# Sediment remediation through activated carbon amendment

## Long-term monitoring of a field pilot in Trondheim Harbour

Forskningsrådet Havkyst Prosjekt 185032
Sluttrapport, april 2011

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## Background of Project

Goals: Havkyst project 185032 was a follow-up of an NFR-financed Strategic Institute Program on sediments at NGI that terminated at the end of 2007 (2004-2007). In the context of the current HavKyst project, activated carbon amendment has been applied (April 2008) as a novel remediation technique in a pilot project in Trondheim Harbour, cofinanced by NFR and Trondheim Harbour Authorities. The present project aimed at the establishment of novel pilot testing fields and their long-term follow-up and monitoring in Trondheim Harbor.

The specific goals addressed in this Havkyst project are expressed in the following questions:

Research Aim: Pilot testing of field implementation of Activated Carbon Amendment to sediments in Trondheim Harbour, as an inexpensive and practical in-situ remediation technology.

The technique of Activated Carbon Amendment has many advantages:

- Better long-term effects than conventional capping, as newly deposited sediment is mixed with the existing sediment and remediated by the activated carbon.
- No need for dredging and deposition, thus avoiding all controversies around this technique.
- No reduced sailing depth
- No need for traditional capping masses, therefore reduced need for transport.

## Main question and goals:

A. How would AC amendment be deployed for in situ treatment of sediment with overlying water?
So far, it has only been used on tidal flats. In most Norwegian situations, it will be necessary to apply it to sediments that are constantly underwater.

B. How does amendment with AC influence the biodiversity and bioaccumulation of organic contaminants in sediments under field conditions?
The most important goal of AC amendment is to reduce uptake in organisms, foodchains and humans in order to alleviate seafood consumption restrictions.

C. How does amendment with AC influence the release of organic contaminants in sediments under field conditions?
It was researched how AC reduced the sediment-to-water flux of organic pollutants in Trondheim Harbour.

## Organisation

This project was a collaborative effort between the Norwegian Geotechnical Institute (NGI), Stockholm University (SU) and Trondheim Harbour. The project was led by Prof. Gerard Cornelissen (NGI). Dr. Marie Elmquist did much of the work as a post-doctoral researcher. Assistance in the project was from Prof. Gijs D. Breedveld, Dr. Amy M. P. Oen, Dr. Espen Eek, Dr. Hans Peter Arp, Marianne Kvannås, Anita Nybakk (NGI). The biological parts of the research were led by Prof. Jonas S. Gunnarsson (SU), with assistance from Dr. Jenny Hedman, Göran Samuelsson and Øystein Stokland (Marine Bunndyr AS). Staff from Trondheim Harbor included Marit Sølvberg, Olaf Rovik, Per Bakken, Jan Mostervik, Tor Øyvind Berg and Tor Ove Gaare.

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# Activated Carbon for Sediment Remediation

## Hydrophobic Organic Compounds

Norway, as well as many other countries, is faced with significant environmental problems posed by classical hydrophobic organic contaminants in marine sediments (HOCs) like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls, (PCBs), and polychlorinated dibenzodioxins and -furans (PCDD/Fs). In addition, "new" priority pollutants like brominated flame retardants (polybrominated diphenyl ethers, PBDEs) have been detected in water and sediment. As a result of these high pollution levels, consumption restrictions exist for fish and other seafood from many fjord areas in Norway. Removal with subsequent treatment or disposal of all contaminated sediments would be a billion-kroner task, so it is highly necessary to find practical and cost-effective methods to reduce the risk of HOCs in sediments without removing the material.

## Strong sorption to Carbonaceous Materials

Recent research shows that carbonaceous materials such as soot, charcoal, unburned coal and kerogen, exhibit very strong affinities for HOC binding (sorption). These so-called "black carbon" materials are present in all sediments and can significantly increase the overall HOC binding of these natural matrices. The Norwegian Geotechnical Institute (NGI), has carried out important research in the elucidation on the role of soot and coal in HOC sorption to sediments.

This strong sorption of 'black carbon' for HOCs has important consequences, as it will decrease persistent HOC uptake in biota and thereby reduce transport in the food chain and transport from contaminated sediments to overlying water.

## Activated carbon amendment to reduce risks

Stanford University was the first institute in the world to note that this strong sorption behaviour could be used in an engineering perspective. By deliberately adding a clean carbonaceous material such as activated carbon (AC) to sediment, one should be able to increase its sorption strength, and consequently sequester (very tightly bind) HOCs and thereby decrease uptake in biota and transport to overlying water. Pilot experiments in the laboratory showed that AC amendment was indeed effective. For example, the addition of 3.4% AC to a harbor sediment lowered the potential exposure of biota to PAHs by 90-95%.

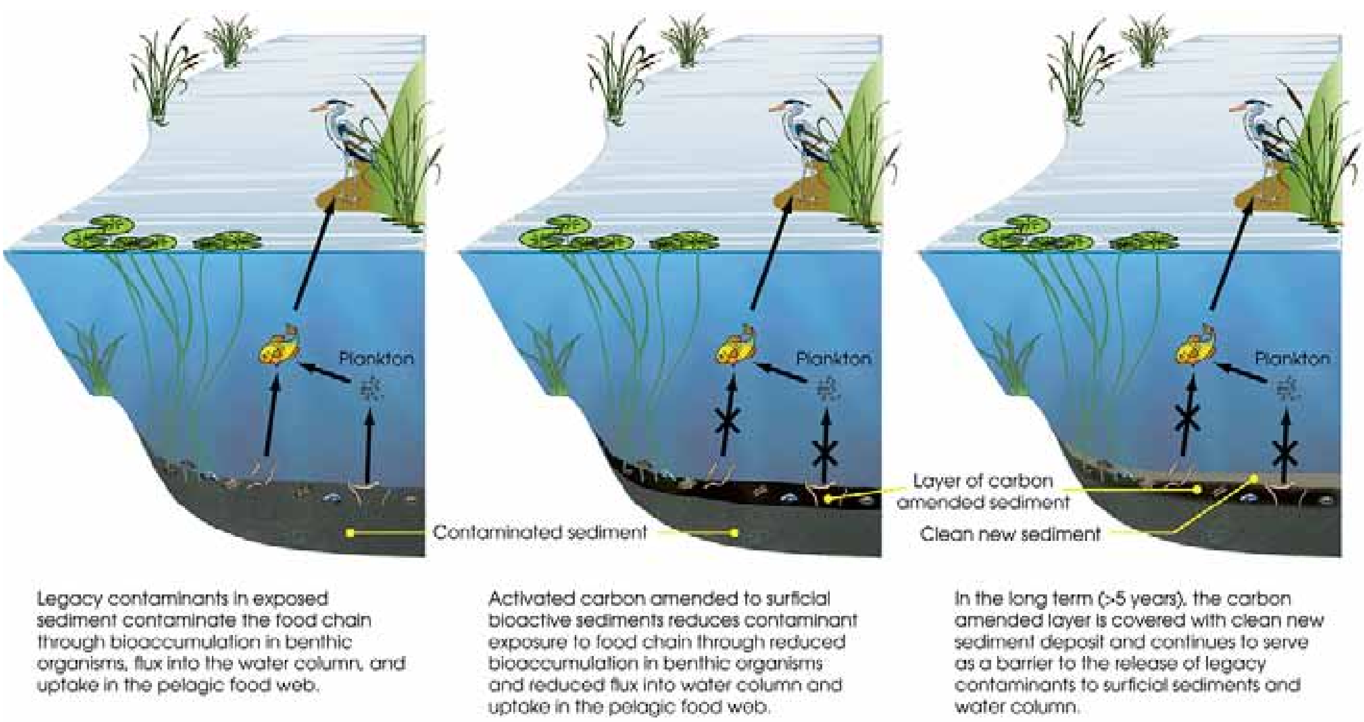



***Figure 1.*** *Activated Carbon Amendment*

The advantages of AC amendment over many other remediation methods include i) it can be used as an in situ risk reduction method, ii) the price is low (at about 10 NOK/m2 cost for the AC), and iii) it overcomes significant controversies associated with disposal of dredged materials. Also, unlike dredging, which requires removal of the full depth of contamination, AC amendment of sediment need only treat the upper sediment layer comprising the biologically active zone. The most important advantage over capping, for example, is that AC actively binds the pollutants and is probably more effective in long-term risk reduction.

These and other considerations indicate that AC amendment is a promising method for the reduction of risks of HOCs in sediment. This way, uptake in biota and biomagnification through the food chain will be lowered. As a consequence, ecosystem health will increase, and levels of toxic compounds in seafood will decrease and consumption restrictions can be lifted. In addition, much money can be saved if the cost of cleaning up contaminated sediments is reduced by efficient, innovative environmental technologies such as AC amendment.

### Long-term stability of AC-immobilized contamination

AC is a highly condensed and inert material that is stable under environmental conditions for a long time. In addition, organic compounds are sorbed to AC so strongly that they will not be released within short time frames. Therefore it is almost certain that the contamination will be stable and unavailable for uptake and leaching for at least 50-100 years.

### Earlier field pilots

Only two earlier pilot studies in the field have been established: one at Hunters Point, San Francisco, CA, and the other at Grasse River, NY. The first field test aimed at remediating Polychlorinated Biphenyl (PCB)-contaminated mud flats in the San Francisco Bay, the second field study was done in a freshwater river bed also contaminated with PCBs. In both of these studies heavy equipment was used to mix the AC into the sediment, experimental plots were relatively small (maximally 5 x 5 m), and granulated AC was used without additions of sand or clay. Both studies demonstrated a decreased bioaccumulation by benthic biota, a decreased PCB porewater concentration, and no significant negative effects on benthic organisms. An overview of all ongoing AC field trials is given in Figure 2.

## The present study in Trondheim Harbour

The present study was done in a marine underwater environment in Trondheim Harbor, Norway, and describes a field experiment where thin-layer in situ capping with Activated Carbon (AC) was tested using three different methods:

a) AC only,
b) AC covered by a thin layer of sand,
c) AC mixed with clay.

Comparisons were made to capping with sand only and to a control site without the addition of any capping material. To supplement the previous USA pilots, the current study added several elements that have not been studied before;

1) no sediment-AC mixing was done to preserve the benthic community and to reduce handling costs;

2) AC-clay mixtures and AC covered by a thin sand layer were employed to facilitate underwater AC placement and prevent erosion of the AC amendment;

3) the experiment was carried out in a marine underwater system, and was the largest in the world during its establishment;

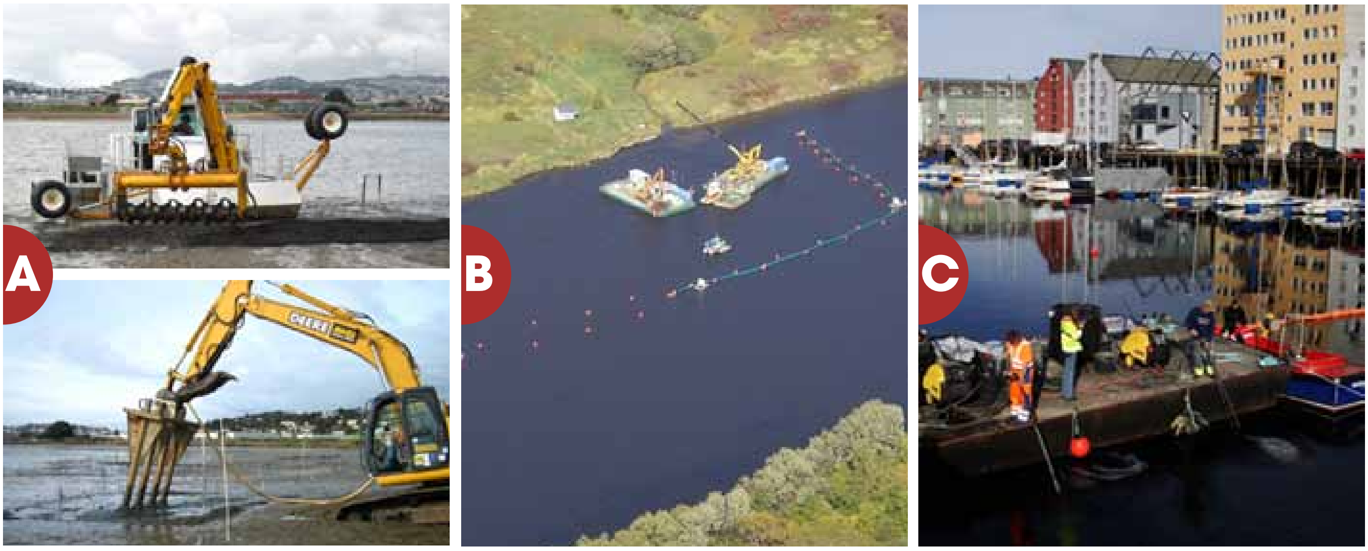
4) in situ sediment-to-water PAH fluxes were measured using recently developed benthic flux chambers;

5) the studied compounds were polycyclic aromatic hydrocarbons (PAHs);

6) in situ pore water concentration profiles were measured using a new passive sampler technique, where the sampler is directly inserted into the sediment and left in situ;

7) effects of the AC were also studied on the benthic macrofauna compositition and biodiversity (this has only been described for mudflats before).

***Figure 2.*** *Pilot-scale demonstrations of activated carbon amendment into sediment at five field sites.*



***A)*** *Application of activated carbon in a tidal mud-flat at Hunters Point Navy Shipyard, San Francisco Bay, CA using two application devices (2004 and 2006). The Aquamog (top) using a floating platform approached the site from water and used a rototiller arm while the slurry injection system (bottom) was land based and applied a carbon slurry directly into sediment.*

***B)*** *Application of activated carbon under 15 feet of water at Grasse River, NY, USA (2006). The site was enclosed with a silt curtain and application was performed using a barge mounted crane. Placement and mixing of the AC was achieved using two devices: 1) a 7-by-12-foot rototiller-type mixing unit; and 2) a 7-by-10-foot tine sled device.*

***C)*** *Application of activated carbon slurry directly onto sediments at Trondheim Harbor, Norway (2008). AC-salt water slurries with/without powdered bentonite clay were pumped 3-5 ft above the sediment bed under 20 ft of water. Part of the AC-only field was successfully covered with 5 mm sand to protect from erosion.*

***E)*** *Application of AC-clay mixture at 100 and 300 ft depth, Grenlandsfjords, Norway (2009), led by NGI and NIVA. A hopper dredger was used to pick up clean clay from an adjacent site. After AC-clay mixing, the trim pipe was deployed in reverse to place an AC-clay mixture on the sea floor. Sediment-profile imaging and sediment coring (bottom figure) showed that placement of an even active cap was successful.*

***D)*** *Application of activated carbon in a pelletized form (SediMiteTM ) using an air blown dispersal device over a vegetated wetland impacted with PCBs near James River, VA, USA (2009). Picture below illustrates bioturbation induced breakdown and mixing of pelletized carbon with a fluorescent tag in a laboratory aquarium.*

# The field trial in Trondheim

## Field establishment

The field experiment was carried out in a channel in the outer part of the Trondheim harbour, Norway (Kanalen Figure 3).

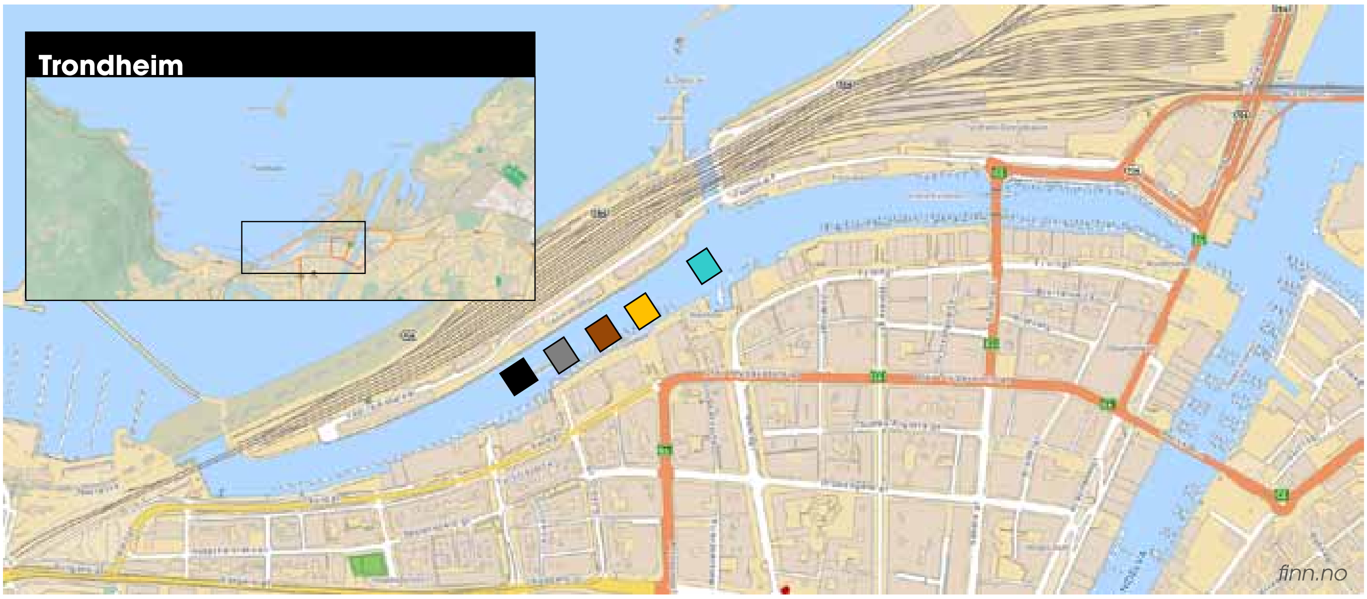



***Figure 3.*** *Location of the pilot fields at Kanalen, Trondheim. Field size: 15 x 15 m. At least 100 m from the amended fields to the reference field (blue). Black: AC-only; Grey: AC+clay; Dark brown: AC+ sand; Yellow: Sand-only.*

## Approach

Water depth is 4-6 m depending on the tide. Sediments in the Canal were moderately contaminated with PAHs and PCBs.

Five experimental field sites were established in April 2008:

1. reference site, no capping,
2. site capped with AC only,
3. site capped with AC mixed with bentonite clay,
4. site capped with AC and then covered by 5 mm of sand, and
5. capping with sand only (5 mm), to discern the effect of AC from that of the sand.

The purpose of the clay was threefold:
i) to create a viscous slurry to facilitate placement,
ii) to maintain the AC in place, i.e. protect it from lateral advection and increase the longevity of the capping treatment (tidal current up to 20 cm s-1) and
iii) add a more natural and viable substrate to the benthic fauna. The purpose of the sand capping over the AC was also to protect the AC from erosion. The size of the experimental fields was ca 200 m$^2$ (slightly smaller than 15 x 15 m). The amount of AC was 5 kg AC per m$^2$.

Powdered AC was used since it had proven effective for lowering pore water concentrations in pilot laboratory trials with several sediments. AC was mixed with a 10% w/w NaCl solution in a cement blender (AC:water 1:3 v/v; 10 min) on a pontoon in the harbor. The purpose of the salt was to saturate the AC pore system with water that was slightly heavier than surrounding water, to facilitate AC particle settling. For the AC-only and AC+sand fields, this slurry was pumped out with a flexible hose (Ø 5 cm) and released approximately one meter above the sediment bed. For the AC+sand fields, a 5-mm thick sand cap (particle size 0-1 mm construction sand) was placed on top of the AC cap, 24 h after placing the AC, by spraying the dry sand under the water surface using sand blasting equipment. For the AC+clay field, AC and bentonite clay were mixed 1:1:6 with 10%-NaCl solution and pumped out as described above.

# Successful placement

Underwater ROV video observations were made by GeoSi, and revealed the following information for the different fields:

1. AC-only: the AC was clearly visible on the seafloor on day 1 as a black 5 mm layer on top of the sediment covering most of the field except a few small patches of bare sediment (Figure 4b). After 5 months the sediment surface was not black anymore, but of more natural gray-brownish color. A vertical section of the sediment revealed that the AC layer was still in place forming an approximately 5 mm black layer covered with a few mm of newly sedimented clay.

2. AC+clay: the AC+clay suspension was spread patchily on the sediment surface on day 1 (Figure 5a). Five months later, however, the ROV images revealed a more homogeneous and smooth sediment surface (Figure 5b), probably due to the bioturbation activity of the macrofauna, and the field was looking very similar to the reference site, except for the absence of algal mats and other epiphytes visible at the reference site, which did not reappear within 5 months. The ROV observations also revealed the presence of epibenthic macrofaunal species, e.g. a few asteroid seastars (Asteroidea) and many highly mobile brittle stars Ophura sarsi.

3. AC+sand: Video recordings during sand placement showed that the covering of AC by sand was successful. The AC remained on the sediment surface while the sand was deposited on top of it (Figure 6a). The sand formed a 0.5 - 1 cm surface layer protecting the AC from resuspension and erosion. Five months later the sand was still on the sediment and no AC was visible at the surface. Vertical sections showed that the AC was still in place forming a ca 5 mm dark layer under the sand (Figure 6c).

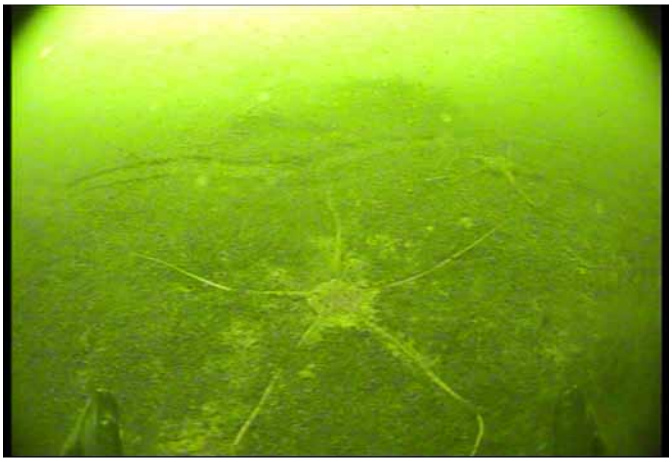


*Figure 4a*

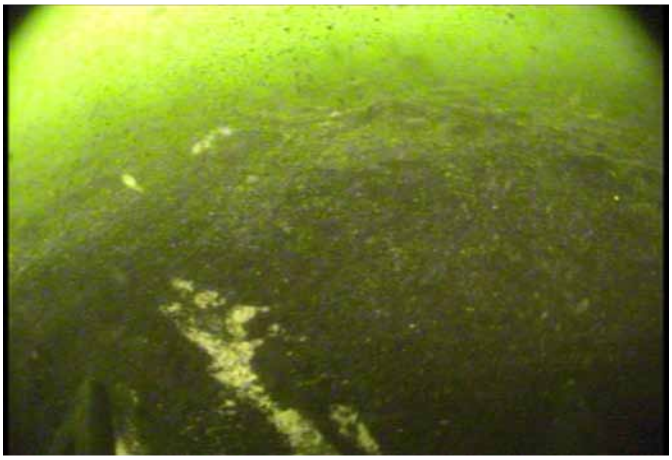


*Figure 4b*

***Figure 4.*** *Sediment surface images taken with ROV video camera. a) Reference site and b) AC-only field one day after placement. Note the presence of several epibenthic brittle stars Ophiura sarsi at the reference site a) and the black surface layer of AC in b).*

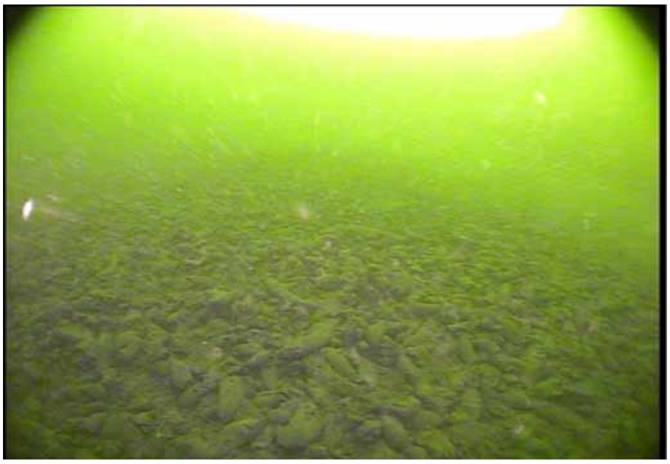


Figure 5a


Figure 5b

***Figure 5.*** *The AC+clay field after one day a) and 5 months b). Shortly after amendment the viscous slurry patchily covers the sediment with clay lumps. After 5 months the AC+Clay cap layer is evenly spread out due to the bioturbation activity of benthic macrofauna such as the epibenthic brittle star Ophiura sarsi, shown below (b).*


Figure 6a


Figure 6b


Figure 6c

***Figure 6.*** *The AC+sand field during sand placement a), after one day b) and after five months c) after amendment. A polychaete worm shows a stress response in b), i.e, lays on the sediment surface, (normally it stays burrowed in the sediment). In c) the sediment was disturbed with the ROV revealing the AC layer under the sand on top. After resuspension the AC sedimented out again relatively fast.*

# Chemical effectiveness

## AC contents in the capped sediments

AC was initially applied as a 2-5 mm thick surface layer. Bioturbation by the benthic macrofauna mixed the AC into the sediment down to a depth of around 3-4 cm (Figure 7), which is a normal bioturbation depth in marine coastal systems.

Recovered amounts of amended AC were 1.6 ± 0.8, 1.7 ± 1.3 and 3.0 ± 0.7 kg m$^{-2}$ for the AC-only, AC + sand and AC+clay fields, respectively (Table 1). Since 5 kg m$^{-2}$ of AC was initially applied, this implies that approximately 30% of the AC was found back on the seafloor for both AC-only and AC+sand, and approximately 60% for AC + clay. These losses are primarily due to the small size of the fields (15 x 15 m) in relation to the falling depth of the slurries (1-2 m), and are expected to be less for remediation operations at a larger scale. The AC-clay slurry gives about 50% lower losses than AC-only or AC+sand. We hypothesize this is caused by the viscosity of the 1:1 v/v AC-clay slurry. These recoveries suggest that dosing AC mixed with a clay slurry is better than dosing AC alone.

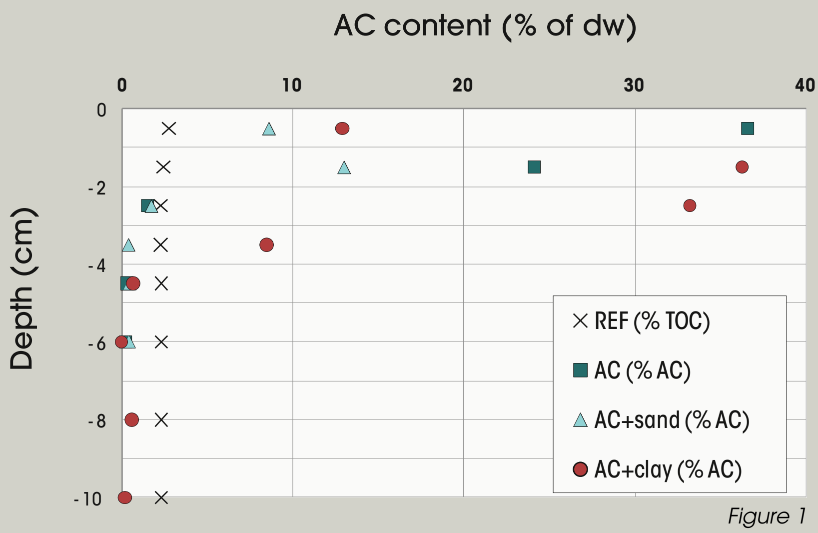



***Figure 7.*** *AC content as a function of depth.*

| | TOC (% of dw) | AC (% of dw) | AC (kg m$^{-2}$) |
|---|---|---|---|
| REF | 2.5 ± 0.2 | 0 | 0 |
| AC | 17 ± 7 | 19 ± 8 | 1.6 ± 0.8 |
| AC+sand | 17 ± 11 | 20 ± 13 | 1.7 ± 1.3 |
| AC+clay | 27 ± 6 | 32 ± 7 | 3.0 ± 0.7 |

***Table 1.*** *TOC and AC contents of the surface sediment (0-3 cm) 12 months after amendment.*

## Sediment-to-water flux measurements

This parameter was measured using benthic diffusion chambers, where a closed stainless steel chamber containing an infinite sink material for HOCs (a semi-permeable membrane device, SPMD) was placed on the seafloor at the field sites during 3 months. Sediment flux measurements were carried out at two occasions at 0-3 and 9-12 months after amendment.

Fluxes were significantly reduced compared to the reference field for AC+clay (both 0-3 and 9-12 months after placement), AC-only (only 9-12 months) and AC+sand (only 0-3 months), but not for sand-only indicating that the effect was due to the AC and not the sand (figure 8).

All in all the flux data indicate that AC amendment can lead to a reduction in PAH fluxes from the sediment bed to overlying water. However, the reductions are not as substantial as the 90-99% effectiveness reported for conventional 30-50 cm thick sand caps (Eek et al 2010). The AC+clay slurry was the most effective capping treatment in reducing sediment-to-water fluxes (reduction factor two to ten compared to the reference field), probably because more AC was present on this field than on the other ones, and the sediment was more evenly covered by AC.

## In situ porewater concentration, $C_{PW}$

NGI developed a novel method where we inserted the passive sampler material polyoxymethylene (17 µm; POM-17), mounted on a rod, directly into the sediment and depicted in Figure 9.

In the water 0-5 cm above the sediment (the rods protruded 5 cm above the sediment), freely dissolved aqueous concentrations ($C_W$) measured by POM-17 passive samplers above the AC+clay field were similar to those above the reference field (Figure 10). The same situation was observed for the deeper sediment samples (5-10 cm

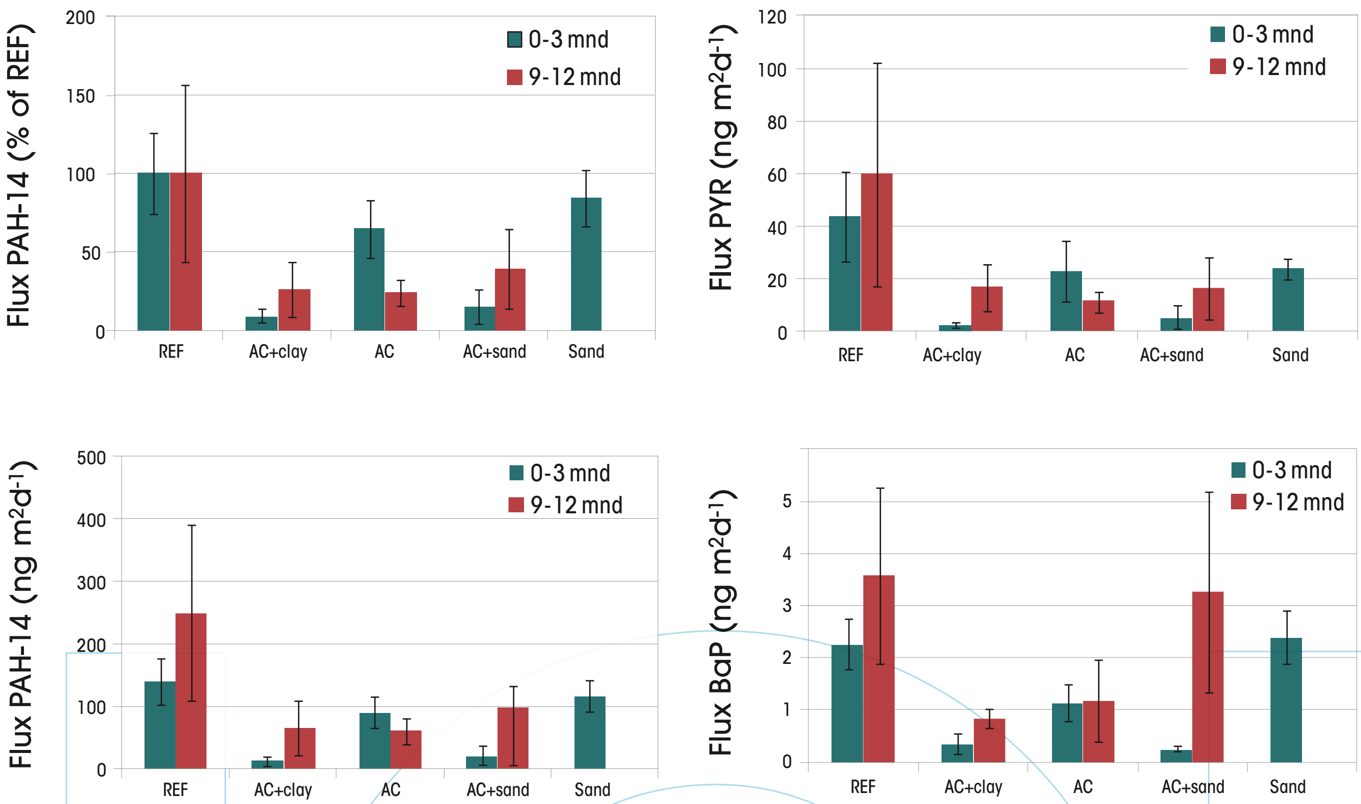



***Figure 8.** The in-situ measured sediment-to-water flux for total PAH-14, for the amended fields relative to the reference field. Measurements lasted 3 months, and were done 0 to 3 and 9 to 12 months after field establishment. Similar figures for absolute fluxes for PAH-14, PYR and BAP.*

*Figure 9.* Rod with thin POM-17 µm passive samplers mounted in 5-cm resolution, to be inserted directly into the sediment to measure sediment porewater HOC profiles.

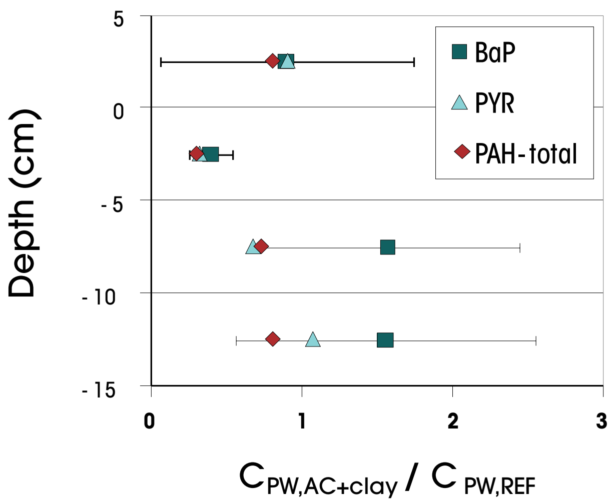



*Figure 10.* Porewater PAH concentration profiles, determined by POM-17 passive samplers mounted on a rod and directly inserted into the sediment, and presented as the ratio between porewater concentration $C_{PW}$ in the AC+clay field and $C_{PW}$ in the reference field, with standard deviations in triplicate measurements. Ratios are shown to be able to present the different compounds in one figure and to correct for concentration variations with depth in the reference field. Negative depth: porewater concentration in the sediment; positive depth: concentration above the sediment surface.

and 10-15 cm) where no AC was observed. On the other hand, in the sediment layer where AC was observed (0-5 cm), $C_{PW}$ was significantly lower in the AC+clay field than in the reference field ($C_{PW,AC+clay}$/ $C_{PW,REF}$ significantly below one for all PAHs; Figure 10 and Figure 7). This means that AC amendment is most effective in the biologically active 0-5 cm layer.

## Effect of AC aging in the field

The general approach in this experiment was to bring field-aged, AC-amended sediment back to the laboratory and compare the AC sorption of such field-aged AC to that of freshly amended AC.

Field aging does not seem to lead to dramatic decreases of AC effectiveness, and field-aged AC brought back to the laboratory still strongly sorbs both freshly extra-spiked PAHs and native ones (Figure 11). The most important implication of these findings is that aged amended AC will still be effective several years after remediation has been completed. Thus also possible contaminants in newly settling material will be sequestered by AC, on the condition that bioturbation or other processes result in sufficient mixing of the AC-containing and newly depositing layers.

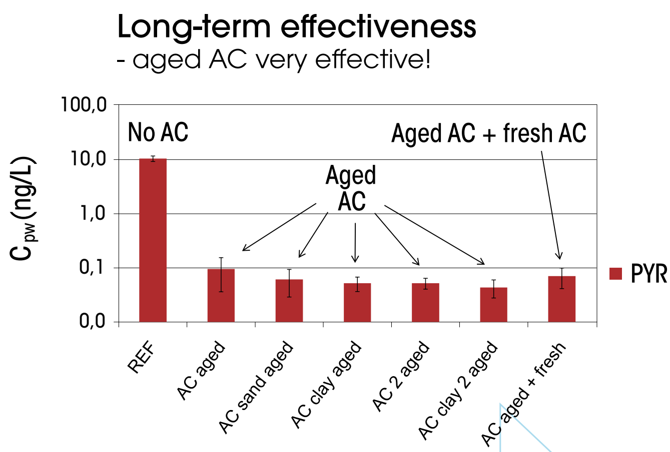



*Figure 11.* The spiked PAH porewater concentration. The aged AC is still very effective (water concentration in log scale) and adding extra fresh AC does not change the concentrations.

# Biological monitoring

## Uptake of pollutants in organisms

The thin-layer capping technique used in the pilot plots in Trondheim harbor, provides less disturbance of the contaminated sediment and is probably relatively benign to the organisms, and at the same time hopefully generates a positive reduction in pollutant uptake in organisms.

To study the potential reduction in contaminant transfer into organisms, a bio-accumulation study was carried out at Stockholm University in kayak cores (transparent plastic tubes) containing sediment and overlying water from Trondheim harbor. Sediment cores were taken from the experimental plots with activated carbon (AC-clay, AC-sand and AC) and the reference plot (REF), transported to Stockholm University. Clean animals were added to the microcosms, to study differences in contaminant accumulation in animal body tissue. Sediment digging ragworms, Nereis (Hediste) diversicolor and mussels Abra nitida, were exposed to for 5 weeks.

Generally good animal survival and animal condition indicate that the microcosm environment was decent for the organisms, and normal animal activity was also observed during the experiment. The worms were observed to dig a network of burrows deep into the sediment, and the siphons (ventilation tubes) from mussels were protruding up from the sediment. Representative animal behavior together with good animal conditions suggests that normal biological processes can be assumed during the experiment.

## PAH and PCB levels in Abra nitida and Nereis diversicolor

The multivariate analyses of the 10 PAHs in the mussels revealed significantly lower contaminant levels in the mussels in the activated carbon mixed in clay (AC-clay) treatment compared to mussels from the reference (REF) sediment (Figure 12,13). Reduction in bioaccumulation by AC-clay for the ten PAHs was as high as 94% ± 5 (mean ± SD).

Also some PCBs were measured for the organisms. The PCB levels in the worms showed significantly reduced uptake of contaminants in worms from the two activated carbon treatments, AC-clay and AC, compared to REF (Figure 14). As for PAHs, the AC-sand treatment did not generate a reduction in worm tissue levels of PCBs.

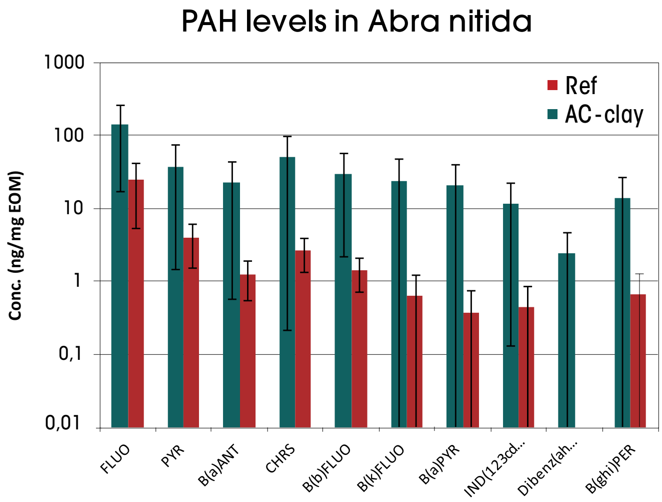



***Figure 12.*** *PAH concentrations in the mussel A. nitida. Significant lower PAH levels were seen in AC-clay compared to REF. Note the logarithm-scaled y-axis. EOM = organisms lipid.*

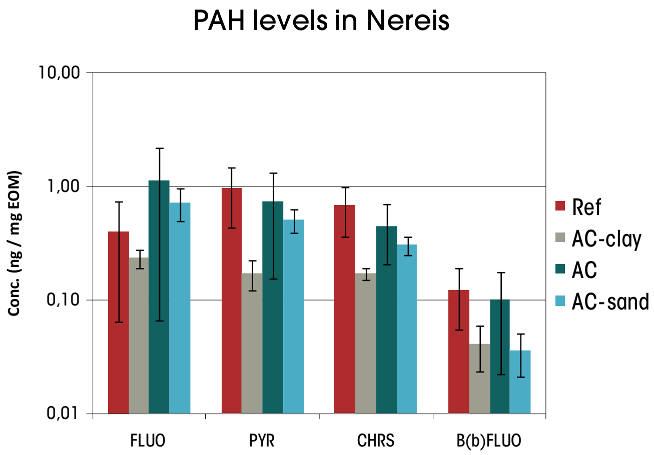



***Figure 13.*** *PAH concentrations in the ragworm N. diversicolor. Significant lower PAH levels were seen in AC-clay compared to REF, AC and AC-sand. Note the logarithm-scaled y-axis. EOM = organisms lipid.*

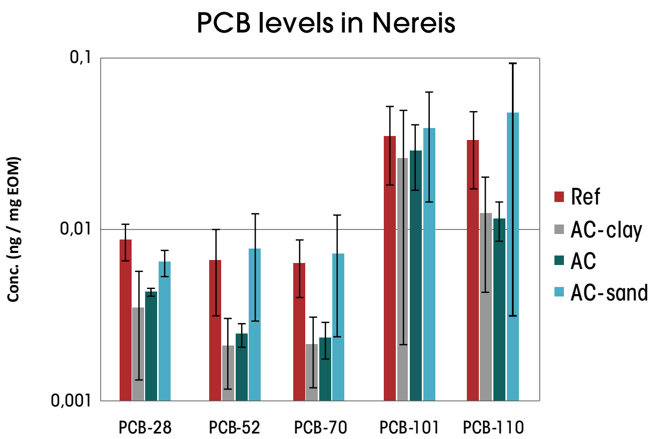



***Figure 14.*** *PCB concentrations in N. diversicolor. Significant (p=0.02) lower PCB levels were seen in AC-clay and AC compared to REF and AC-sand. (Log-scaled y-axis)*

In conclusion, promising bioaccumulation results were seen for the AC-clay treatment, which could significantly reduce PAHs and PCBs in the sediment digging worms, as well as PAHs in the mussels. The effects were even better than for the fluxes and freely dissolved concentrations, and we hypothesize this was caused by optimized AC-sediment mixing in the organism guts.

## The benthic habitat: is the AC-treated sediment still a good place to live?

Species abundance (total number of individuals per species) was significantly reduced in all the capping treatments compared to the reference (Table 2). The species richness (total number of taxa) was also reduced in all the capping treatments compared to the reference, especially in AC-only and AC+sand in 2009. The BQI index was not different among treatments in 2008, but in 2009 BQI values were significantly lower in AC-only (2.8 ± 3.1) and AC+sand (5.0 ± 2.3) than in the reference field (9.4 ± 0.8). The most obvious effects are on species' abundances, which decrease by 50 % or more in all the capping treatments, including AC+clay.

***Table 2.*** *Benthic fauna, species richness, abundance and diversity*

| Treatment | Richness | | | Abundance | | | Biodiversity H' | | | Benthic Quality Index | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2007 | 2008 | 2009 | 2007 | 2008 | 2009 | 2007 | 2008 | 2009 | 2007 | 2008 | 2009 |
| Reference | 37 | 24 | 25 | 147 | 269 | 379 | 3.2 | 3.3 | 3.2 | 8.9 | 10.4 | 9.4 |
| | (5) | (4) | (9) | (39) | (62) | (199) | (0.2) | (0.1) | (0.2) | (0.6) | (0.7) | (0.8) |
| Sand | | 15 | 16 | | 64 | 81 | | 2.6 | 2.8 | | 8.0 | 8.6 |
| | | - | (0.7) | | - | (26) | | - | (0.1) | | - | (0.1) |
| AC-only | | 19 | 6 | | 59 | 14 | | 3.4 | 2.3 | | 10.0 | 2.8 |
| | | (1.4) | (3.5) | | (4.2) | (12) | | (0.2) | (0.6) | | (0.3) | (3.1) |
| AC+clay | | 20 | 21 | | 176 | 67 | | 3.1 | 3.6 | | 9.8 | 9.5 |
| | | (13) | (10) | | (195) | (46) | | (0.4) | (0.7) | | (3.2) | (2.5) |
| AC+sand | | 17 | 7 | | 72 | 12 | | 2.8 | 2.4 | | 8.9 | 5.0 |
| | | (4.2) | (5.7) | | (30) | (2.1) | | (0.1) | (1.3) | | (0.9) | (2.3) |

| |
|---|
| very good |
| good |
| moderate |
| poor |
| bad |

*Table legend: Richness = average number of taxa per field per 0.1 m2;*
*Abundance= average total number of species per 0.1 m2.*
*Diversity indices: H´ = Shannon-Wiener index; BQI = Benthic Quality Index.*
*Colors refer to ecological status classification: i.e. blue: very good (none here), green: good, yellow: moderate, orange: poor, red: bad.*
*Numbers in brackets are standard deviation.*

There are, however, notable differences among the capping treatments and AC+clay was the most benign to the benthic community, because neither species richness nor diversity were significantly impacted compared to the reference (Table 2). However, these effects could be temporary so that benthic communities recover after a few years. It cannot be excluded, however, that somewhat different communities develop after capping.

## Biotic indices and recommendations

Following the European Water Framework Directive WFD guidelines, the Norwegian Pollution Control Authority has adopted a classification system, where benthic communities are classed into five categories according to their ecological status. The classification is largely based on benthic diversity defined by the Shannon-Wiener index (Table 2), and the transition from a "Good" to a "Moderate" status (GM boundary) indicates that remediation actions need to be taken. Contrary to the Shannon-Wiener index, the BQI index, recently adopted within the WFD in Sweden accounts not only for the diversity but also for the species' sensitivity to pollution. The BQI values are also used to classify the ecological status into one of five statuses as recommended by the WFD.

According to these criteria the ecological status of the capped field sites ranged between "Good" and "Moderate" in all treatments for classification based on the Shannon-Wiener index H', and between "Good" and "Bad" for classification based on the BQI (Table 2). Thus according to both of these classification methods the ecological status was at least moderate in all treatments, except for two of them using the BQI approach (AC-only and AC+sand in 2009). Clearly the AC+clay treatment again proved most benign ("good" according to the H'-index, "moderate" according to BQI).

# General conclusions and recommendations

## Costs
The amount of AC required to remediate a site with 5% in the top 10 cm of bioactive sediment is about NOK 500,000 per ha at a bulk cost of AC of about NOK 10. By comparison, dredging and disposal cost for the Hudson River, USA, cleanup has been projected at NOK 15 mill per ha. Thus, the material cost of AC required for treatment is a very small fraction of typical full cost of remediation by dredging and disposal.

## Potential use of biochars and carbon sequestration
Charcoals, especially anthropogenic ones created under high-temperature conditions ("biochar"), are known to persist for thousands of years in soils and sediments, indicating carbon storage opportunities for greenhouse gas abatement. Carbons manufactured from biomass waste products such as pine chips, corn stalk, and poultry litter thus offer an exciting opportunity for efficient resource utilization and carbon sequestration along with sediment remediation.

In addition, the U.S. Environmental Protection Agency's new Green Remediation strategy aims to minimize the environmental footprints of a cleanup. Therefore, technologies that can diminish or reverse the carbon footprint while reducing risks will likely be favored in the future.

For example, a recent complete life-cycle analysis done by NGI (M. Sparrevik) revealed that AC from biomass is better on the whole than AC from coal, because of this "biochar" carbon storage effect.

## Future research needs
Sorbent amendment does not decrease total sediment concentrations of contaminants. Rather, it decreases contaminants available for bio-uptake and transport to surface- and groundwater. Sediment risk management is often based on bulk total concentrations and chemical mass with these measures being considered indicative of exposure. Although regulatory confidence and comfort are building for the explicit consideration of bioavailability in assessments and remedial decisions, there is still a bias against remedies other than removal.

There are also natural perceptions and regulatory precedents to "get it out". This surgical view of sediment remediation is appropriate in many cases but there are numerous situations where removal is not warranted and can be destructive or potentially ineffective for risk reduction. A more balanced evaluation of less invasive remedial measures such as in-situ remedies can be achieved by broadening the decision context to include all relevant factors, such as short- and long-term ecological impacts and benefits, residual impacts, and performance. Comparisons of alternatives could involve comparative life cycle assessments such as the one mentioned above.

**Further research is needed in the following areas:**

1. development of novel amendments that can actively bind contaminants of concern other than HOCs;
2. improved fundamental understanding of mechanisms of HOC binding to AC, especially in the sediment matrix where fouling can be a concern;
3. pilot-scale studies at various hydrodynamic and ecological environments to understand where the technology is best suited;
4. assessment of ecosystem recovery;
5. potential for microbial processes to degrade sorbed contaminants
6. full-scale demonstration to go beyond what can be learned through small-scale pilot-studies and such as initiated in the Grenlands fjords;
7. life-cycle analyses including carbon footprints of different sediment remediation technologies.

**General recommendations and conclusions**

Based on the results from this study we recommend that AC mixed with clay should be investigated further as a sustainable remediation method, as this treatment yielded best reduction of PAH fluxes, best AC recoveries, and only relatively mild effects on the benthic community. Also, AC could successfully be placed underwater at 4-6 m depth with relatively simple equipment consisting of a cement blender and standard pump.

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## Contact:

Gerard Cornelissen, gco@ngi.no (project leader and main report author)
Jonas Gunnarsson, jonas@ecology.su.se (biology project leader and contributing author)

## Key personnel:

**NGI –** Marie Elmquist Kruså (post-doctoral researcher), Gerard Cornelissen, Gijs Breedveld, Espen Eek, Amy Oen, Hans Peter Arp, Anita Nybakk, Marianne Kvennås. **Stockholm University –** Jenny Hedman, Göran Samuelsson (contributing author), Jonas Gunnarsson. **University of Maryland Baltimore County (UMBC) -** Upal Ghosh (contributing author).

## Contributors:

The Research Council of Norway (Havkyst), Norwegian Geotechnical Institute, Department of Systems Ecology, Stockholm University – Sweden



Main office:
PO Box 3930 Ullevaal Stadion
NO-0806 Oslo, Norway

Street address: Sognsveien 72, NO-0855 Oslo
T: (+47) 22 02 30 00, F: (+47) 22 23 04 48
ngi@ngi.no

www.ngi.no