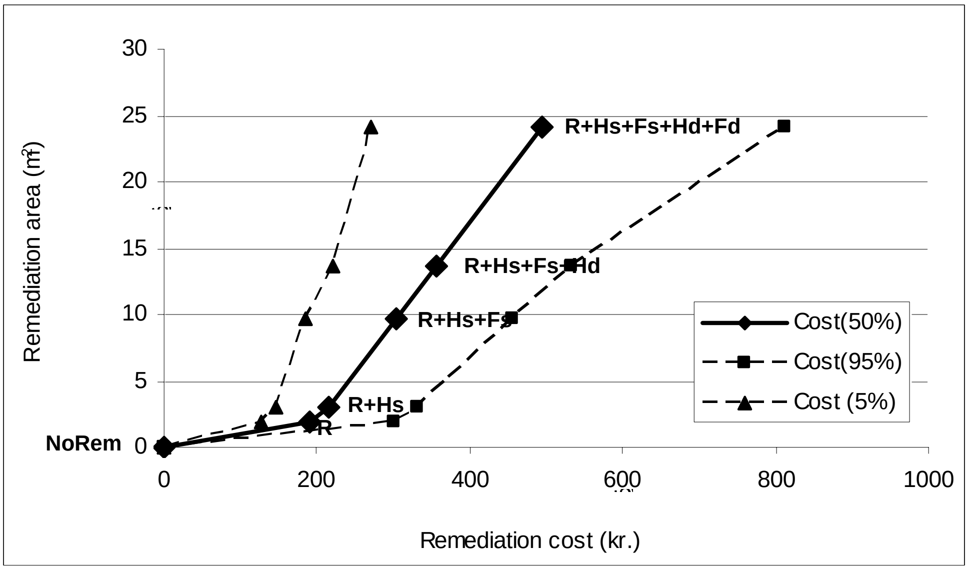


Figure 14. *Expected costs as a function of remediated area (Frierfjorden)*

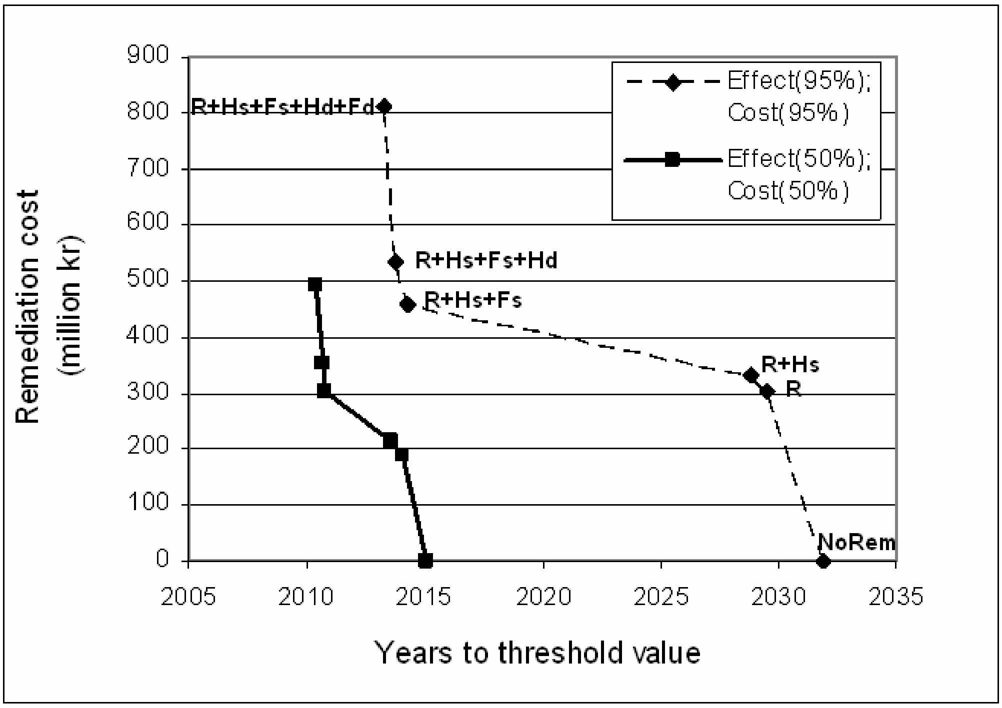


Figure 15. *Cost-effectiveness of different remediation areas (example for crab)*
Note: illustrated for effects measured in crab in Frierfjorden due to remediation measures in Frierfjorden

3.4 Risk control methods using SEDFLEX

Risk control methods often use expected value – variance curves to evaluate trade-offs between return and uncertainty of a decision (Ayyub 2003). **Figure 16** illustrates an application of such risk control approach to sediment remediation using output from SF-tool and the remediation cost model. The figure shows the marginal cost-effect of each remediation area, calculated as the difference between the SF-tool computed probability distributions for the remediation scenarios defined in **Table 1**, divided by the probability distribution of remediation cost for that particular area.

(12) $$E(CE_i) = \frac{E(dY)}{E(C_i)} = \frac{E(Y_j) - E(Y_{j+1})}{E(C_i)}$$

where

E(CE*i*) ≡ expected cost-effectiveness of remediation in fjord area *i* (R, Hs, Hd, Fs, Fd)

Y*j*≡years to dietary health advisory limit value with remediation scenario j (table 1)

C*i*≡ remediation cost for fjord area i

The integrated uncertainty model (**Figure 1**) presented some problems which require attention in future work. Positive rank correlations were specified between the probability distributions of NoRem and other remediation scenarios' simulation output from the SF-tool. Rank correlations could be no higher than 0,447 for the correlation matrix to be positive semi-definite. Despite this correlation resulting joint distribution still lead to negative cost-effectiveness values for some simulation iterations. E(CE) is therefore also limited to non-zero values in the calculation of equation (1). This leads to a probability spike at E(CE)=0 and biases in the absolute value of expected cost-effectiveness, as well as its standard deviation. However, the relative rank of expected values and standard deviations is preserved. This weakness will be remedied in future versions of SF-tool by computing marginal effects of each individual fjord area directly.

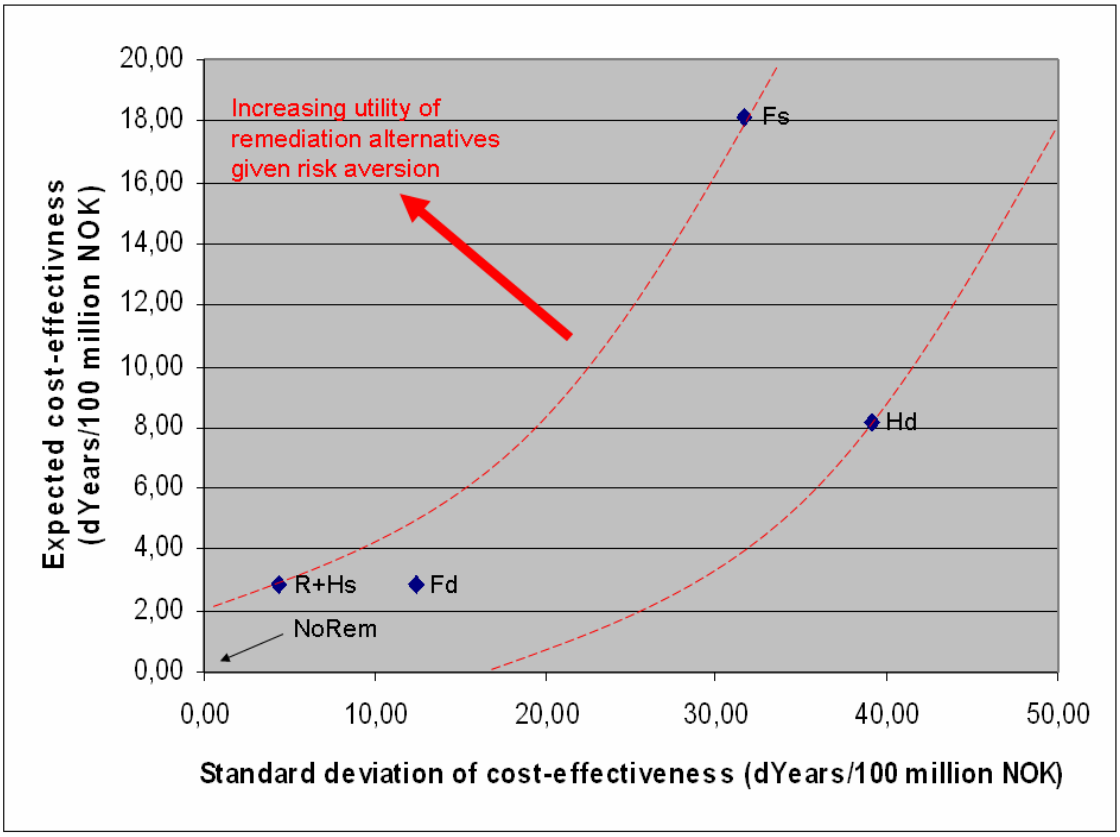


Figure 16. *Expected Value – Standard Deviation approach to cost-effectiveness analysis of remediation measures.*

In **Figure 16** fjord areas R+Hs and Fd are low cost-effectiveness - low uncertainty remediation areas, whereas Fs and Hd are high cost-effectiveness - high uncertainty options. Risk averse managers will prefer options as close to the upper left hand corner of **Figure 16** as possible (high return - low uncertainty). Dotted lines in the figure are an example of so-called indifference curves where a decision-maker is indifferent to trade-offs between expected cost-effectiveness (CE) and standard deviation of CE [19]. For a risk averse manager it is clear that Fs is a better option than Hd. But depending on *the level of* risk aversion remediation in R+Hs, and even Fd, may be preferred to Fs. Very risk averse managers may be willing to trade large reductions in expected cost-effectiveness against large reductions in standard deviation of cost-effectiveness. Such managers may be inclined to conduct remediation in e.g. R+Hs, before Fs, especially if such an alternative also implies smaller absolute resource commitments (which is unfortunately not the case in the Frierfjord example).

Given the large expected cost-effectiveness of Fs, a solution to the management dilemma between R+Hs and Fs would be to carry out pilot measures that reduced uncertainty about thin capping remediation costs and effects in the Frierfjord shallow alternative (Fs). County planners have taken a similar course in practice by commissioning trials of thin capping.

4. Conclusions

This report has demonstrated the use of uncertainty analysis for remediation costs equivalent to a "level 2" analysis in the terminology of the Norwegian EPA (SFT). However, the uncertainty analysis model/approach summarised in **Figure 1** is generic, and the level of risk analysis to which it is applied depends on the decision context and the site-specificity of the data available.

Comparing confidence bounds of remediation costs with effectiveness in lifting health advisories and associated economic benefits, is currently helping the county planners to screen remediation alternatives at an aggregate regional level. Some fjord areas are significantly more cost-effective for remediation purposes than others. Observing the 95% confidence bounds the SF-tool indicates that remediation has an incremental effect mainly for boxes R, Fs and Hs; that the greatest effect is achieved for box Fs; and that the marginal effect/area for Hd and Fd is lower than for Fs, i.e. effects are not linear in terms of the area remediated. The cost-effectiveness analysis uncovers considerable uncertainty in both costs and effect at this pre-feasibility stage of the analysis.

Further data collection is justified to reduce parameter uncertainties in the SedFlex abiotic, biotic and cost models, before large scale remediation efforts can be approved or rejected with requisite confidence. The most-cost-effective alternative is also the most uncertain (thin capping in Fs), indicating large potential returns to further data collection for this alternative through early implementation of pilot projects on thin capping. Consistent uncertainty and sensitivity analysis of all model components illustrated in **Figure 1** will furthermore allow county planners to determine for which parameters data collection has greatest information value.

5. References

Ayyub, B. M. (2003). Risk analysis in engineering and economics., Chapman & Hall/CRC. Boca Raton.

Breedveld, G. D., T. Bakke, et al. (2005). Risk assessment guidelines for contaminated sediment (in Norwegian). TA-2085., Norwegian Pollution Control Authority.

Brånås, M. (2003). Kost-nytte.analyse, fase 1. Pilotprosjektet Trondheim havn. Rapport nr. 2003-016, Trondheim Havn, SCC, Selmer Skanska, DNV.

DNV (2000). Kostnader ved tiltak i forurensede sedimenter og kildebegrensning. Rapport nr. 2000-3513, Det norske Veritas (DNV).

Eek, E. (2003). Pilotprosjekter om forurensede havensedimenter. Erfaringer fra pilotprosjektene, fellesmøte i Sandefjord 14-15 mai 2003, NGI.

Eek, E. (2005). Capping of contaminated sediments. Anbefalinger ved prosjektering av tildekking av forurenset sediment. NGI 20021244-4, Norges Geotekniske Institutt (NGI).

Evenset, A., L. H. Larsen, et al. (2005). Forebygging og sanering av miljøgift forurensning i Tromsø havneområde og Tromøysund. Tiltaksplan 2005-2012. Rapport nr. APN-421.2508.03, Akvaplan niva.

Forsvarsbygg (2003). Haakonsvern orlogstasjon, Bergen. Forurenset grunn og sjøbunnsedimenter. Utførte undersøkelser og tiltak på land og sjø. Sluttrapport. Rapportnr. 610012-1, Forsvarsbygg, NCC, Multiconsult AS.

Fylkesmannen_Vest-Agder (2005). Erfaringsnotat om tildekking av forurensede sedimenter(oppdatert 20/1-05), Fylkesmannen i Vest-Agder, Miljøvernavdelingen.

Hauge, A. (2005). Tiltaksanalyse for opprydding i forurenset sjøbunn. Teknisk Notat 07-10-2005. Forurensede sedimenter - Tiltaksplan i Grenland.

Hauge, A. and J. Skei (2005). Helhetlig tiltaksplan for forurensede sedimenter i Oslo havnedistrikt. Forslag. Oslo, juni 2005, Oslo Kommune.

Hydro (2003). Mudringsprosjekt. Søknad i henhold til Forurensningsloven §11 om tillatelse til mudring i sjø od disponering av masser ved Herøya Industripark i Porsgrunn Kommune. 21.05.2003, Grenland Havnevesen, Eramet, Hydro.

Laugesen, J., T. Møskeland, et al. (2001). Tiltaksanalyse for opprydding i forurensede sedimenter i Kristiansandsfjorden. Rapportnr. 2001-0807, DNV.

Myhre, K. (2002). Tiltaksplan for opprydding av forurensede sedimenter i Stavanger Havn. Miljørapport nr 1- 2002, Fylkesmannen i Rogaland. Miljøvernavdelingen.

NCC (2003). Erfaringsrapport fra miljømudring. Kamfjordkilen, Sandefjord. 17 november 2003, NCC, NGI, NIVA for Sandefjord Kommune.

Næs, K., J. Persson, et al. (2004). Dioksiner i Grenlands-fjordene (DIG). Oppsummering av forskningsprosjektet. Rapport LNR 4876-2004., Norwegian Institute for Water Research (NIVA).

Persson, N. J., I. T. Cousins, et al. (2006). "Modeling the long-term fate of polychlorinated dibenzo-p-dioxins and furans in the Grenlandsfjords, Norway." Science of the total environment (in press).

Saloranta, T. (2005). Simulating the fate of dioxins in the Greland fjords. Rein Fjord project note September 13, 2005., NIVA.

Saloranta, T. (2005). Simulating the fate of dioxins in the Grenland fjords:Remediation scenarios for the outer fjords. ReinFjord project note, November 2, 2005, NIVA.

Saloranta, T. M., J. Armitage, et al. (2006). SF-Tool multimedia package: Model code description and application examples from the Grenland fjords, NIVA-report 5216, Norwegian Institute for Water Research, Oslo, Norway.

Soldal, O. (2004). Tiltaksplan Bergen Havn. Fase II, Interconsult, NGI, NIVA, Asplan Viak Bergen AS, Universitetet i Bergen, NCC Anlegg for Fylkesmannen i Hordaland, Miljøvernavdelingen.

St.meld.nr.12 (2001-2002). Rent og rikt hav. Tilråding fra Miljøverndepartementet av 15. mars 2002, godkjent i statsråd samme dag. (Regjeringen Bondevik II).

VKM (2004). Comments on proposed maximum levels for dioxin-like PCBs in food Panel on Contaminants, Norwegian Scientific Committee for Food Safety, Adopted 25 November 2004.

Økland, T. E. (2005). En gjennomgang av kostholdsråd i norske havner og fjorder fra 1960-tallet til i dag. Kostholdsråd i norske havner og fjorder. November 2005, Mattilsynet, VKM, SFT.

Appendix 1

Table A1-1 - Database of historical remediation costs in Norway – total costs by site

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		Unit	Trondheimsfjord-Ilsvika	Sandefjord	Kristiansand-Hannevikbukta	Kristiansand-Falconbridge	Haakonsvern-fase 2-4	Haakonsvern-fase 1 småbåthavn	Bergen Havn - dredging all (<20m)	Bergen Havn - capping all (<20m)	Bergen Havn capping(20-30m)	Bergen Havn - capping all(>30m)	Tromsø	Eitrheimsvågen/Odda	Horten kanal	Oslo Havn	Stavanger Havn	Hornya (2004)
2	**SITE CHARACTERISATION**																	
3	Sediment area	m²	10 800	87 000	330 000	7500++	330 000	25 000	2 700 000	2 700 000			312 000	30 000	10 000	1 000 000	400 000	25 000
4	Water depth	Min (m)		3	7	15				0	20	30				15		6
5		Median (m)	20							10	25	40			2	18		
6		Max (m)		7	27	27	65	10	20	20	30	50		10		20	40	11
7	Bottom topography	type	?															
8		average slope	?															
9	Distance from land	Median(km)	?															
10	Local current (mean)	cm/s	?						4	4	4	4						
11	Contaminant type	type	PCB, PAH, TBT	PCB, PAH, TBT,	Dioxins, HCB, PCB, PAH, TBT		PCB	PCB	PCB, Hg	PCB, Hg	PCB, Hg	PCB, Hg	PAH, TBT					dioxins, CHC
12	Sediment type	type	sand,silt						clay, silt	clay, silt	clay, silt	clay, silt						clay, silt
13	Sediment depth (dredged)	m	1	1			0	0	0				0					1
14	Sediment volume (dredged)	m³	10 800	41 000	0	3 000	66 000	4 100	810 000				93 600	15 000		500 000		25 000
15	Cap thickness (sand, local)	m	na	0	1	,3 pukk;0,25 sand			1	0	0	0		0		0		
16	Cap thickness (clay, extensive)	m														0		
17	Year of cost data	Year	2 003	2 003	2 003	2 003	1 999	1 998	2 001	2 001	2 001	2 001	2 005			2 005	2 004	2 004
18	Costing context	p-projected b-competitive bid a-actual	a	a	a, excl VAT		a, incl VAT	a, incl VAT	p	p	p	p	a	a		p, excl VAT	p	a
19	**REMEDIAL MEASURE:**																	
20	**VARIABLE COST COMPONENTS**	NOK	13 400 000	16 000 000	9 200 000		161 000 000	25 000 000	1 282 500 000	492 750 000			60 900 000	32 104 935	3 500 000	135 000 000		23 000 000
21	**Physical measures in sediment**																	
22	Preparation/clearing sea bottom	NOK		1 500 000										155 750				5 000 000
23	Capping (geotextile cover and sand, gravel	NOK								492 750 000								
24	Capping (geotextile only)	NOK												14 242 546				
25	Capping (cement "matress")	NOK													3 500 000			
26	In situ treatment/ Stabilisation	NOK																
27	Capping, thin (clay, thin layer 10cm)	NOK																
28	Capping, ordinary (sand/clay, 30-50 cm lay	NOK			9 200 000													
29	Dredging (hydraulic)	NOK		9 000 000			110 000 000	15 000 000	351 000 000									
30	Dredging (mechanical)	NOK	1 900 000															12 000 000
31	Deposition (deep water)	NOK																
32	Deposition (shallow water, geotextile bags	NOK							113 400 000									
33	Deposition (shallow, capping w on-site sed	NOK		5 500 000					69 100 000									
34	Preparattion clean-up on land (shoreline dep	NOK					16 000 000											
35	**Shoreline deposition**																	
36	Simple wo dewatering	NOK					35 000 000	10 000 000	283 500 000									6 000 000
37	Advanced w dewatering	NOK	7 000 000											14 531 865				
38	Other costs (unspecified)	NOK																
39	**Transportation costs**																	
40	Transportation	NOK																
41	**Treatment/deposition on land**																	
42	Deposition (subterranean, rock)	NOK							162 000 000									
43	Dewatering	NOK																
44	Separation	NOK																
45	Stabilisation in deposition site	NOK	4 500 000															
46	Biological treatment	NOK																
47	Deposition on land (municipal)	NOK																
48	Deposition on land (NOAH, open landfill)	NOK							283 500 000									
49	Other costs (unforeseen costs)	NOK												3 174 754				
50	**FIXED COST COMPONENTS**	NOK	3 538 000	3 000 000	960 000			5 000 000						4 682 753		63 000 000		3 000 000
51	Sediment status evaluation costs	NOK	800 000	1 000 000	660 000									1 480 940				
52	Mobilisation and demobilisation costs	NOK	38 000															
53	Diffusion control measures costs	NOK		1 500 000														
54	Monitoring and evaluation costs	NOK	800 000	500 000	300 000			5 000 000						70 908				
55	Consulting costs	NOK	200 000															
56	Project administration costs	NOK	300 000											2 856 272				
57	Reporting costs	NOK	1 400 000															
58	Other costs (unspecified)	NOK												274 633				
59	**TOTAL COST (reported)**	**NOK**	**17 300 000**	**19 000 000**	**21 000 000**		**165 000 000**							**36 000 000**		**180 000 000**		**26 000 000**
60	**TOTAL COST (calculated)**	**NOK**	**20 476 000**	**22 000 000**	**11 120 000**		**161 000 000**	**35 000 000**	**1 282 500 000**	**492 750 000**				**41 470 441**				**26 000 000**
61																		
62	Unit variable costs	Mean (kr/m²)	1 241	184	28		488	1 000	475	183	n.a.	n.a.	195	357	350	135	n.a.	920
63																		
64	Unit costs (in situ treatment)	Min. (kr/m³)	294						543									
65		Mean (kr/m³)																
66		Max. (kr/m³)	589						783									
67	Unit costs (in situ treatment)	Min. (kr/m²)																
68		Mean (kr/m²)								183	215	236		360				
69		Max. (kr/m²)																
70	**Source:**		11	13	0	0	11,17	17	14	14	14	14	18	15	0	19	20	16

Table A1-2 - Database of historical remediation costs in Norway - average unit costs by site

Data in **red** are reported unit values; data in **black** are calculated based on total costs reported in literature	Locality	Trondheimsfjord-Ilsvika	Sandefjord	Kristiansand-Hanneviksbukta	Kristiansand-Falconbridge	Haakons-vern fase 2-4	Haakonsvern fase 1 småbåthavn	Bergen Havn - dredging all (<20m)	Bergen Havn - capping all (<20m)	Bergen Havn capping (20-30m)	Bergen Havn - capping all(>30m)	Tromsø	Eitrehiems-vågen/Odda	Horten kanal	Oslo Havn	Stavanger Havn	Herøya	Unit costs remedial measures					
	Unit																	Min. (kr/m³)	Median (kr/m³)	Max. (kr/m³)	Min. (kr/m²)	Median (kr/m²)	Max. (kr/m²)
REMEDIAL MEASURE:																							
VARIABLE COST COMPONENTS																							
Physical measures in sediment																							
Preparation/clearing sea bottom	NOK/m²	n.a.	17	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2	n.a.	n.a.	n.a.	200				2	17	200
Capping (geotextile cover and sand, gravel)	NOK/m²	n.a.	n.a.	n.a.	200	n.a.	n.a.	n.a.	183	215	236	n.a.	n.a.	n.a.	n.a.	325	n.a.				183	215	325
Capping (geotextile only)	NOK/m²	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	158	n.a.	n.a.	75	n.a.				75	117	158
Capping (cement "matress")	NOK/m²	n.a.	n.a.	n.a.	500	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	350	n.a.	n.a.	n.a.				350	425	500
In situ treatment/ Stabilisation	NOK/m²	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.				0	#NUM!	0
Capping, thin (clay, thin layer 10cm)	NOK/m²	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	10	n.a.	n.a.				10	10	10
Capping, ordinary (sand/clay, 30-50 cm layer)	NOK/m²	n.a.	n.a.	20	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	39	n.a.	n.a.				20	30	39
Dredging (hydraulic)	NOK/m³	n.a.	103	n.a.	n.a.	333	600	130	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	103	232	600			
Dredging (mechanical)	NOK/m³	176	n.a.	n.a.	n.a.	n.a.	n.a.	65	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	75	n.a.	480	65	125	480			
Deposition (deep water)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	90	n.a.	n.a.	90	90	90			
Deposition (shallow water, geotextile bags)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	140	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	140	140	140			
Deposition and capping w on-site sediment	NOK/m³	n.a.	134	n.a.	n.a.	n.a.	n.a.	110	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	110	122	134			
Preparattion clean-up on land (shoreline deposition)	NOK/m³	n.a.	n.a.	n.a.	n.a.	242	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	242	242	242			
Shoreline deposition																							
Simple wo dewatering	NOK/m³	n.a.	n.a.	n.a.	n.a.	530	2439	350	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	240	240	440	2439			
Advanced w dewatering	NOK/m³	648	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	969	n.a.	n.a.	n.a.	n.a.	648	808	969			
Other costs (unspecified)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	#NUM!	0			
Transportation costs																							
Transportation	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	20	n.a.	n.a.	20	20	20			
Treatment/deposition on land																							
Deposition (subterranean, rock)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	200	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	200	200	200			
Dewatering	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	#NUM!	0			
Separation	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	#NUM!	0			
Stabilisation in deposition site	NOK/m³	417	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	417	417	417			
Biological treatment	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	#NUM!	0			
Deposition on land (municipal)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1840	n.a.	n.a.	n.a.	n.a.	n.a.	1840	1840	1840			
Deposition on land (NOAH, open landfill)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	350	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	350	350	350			
Other costs (unforeseen costs)	NOK/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	212	n.a.	n.a.	n.a.	n.a.	212	212	212			
FIXED COST COMPONENTS	% of variable costs	26 %	19 %	10 %	n.a	n.a.	20 %	n.a.	n.a.	n.a	n.a	n.a.	15 %	n.a.	47 %	n.a	13 %	10 %	18,8 %	47 %			
Sediment status evaluation costs	% of variable costs	6 %	6 %	7 %	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	5 %	n.a	n.a	n.a	n.a	4,6 %	6,1 %	7,2 %			
Mobilisation and demobilisation costs	% of variable costs	0 %	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	0,3 %	0,3 %	0,3 %			
Diffusion control measures costs	% of variable costs	n.a	9 %	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	9,4 %	9,4 %	9,4 %			
Monitoring and evaluation costs	% of variable costs	6 %	3 %	3 %	n.a	n.a	20 %	n.a	n.a	n.a	n.a	n.a	0 %	n.a	n.a	n.a	n.a	0,2 %	3,3 %	20,0 %			
Consulting costs	% of variable costs	1 %	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	1,5 %	1,5 %	1,5 %			
Project administration costs	% of variable costs	2 %	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	9 %	n.a	n.a	n.a	n.a	2,2 %	5,6 %	8,9 %			
Reporting costs	% of variable costs	10 %	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	10,4 %	10,4 %	10,4 %			
Other costs (unspecified)	% of variable costs	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	1 %	n.a	n.a	n.a	n.a	0,9 %	0,9 %	0,9 %			
Unit variable costs (not including fixed costs)	Mean (kr/m²)	1241	184	28	n.a.	488	1000	475	183	n.a.	n.a.	195	357	350	135	n.a.	920	28	421	1241			

Note calculated based on total costs in Table A1-1

Sources:

0.DNV (2000)
1.US EPA Remediation Guidance Document (EPA 905-R94-003)
2.Haakonsvern (pers com.)
3.Norzink, Odda (pers com)
4.NGI(pers com Audun Hauge)
5.US Army Crops (pers com Norman Francinques)
6.Järnsjöprosjektet
7.Jordrenseteknologier: (Boom verlag 1992)
8.Market price for municipal landfill
9.DNV (2001)
10.NIVA(1999)
11. DNV Consulting (2003)
12. NGI(2003) Pilotprosjekter om forurensede havnesedimenter (utkast)
13 NCC(2003) Erfaringsrapport fra miljømudring Kamfjordkilen, Sandefjord.
14. NIVA, NGI, Interconsult (2002) Tiltaksplan for Bergen Havn
15. pers com. Emil.jonsendal@boliden.com
16. pers com arve.solberg@hydro.com
17. Forsvarsbygg (2005)
18. Evenset(2005)
19. Hauge og Skei (2005)
20. Myhre(2002)

List of sources to data in Table A1-1

Appendix 2 Phase I - Remediation cost results

Introduction

Appendix 2 shows input data and results from the first phase of uncertainty analysis of remediation costs in the Grenland Fjords, and Frierfjorden specifically. The uncertainty analysis is based on a review of available published data from previous remediaiton pilot projects in Norway. In phase II of uncertainty analysis experts on remediation costs (NGI) were asked to validate and revise input probability distributions. The result of this revision, viewed above, was a significant downward adjustment in expected remediation costs, and some reduction in uncertainty.

Summary of PDFs in cost model phase I

Table A2-1 provides asummary of the probability density functions (PDFs) used in the remediation cost calculation model. Expected value is the mean calculated using parameters given in the table.

Table A2-1 Summary of probability density functions (PDFs) describing uncertainty of remediation costs

	A	B	C	D	E	F	G	H	I	J
2	Item	PDF variable	Unit	Probability distribution (PDF)	Min	Median/ mean/mode	Max	Bottom %	Upper %	Expected (value)
3	Fixed costs	*fc*	% of variable costs	Triangular*	10 %	19 %	25 %	5	95	18 %
4	Dredging depth	*dd*	m	Uniform	1		2			1,50
5	Dredging cost	c_{dr}	kr/m3	Triangular(fit)	65	65	706,5			278,83
6	Capping cost (ordinary, sand)	c_{oc}	kr/m3	Triangular	-20 %	130	20 %			130,00
7	Active sediment layer (shallow)	as_s	m	Uniform	0,02		0,06			0,040
8	Capping safety factor (shallow)	csf_s		Uniform	5		10			7,50
9	Active sediment layer (deep)	as_d	m	Uniform	0,001		0,02			0,011
10	Capping safety factor (deep)	csf_d		Uniform	0		10			5,00
11	Capping cost (thin, clay)	c_{tc}	kr/m3	Uniform	50		200			125,00
12	Shoreline deposition costs	c_1	kr/m3	Triangular	192	240	288			240,00
13	Transport costs	c_t	kr/m3/km	Uniform	4		6,667			5,33
14	Cost deposition NOAH	c_4	kr/m3	Uniform	80		160			120,00
15	Cost deep water deposition	$c_{2\&3}$	kr/m3	Uniform	72		108			90,00
16	Pre/post bid price variation(Haakonsvern1&2)	*b*	kr	triangular	-46 %		103 %			86 %
17	Own weight sediments		tonne/m3	none						1,3
18	Mean sediment depth deep water diposal site		m							
19	Mean depth Gunnekleivfjord		m	none						4,76
20	Transport distance NOAH	*km*	km							125

Note: * triangular with confidence intervals at %.

Expected costs

Table A2 below shows the expected costs of remediation scenarios simulated in SF tool.
The alternative including dredging of Skien River and disposal in and capping of Gunnekleiv fjord are excluded both due to (i) lack of effect shown by SF tool and (ii) excessive sediment volume compared to Gunnekleiv fjord. The alternative including disposal at NOAH Langøya is excluded from the analysis due to excessive transport costs. The alternative including deep water disposal (Hs + deep water disposal) is technically most feasible and the cheapest, and is therefore kept in the cost calculations for all scenarios. Costs increase incrementally from 600 million kroner to 905 million kroner as additional areas (Hd, Fs, Fd) are assumed capped in SF tool.

Table A2-2 Expected costs of remediation scenarios simulated in SF tool

SF remediation scenario areas	Method	Area	Expected cap thickness	Expected volume	Expected costs	Comment	
		m2	m	m3	kr		
	Dredging Rs (Skien River)	2 045 193		3 067 790	855 401 996	not evaluated further	
	Dredging Hs	1 017 778		1 526 667	425 685 677		
	Capping Rs (rest of Gunnekleiv)	479 202	0,30	143 760	18 688 861	not evaluated further	
Disposal alternative 1	Disposal (Gunnekleiv)	320 728		1 526 667	366 400 105	not evaluated further	
	Transport (deep water)			1 526 667	32 568 898	4	km
Disposal alternative 2&3	Disposal (deep water)			1 526 667	137 400 039		
	Transport (NOAH)			1 526 667	1 017 778 068	not evaluated further	
Disposal alternative 4	Disposal (NOAH)			1 526 667	183 200 052	not evaluated further	
	Fixed costs (Hs dredging, capping, deep water disposal)				106 094 681		
Hs+deep water disposal	**Total costs**				**701 749 295**		
	Capping Fs	6 796 813	0,20	1 359 363	169 920 319		
	Fixed costs (capping Fs)				30 265 260		
Hs+Fs+deep water disp.	**Total costs**				**901 934 874**		
	Capping Hd	2 992 938	0,05	157 129	19 641 155		
	Fixed costs (capping Hd)				3 498 373		
Hs+Fs+Hd+deep water disp.	**Total costs**				**925 074 403**		
	Capping Fd	10 481 110	0,05	550 258	68 782 286		
	Fixed costs (capping Fd)				12 251 118		
Hs+Fs+Hd+Fd+ deep water d	**Total costs**				**1 006 107 806**		

Cost uncertainty

Cost uncertainty was simulated in @Risk™ software. The model was run 3000 using Latin Hypercube sampling from the PDFs shown in Table 5. Latin Hypercube (LHC) sampling reproduces the input PDFs better than Monte Carlo simulation, particularly for smaller sample sizes, because LHC has 'memory' of where it has sampled previously, whereas Monte Carlo sampling does not (Vose, 1996).

Figure A2-3 shows that with the uncertainty specified in Table 5 only 5% of outcomes are less than 465 million kroner, while only 95% are less than 1,7 billion kroner. The most important variables driving variation in total costs as seen in the Tornado graph are: (i) unit dredging costs (0,707), (ii) capping safety factor (deep) (0,451), (iii) dredging depth (0,352), and (iv) unit capping cost (thin cap) (0,271) (Figure A2-4).

Figure A2-3 PDF total remediation costs

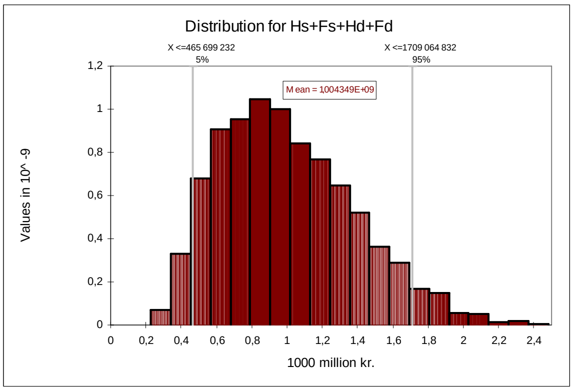
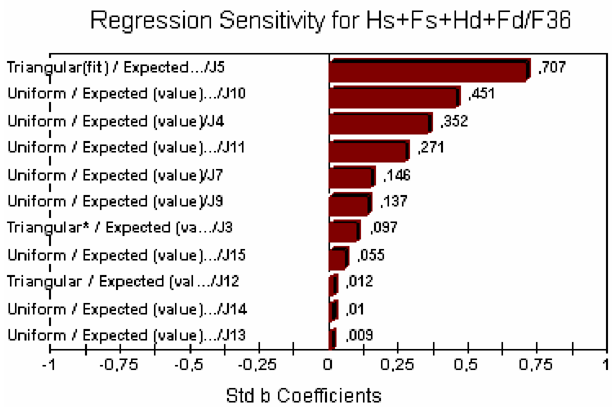


Figure A2-4 Tornado graph



A similar PDF for total costs can be output for each of the scenarios modelled in SF tool.

Norwegian Institute for Water Research

Gaustadalléen 21 • NO-0349 Oslo, Norway
Telephone: + 47 22 18 51 00 • Faks: 22 18 52 00
www.niva.no • post@niva.no