REPORT

Sediment capping with activated biochar in Bureå, Sweden

LITERATURE REPORT

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Summary

In the scope of a pilot test for sediment capping of contaminated sediments from the Bureå bay (Sweden), funded by the Geological Survey of Sweden (SGU), NGI provides literature context on the remediation approach proposed, i.e. thin-layer capping with an active sorbent to reduce the sediment-to-water flux of contaminants and protect the biota. The relevance of sediment capping as a remediation approach is discussed in comparison with other approaches like dredging, and the theoretical principles behind the method are detailed. Sediment capping with active sorbents like activated carbon and activated biochar is discussed in further detail since this is the approach chosen for the pilot test in the bay of Bureå.

This report discusses multiple cases in Norway, USA and Netherlands where contaminated sediments were remediated by sediment capping, including with activated carbon. The advantages of capping with a thin layer of activated biochar are discussed, for example the chemical effectiveness, the overall sustainability as a remediation strategy, economical costs and geotechnical advantages at sites where traditional capping would cause settlements. Disadvantages of the method are also raised, including deleterious effects of fine-grained activated carbon on sediment biota, sensitivity to erosion, and the possible formation of methylmercury. The report concludes on the site-specificity of the relevance of a capping approach.

The overall conclusion of the literature report is that sediment thin-layer capping by activated biochar holds promise as a sustainable technology to achieve short-term risk reduction similar to conventional capping and better overall risk reduction than environmental dredging, with possibly lower costs and definitely lower environmental impacts than traditional sediment cleanup technologies. Care should be taken to protect sediment biota from the potential negative direct impacts of too finely powdered material.

Contents

1 Introduction 6
2 Theoretical principles of sediment capping as a barrier for contaminant diffusion 6
3 Use of sediment capping for remediation of contaminated sites, in Norway and elsewhere 8
4 Capping with activated materials, including biochar 15
5 Advantages and limitations of the sediment capping methods 17
6 References 20

Review and reference page

1 Introduction

This literature study is done in the scope of the project " Sediment capping with activated biochar in Bureå, Sweden " funded by the Geological Survey of Sweden (SGU) within the framework of the Government Mission Polluted Sediment. This project is testing the effectiveness of sediment capping with activated biochar as a remediation strategy for the PAH- and metal-contaminated Bureå Bay (Sweden).

The aim is to provide relevant historical and scientific context and experience at an international scale, for a remediation strategy that is to date not common in Sweden.

2 Theoretical principles of sediment capping as a barrier for contaminant diffusion

Dispersion of contaminants from polluted sediments can occur via different mechanisms, including diffusion, transport by erosion and particle suspension and bioturbation. The purpose with sediment capping with clean masses is to isolate the contaminated sediment from the organisms living in/on the sea bed, and from the water above. The capping limits 1) the dispersion of contaminated particles by suspension, 2) the diffusion of contaminants from sediment porewater to the water above, and 3) the direct contact between benthic fauna and contaminated sediment (Patmont et al., 2015).

A sediment cap can be built with passive material (sand or gravel) or can include a layer with specific functions such as low-permeability or high sorption capacity. The thickness of a conventional sediment cap is typically 20 cm or thicker. The thickness of the capping which is actually effective to limit diffusion is smaller than the total thickness, because the bottom part is partly mixed with sediment and the top part (up to 10 cm) is affected by bioturbation and erosion/suspension. Erosion can be limited by addition of rocks or other coarse material on top.

Assuming that diffusion is the dominant dispersion mechanism from contaminated sediments, covering the contaminated seabed is a possible measure to reduce the spread of contaminants (Figure 1; Eek et al., 2008). When contaminated sediments are capped with clean materials, contaminants from the sediment diffuse into the pore water in the cap and, depending on the sorption properties of the material used, adsorb to the cap material. Just after application of the cap, concentrations in the pores of the capping material are low within the whole capping thickness. Contaminants diffuse upwards from the sediment to sea water, through the capping material. Concentrations increase at the bottom, faster than at the top, thus the concentration depth profile evolves during a transient phase. When the new steady-state flux from the capped sediment is reached, the flux is in principle lower than the steady-state flux without capping. This is a result of an increase of the diffusive path length above capped sediments, including the DBL above the cap (Figure 1). Furthermore, the effective diffusivity in the cap is reduced relative to that in free water, since a smaller cross-sectional area is available for diffusion and because of the tortuous diffusion path in the cap (equation {2}).

$$J_{i\,\mathrm{cap}} = \frac{\varepsilon \cdot D_i}{\tau \cdot (h_{\mathrm{cap}\,d} + \delta_{\mathrm{DBL}})}(C_{i\,\mathrm{pw}} - C_{i\,\mathrm{w}}) \qquad \{2\}$$

where $h_{\mathrm{cap}d}$ is the thickness of the (undisturbed part of the) capping layer in cm, δ_{DBL} the diffusive bonder layer in cm, ε is the porosity and τ is the tortuosity. ε and τ are dimensionless (Boudreau, 1997).

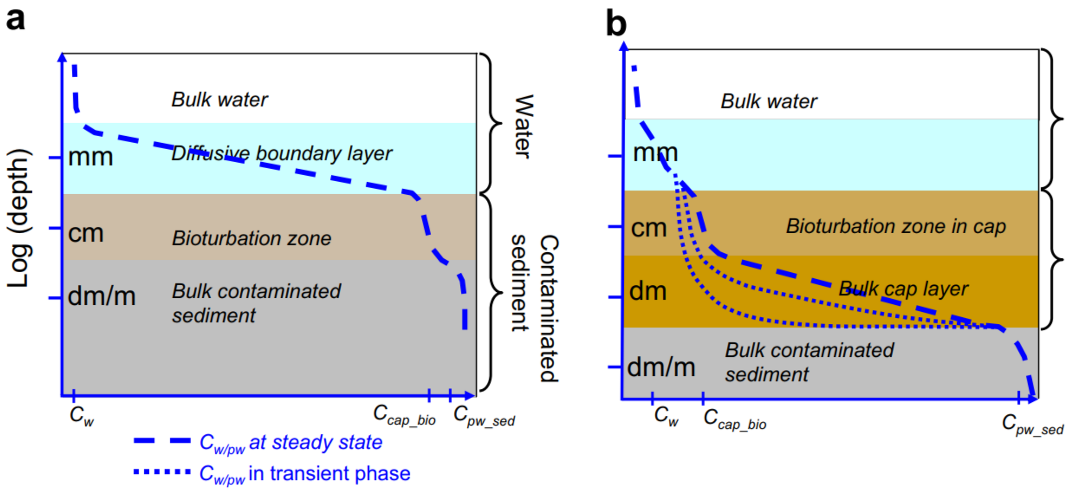


Figure 1: Vertical dimensions and theoretical water concentration profile of contaminants from a sediment (C_{pw_sed}) through a cap and/or the diffusive bounder layer (DBL) to the bulk water (C_w). Almost constant concentration in the bioturbation zone (C_{cap_bio}) is explained by the fact that this layer presents smaller resistance to transport. A linear concentration gradient in the DBL and in the bulk cap layer translates the fact that diffusion is the main transport mechanism in these layers. Figure from Eek et al., 2008.

The covering approach leads to physical containment of contaminated particles, and to lower concentrations of contaminants in the sediment layer where benthic fauna and plants live.

3 Use of sediment capping for remediation of contaminated sites, in Norway and elsewhere

Sediment capping is one of several methods available for remediating contaminated sediments (Table 1).

Table 1: Existing methods for remediation of contaminated sediments.

Method	Principle	Main Limitations and uncertainties
Dredging and landfilling	Dredging of the contaminated sediments until clean sediment and landfilling in relevant landfill.	Spreading of contaminants over large areas; need for a safe storage of the dredged masses; leaching from dredged materials.
Capping	Capping of the contaminated sediments with a relatively thick isolating layer of clean masses.	Prone to erosion and can in some instances lead to geotechnical instability.
Sorbent cover	Addition of an actively binding material e.g., activated carbon (AC), at the surface of sediment so that contaminant availability of is reduced.	The effect of biochar on benthic fauna is not yet well studied. Fine-grained AC has been shown to negatively affect benthic fauna.
Redox-based stabilisation	Addition of a redox buffer (FeOOH, MnO_2 or nitrate) for limiting the production of methyl mercury (which occurs under sulfate-reducing conditions).	The method is not well documented.
In-situ stabilisation with cement	Addition of cement to the sediment to increase the geotechnical stability of the sediment, decrease its permeability and reduce the leaching of contaminants.	Previous tests show this method is not effective in the case of mercury contamination. Cement negatively affects benthic fauna.
Monitored natural attenuation	Capping of contaminated sediments with clean masses occurs naturally over time, by sedimentation of newly deposited particles. Monitoring documents the evolution of the state of contamination, dispersion and risk at the surface of the sediment.	The time needed to perceive positive effects is uncertain and depends on the locality, bioturbation depth, sedimentation rates and contamination of newly settling particles.

Each remediation approach presents advantages and limitations, with trade-off in the short term vs. in the long term, and the expected effect of each method depends on site-specific conditions such as the type and concentration of contaminant(s) occurring, the topography, the sedimentation rate at the site, contamination degree of the newly settling particles, bioturbation depth and intensity, etc (Table 2; Figure 2). Patmont et al. (2015) calculated hypothetical time-evolution of PCB concentration in fish tissue based on hypotheses on these parameters in various remediation scenarios. The model obtained suggested that in the hypothetical scenario considered, the capping approaches would lead to lower PCB concentrations in fish than dredging, especially in the decades following remediation (Figure 2).

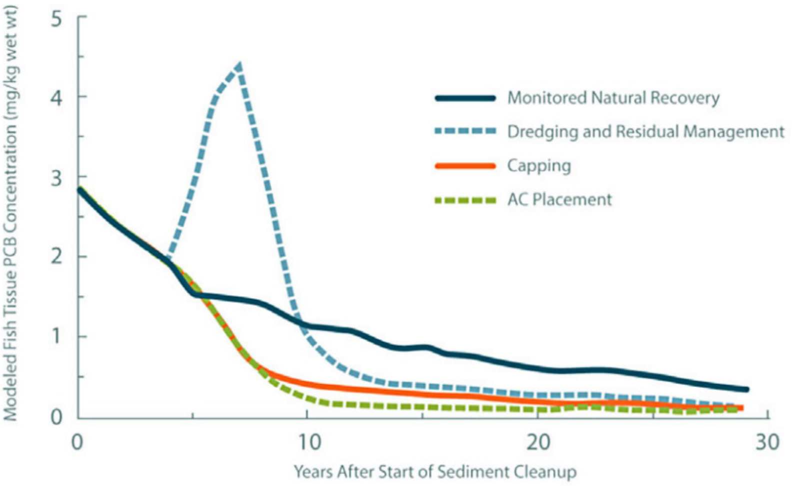


Figure 2: Hypothetical comparative net risk reduction of alternative sediment remediation technologies. Example presented for illustrative purposes using the following fate and transport model input assumptions: average environmental dredge production rate of 400 m^3 per day and release of 3% of the PCB mass dredged (Patmont et al. 2013); average water flow through the cleanup area of 500 m3 per second; implementation of effective upstream source controls; net sedimentation rate of 0.1 cm per year; and typical PCB mobility and bioaccumulation parameters. From Patmont et al., 2015.

For example, PCB reduction over years in fish was shown by Patmont et al. (2020) at a 2-ha lake on the St. Jones River in Dover, Delaware (USA), where PCB-contaminated sediments were covered with AC (Figure 3).

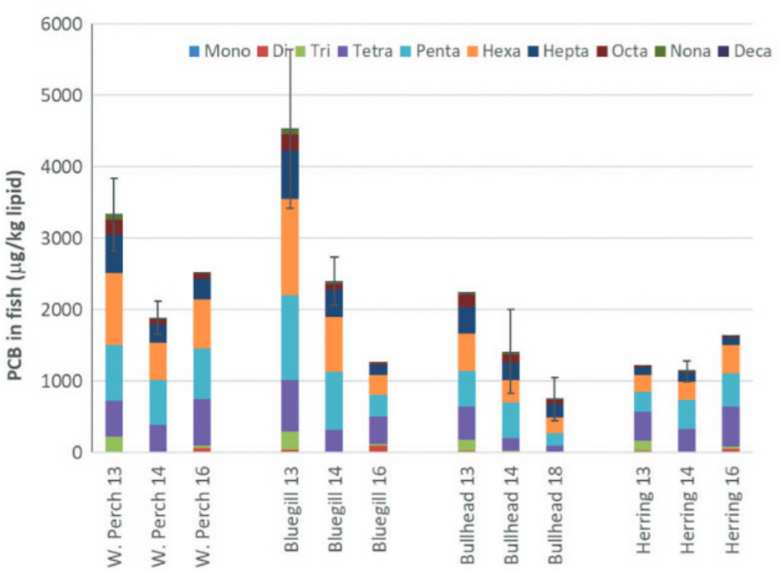
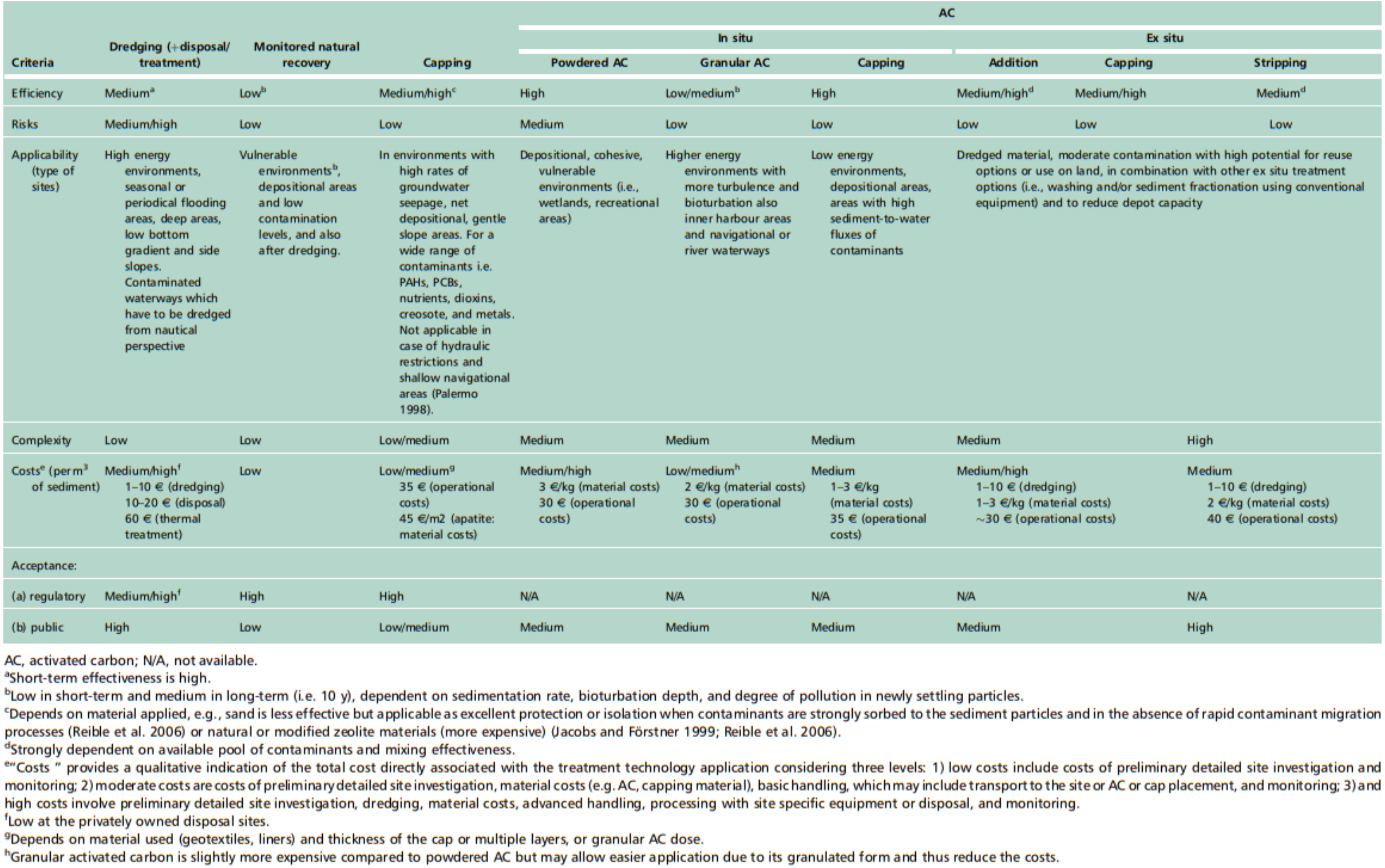


Figure 3: PCB concentration in fish caught in Mirror Lake before (2013, noted "13"), I year after (2014, noted "14") and 3 or 5 years after (2016/2018, noted "16" or "18") application of AC in sediments. From Patmont et al., 2020.

Table 2: Evaluation of remediation strategies, including capping and dredging. From Kupryianchyk et al., 2015



				AC					
				In situ			Ex situ		
Criteria	**Dredging (+disposal/ treatment)**	**Monitored natural recovery**	**Capping**	**Powdered AC**	**Granular AC**	**Capping**	**Addition**	**Capping**	**Stripping**
Efficiency	Medium[a]	Low[b]	Medium/high[c]	High	Low/medium[b]	High	Medium/high[d]	Medium/high	Medium[d]
Risks	Medium/high	Low	Low	Medium	Low	Low	Low	Low	Low
Applicability (type of sites)	High energy environments, seasonal or periodical flooding areas, deep areas, low bottom gradient and side slopes. Contaminated waterways which have to be dredged from nautical perspective	Vulnerable environments[b], depositional areas and low contamination levels, and also after dredging.	In environments with high rates of groundwater seepage, net depositional, gentle slope areas. For a wide range of contaminants i.e. PAHs, PCBs, nutrients, dioxins, creosote, and metals. Not applicable in case of hydraulic restrictions and shallow navigational areas (Palermo 1998).	Depositional, cohesive, vulnerable environments (i.e., wetlands, recreational areas)	Higher energy environments with more turbulence and bioturbation also inner harbour areas and navigational or river waterways	Low energy environments, depositional areas, areas with high sediment-to-water fluxes of contaminants	Dredged material, moderate contamination with high potential for reuse options or use on land, in combination with other ex situ treatment options (i.e., washing and/or sediment fractionation using conventional equipment) and to reduce depot capacity		
Complexity	Low	Low	Low/medium	Medium	Medium	Medium	Medium		High
Costs[e] (per m³ of sediment)	Medium/high[f] 1–10 € (dredging) 10–20 € (disposal) 60 € (thermal treatment)	Low	Low/medium[g] 35 € (operational costs) 45 €/m2 (apatite: material costs)	Medium/high 3 €/kg (material costs) 30 € (operational costs)	Low/medium[h] 2 €/kg (material costs) 30 € (operational costs)	Medium 1–3 €/kg (material costs) 35 € (operational costs)	Medium/high 1–10 € (dredging) 1–3 €/kg (material costs) ~30 € (operational costs)		Medium 1–10 € (dredging) 2 €/kg (material costs) 40 € (operational costs)
Acceptance:									
(a) regulatory	Medium/high[f]	High	High	N/A	N/A	N/A	N/A		N/A
(b) public	High	Low	Low/medium	Medium	Medium	Medium	Medium		High

AC, activated carbon; N/A, not available.

[a] Short-term effectiveness is high.

[b] Low in short-term and medium in long-term (i.e. 10 y), dependent on sedimentation rate, bioturbation depth, and degree of pollution in newly settling particles.

[c] Depends on material applied, e.g., sand is less effective but applicable as excellent protection or isolation when contaminants are strongly sorbed to the sediment particles and in the absence of rapid contaminant migration processes (Reible et al. 2006) or natural or modified zeolite materials (more expensive) (Jacobs and Förstner 1999; Reible et al. 2006).

[d] Strongly dependent on available pool of contaminants and mixing effectiveness.

[e] "Costs " provides a qualitative indication of the total cost directly associated with the treatment technology application considering three levels: 1) low costs include costs of preliminary detailed site investigation and monitoring; 2) moderate costs are costs of preliminary detailed site investigation, material costs (e.g. AC, capping material), basic handling, which may include transport to the site or AC or cap placement, and monitoring; 3) and high costs involve preliminary detailed site investigation, dredging, material costs, advanced handling, processing with site specific equipment or disposal, and monitoring.

[f] Low at the privately owned disposal sites.

[g] Depends on material used (geotextiles, liners) and thickness of the cap or multiple layers, or granular AC dose.

[h] Granular activated carbon is slightly more expensive compared to powdered AC but may allow easier application due to its granulated form and thus reduce the costs.

In Norway, 120 sites were investigated for contaminants in the 90's and among them, 90 were badly contaminated with for example TBT, PAH, PCB and metal elements like Pb, Hg or Cd (Miljødirektoratet.no). Among them, 17 sites were defined as priority areas for remediation (Figure 4), and several of them were already remediated like Oslo, Trondheim and Bergen harbors (Table 3). Sediment capping with clean masses was the remediation strategy adopted in most cases where this was possible and relevant, while dredging and safe storage under sea level or in landfills was done where it was needed for ensuring access to ships (Miljødirektoratet.no). At most sites a combination of both capping and dredging was adopted (Table 3).

In the remediation of Oslo harbor and Trondheim harbor, remediation scenarios involving activated biochar were seriously considered, but not selected due to cost considerations. Recently, however, the remediation of Flekkefjord harbour in Southern Norway, was partly done by the placement of a thin layer of activated biochar as an extra barrier in a relatively thin sand cap.

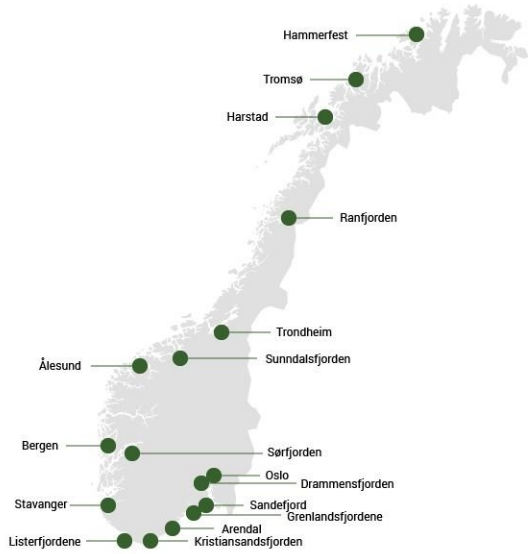


Figure 4: Norwegian fjord areas defined as priority for remediation by the Norwegian Environmental Agency (Map from Miljødirektoratet).

Table 3: Examples of remediated sites in Norway, and type of remediation strategy adopted.

Sediment area remediated	Capping	Dredging
Oslo fjord	With clean sand and clay from construction project	X Disposal under sea, capped with clean masses.
Grunnekleivfjorden	X	
Grenland fjords	X	
Arendal fjord	With sand and gravel	
Puddefjorden (Bergen)	With crushed rocks from construction projects	X
Kristiansand	X	X
Sandefjordsfjorden	X	X
Trondheim	X	X
Tromsø havn	X	X
Harstad	X	X Disposal as a quai-deposit
Farsund harbour	X	
Sørfjorden	X	
Flekkefjord	With clean sand, crushed stones and in one area, activated biochar as an extra protective layer	X
Lungegårdsvann (Bergen)	x (test phase)	

Sediment capping, including capping with activated carbon, has also been tested and applied in the USA and in the Netherlands (Figure 5; Table 4). Note that primarily activated carbon from fossil coal was used in the pilot trials, whereas sustainability aspects recently have shifted material preference over to activated biochar (see chapter 5), such as in the Bureå project and in the full-scale remediation of Flekkefjord Harbour.

Figure 5: In situ treatment field application sites involving capping with activated carbon or similar (numbers refer to Table 4).

Table 4: In situ treatment using carbon-based sorbents (mainly activated carbon): summary of field-scale pilot demonstrations or full-scale projects. From Patmont et al., 2015.

Site number (see Figure 1)	Year(s)	Location	Contaminant(s)	Application area (hectares)	Carbon-based amendment(s)	Delivery method(s)	Average water depth during delivery (m)	Enhancement(s)	Application equipment	Primary reference(s)
1	2004	Anacostia River, Washington, DC	PAHs	0.2	Coke Breeze	Geotextile mat	8	Armored cap	Crane	McDonough et al. (2007)
2	2004, 2006	Hunters Point, San Francisco, CA	PCBs, PAHs	0.01	AC (slurry)	Direct placement	<1	Mechanical mixing (some areas)	Aquamog, slurry injection	Cho et al. (2009 and 2012)
3	2006	Grasse River, Massena, NY	PCBs	0.2	AC (slurry)	Direct placement	5	Mechanical mixing (some areas)	Tine sled injection, tiller (with and without mixing)	Beckingham et al. (2011); Alcoa (2007)
4	2006, 2008	Trondheim Harbor, Norway	PAHs, PCBs	0.1	AC (slurry)	Blended cover, direct placement	5	Armored cap (some areas)	Tremie, agricultural spreader	Cornelissen et al. (2011)
5	2006	Spokane River, Spokane, WA	PCBs	1	Bituminous Coal Fines (slurry)	Direct placement	5	Armored cap	Mechanical bucket	Anchor QEA (2007 and 2009)
6	2009	De Veenkampen, Netherlands	Clean Sediment	<0.01	AC (slurry)	Direct placement	1	None	Laboratory rollerbank	Kupryianchyk et al. (2012)
7	2009	Greenlandsfjords, Norway	Dioxins/Furans	5	AC (slurry)	Blended cover	30/100	None	Tremie from hopper dredge	Cornelissen et al. (2012)
8	2009	Bailey Creek, Fort Eustis, VA	PCBs	0.03	AC (SediMite®)	Direct placement	1	None	Pneumatic spreader	Ghosh and Menzie (2012)
9	2010	Fiskerstrand Wharf, Ålesund, Norway	TBT	0.2	AC (slurry)	Blended cover	40	None	Tremie with biokalk	Eek and Schaanning (2012)
10	2010	Tittabawassee River, Midland, MI	Dioxins/Furans	0.1	AC (AquaGate™), Biochar	Blended cover	<1	None	Agricultural disc	Chai et al. (2013)
11	2011	Upper Canal Creek, Aberdeen, MD	PCBs, Mercury	1	AC (SediMite®, AquaGate™, slurry)	Direct placement	<1	None	Pneumatic spreader, bark blower, hydroseeder	Bleiler et al. (2013); Menzie et al. (2014)
12	2011	Lower Canal Creek, Aberdeen, MD	Mercury, PCBs	0.04	AC (SediMite®)	Direct placement	1	None	Agricultural spreader	Menzie et al. (2014)
13	2011 to 2016	Onondaga Lake, Syracuse, NY	Various Organic Chemicals	110	AC (slurry)	Blended cover	5	Armored cap	Hydraulic spreader	Parsons and Anchor QEA (2012)
14	2011	South River, Waynesboro, VA	Mercury	0.02	Biochar (Cowboy Charcoal®)	Direct placement	<1	None	Pneumatic spreader	DuPont (2013)
15	2011	Sandefjord Harbor, Norway	PCBs, TBT, PAHs	0.02	AC (BioBlok[a])	Direct placement	30	None	Mechanical bucket	Lundh et al. (2013)
16	2011	Kirkebukten, Bergen Harbor, Norway	PCBs, TBT	0.7	AC (BioBlok[a])	Direct placement	30	Armored cap (some areas)	Mechanical bucket	Hjartland et al. (2013)
17	2012	Leirvik Sveis Shipyard, Sandefjord, Norway	PCBs, TBT, Various Metals	0.9	AC (BioBlok[a])	Direct placement	30	Armored cap (some areas)	Hydraulic spreader (up to 30-degree slopes)	Lundh et al. (2013)
18	2012	Naudodden, Farsund, Norway	PCBs, PAHs, TBT, Various Metals	0.4	AC (BioBlok[a])	Direct placement	30	Armored cap, habitat layer	Mechanical bucket	Lundh et al. (2013)
19	2012	Berry's Creek, East Rutherford, NJ	Mercury, PCBs	0.01	AC (SediMite®, granular)	Blended cover, direct placement	<1	None	Pneumatic spreader	USEPA (2013c)
20	2012	Puget Sound Shipyard, Bremerton, WA	PCBs, Mercury	0.2	AC (AquaGate™)	Direct placement	15	Armored cap	Telebelt® (under-pier)	Johnston et al. (2013)
21	2012	Custom Plywood, Anacortes, WA	Dioxins/Furans	0.02	AC (SediMite®)	Blended cover, direct placement	8	None	Agricultural spreader	WDOE (2012)
22	2012	Duwamish Slip 4, Seattle, WA	PCBs	1	AC (slurry)	Blended cover	4	Armored cap	Mechanical bucket	City of Seattle (2012)
23	2013	Mirror Lake, Dover, DE	PCBs, Mercury	2	AC (SediMite®)	Direct placement	1	None	Telebelt® and air horn	DNREC (2013)
24	2013	Passaic River Mile 10.9, Newark, NJ	Dioxin/Furans, PCBs	2	AC (AquaGate™)	Blended cover	1	Armored cap	Telebelt®	In preparation
25	2013	Little Creek, Norfolk, VA	PCBs, various metals	1	AC (AquaGate™)	Direct placement	1	None	Pneumatic spreader (under-pier)	In preparation

AC = activated carbon; PAH = polynuclear aromatic hydrocarbon; PCB = polychlorinated biphenyl; TBT = tributyltin.
[a] BioBlok is licensed by AquaBlok®

4 Capping with activated materials, including biochar

Covering large areas becomes unrealistic if a thick cover is needed for sufficient flux reduction. A reactive barrier, however, enhances the adsorption that takes place in the sediments at the same time as the need for material is kept down, also reducing the GHG emissions during the operation (see chapter 5).

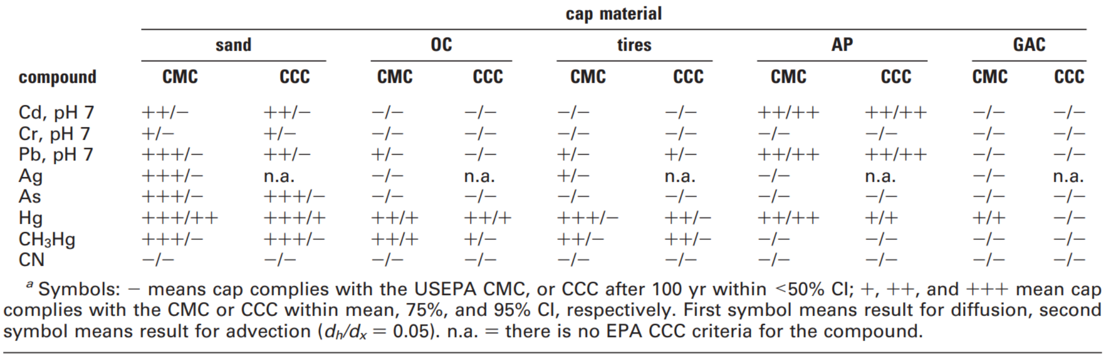
The method consists of adding a layer of activated sorbent (for example biochar) at the surface of the contaminated sediment, so that the sorbent binds contaminants and reduces the dissolved concentration in porewater and thus the bioavailability and diffusive dispersion.

The breakthrough time of contaminants is dependent on the sorption strength of the active capping material. Several active materials were tested in sediment capping, such as activated carbon, organoclay, apatite, coke, zeolites and zero valent iron (USEPA 2013a; Viana et al., 2008). Three of these amendments (activated carbon, organoclay and apatite) have been identified as particularly promising sorptive amendments for in situ remediation (USEPA 2013b). Each amendment presents different advantages depending on the contaminant present in the sediment (Table 5; Viana et al., 2008).

Activated carbon most effectively binds organic substances such as PAHs, other hydrophobic organic compounds (HOC) and methyl-Hg, but it also can bind metals like Hg, Cu, Zn and Pb. For example, Silvani et al. (2017) showed, based on laboratory experiments and modelling, that adding a layer of activated carbon or biochar to sand caps significantly improves the performance of cap layers by increasing the sorbent uptake of dissolved PAHs released from sea-sediments. Indeed, due to its relatively large surface area, pore volume, and absorptive capacity, activated carbon (and biochar) has a decades-long track record of effective use as a stable treatment medium in water, wastewater, and air. As such, this is a well-suited active capping material for in situ sequestration and immobilization of HOCs in various sediment environments (Patmont et al., 2015).

Activated carbon is made from fossil coal ("stenkol") often mined under polluted conditions and transported over long distances, leading to significant negative climate and environmental impacts. Activated biochar is made from organic waste materials, often coconut shells, but also other organic wastes can be used. Both activated carbon and activated biochar are made by first heating the organic material under oxygen-free conditions ("pyrolysis"), after which activation takes place at temperatures over 800 ºC by oxidation with either water vapor or carbon dioxide. This process expands the pore system, and the increased pore volume and pore surface area lead to a higher sorption capacity. Higher sorption affinity is simultaneously generated by the oxidation of functional groups at the carbonaceous pore surfaces. In short, activation thus increases both sorption affinity and sorption capacity, leading to an overall strong increase in sorption strength (Hagemann et al., 2018).

Table 5: Effects of different active capping materials for different contaminants, as assessed by Monte Carlo simulations of breakthrough through the cap (from Viana et al., 2008).



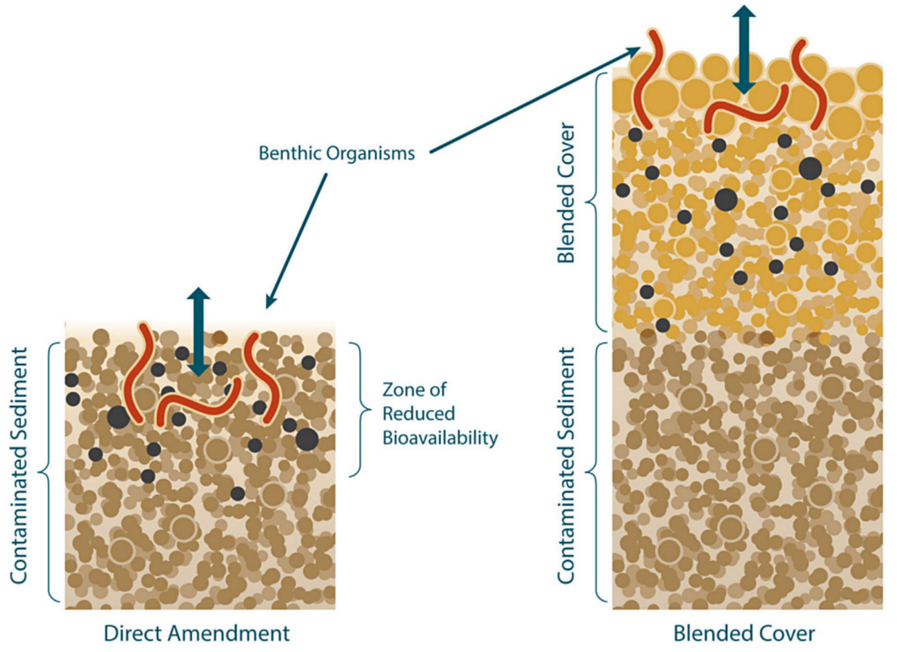
	cap material									
	sand		OC		tires		AP		GAC	
compound	**CMC**	**CCC**	**CMC**	**CCC**	**CMC**	**CCC**	**CMC**	**CCC**	**CMC**	**CCC**
Cd, pH 7	++/−	++/−	−/−	−/−	−/−	−/−	++/++	++/++	−/−	−/−
Cr, pH 7	+/−	+/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−
Pb, pH 7	+++/−	++/−	+/−	−/−	+/−	+/−	++/++	++/++	−/−	−/−
Ag	+++/−	n.a.	−/−	n.a.	+/−	n.a.	−/−	n.a.	−/−	n.a.
As	+++/−	+++/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−
Hg	+++/++	+++/+	++/+	++/+	+++/−	++/−	++/++	+/+	+/+	−/−
CH_3Hg	+++/−	+++/−	++/+	+/−	++/−	++/−	−/−	−/−	−/−	−/−
CN	−/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−	−/−

[a] Symbols: − means cap complies with the USEPA CMC, or CCC after 100 yr within <50% CI; +, ++, and +++ mean cap complies with the CMC or CCC within mean, 75%, and 95% CI, respectively. First symbol means result for diffusion, second symbol means result for advection ($d_h/d_x = 0.05$). n.a. = there is no EPA CCC criteria for the compound.

Capping with activated biochar, a more sustainable alternative to activated carbon from fossil coal, is a remediation method that was tested in several projects worldwide, for example in the USA, The Netherlands and Norway (Patmont et al., 2015; Cornelissen et al, 2012 and 2015).

Several studies suggest that the chemical effectiveness of activated biochar (as well as activated carbon) for limiting contaminant bioavailability is better when using fine-grained biochar (Zimmermann et al., 2005). Because fine-grained biochar is light and easily suspended, it is necessary to apply measures to protect biochar from erosion, both during application of the capping and after. Several methods were tested to apply biochar capping (Figure 6):

- Biochar is applied as a thin layer at the surface of the sea bed. Generally, it is necessary to apply this biochar as a mixture with a matrix like clay or sand. The matrix contributes to transporting the biochar at the bottom of the sea bed and limits later erosion. Such a method was applied in-situ in the Trondheim harbour (Cornelissen, 2011) and in the Grenlandsfjords a thin 3-cm layer of activated carbon mixed with local clean clay was applied at the surface (Eek and Schaanning, 2012; Cornelissen et al., 2012 and 2015). This method counts on bioturbation and other natural mixing processes for mixing the biochar-layer to the top sediment layer where benthic organisms live.
- Biochar is actively mixed with the top layer of sediment (5-30 cm). This way the sediment itself protects biochar from erosion, and the biochar is mixed over the depth where benthic organisms live. This method was applied at the Hunters Point Naval Shipyard, San Francisco Bay, CA (Cho et al., 2009 and Oen et al., 2011).
- A thin layer of activated biochar can be sandwiched between clean masses or be covered by a thin sand layer for erosion protection (such as in Trondheim harbour, Cornelissen et al., 2011).



Sediment amendment involves integration of a sorbent like AC into the surficial bioactive zone of sediments (shown on the left) while blended cover involves placement of a new layer of cover materials (typically a relatively thin layer of clean sand or sediment) that includes a sorbent like AC either dispersed within (shown in right) or placed as a discrete layer as part of a multi-layer cover. Although these approaches have several differences, the ultimate goal of both approaches is to reduce exposure of benthic organisms to HOCs in sediments and also to reduce HOC flux from sediment into water.

Figure 6: Direct amendment versus blended cover application methods for in situ sorbent application. From Patmont et al., 2015.

5 Advantages and limitations of the sediment capping methods

Capping approaches are in principle less invasive than dredging approaches, and typically provide better environmental conditions in the decades after remediation (Figure 2). However, results of remediation based on sediment capping can be threatened by erosion, stability issues and settlements, new contamination or a non-proper choice of capping material. A typical example of situation where capping is less relevant than dredging, is the case of erosion-prone areas impacted by heavy boat traffic or strong currents.

Capping with activated materials such as carbon or biochar is advantageous at sites moderately contaminated over large surface areas with hydrophobic organic compounds or metal elements with a high affinity for the sorbent. Biochar has in itself a large adsorption capacity and its addition increases the content of organic carbon stored at the bottom and adsorbs both organic and inorganic pollutants.

In addition, a light, thin capping can present advantages in instances where the contaminated sediment is particularly soft and would not be stable under a supplementary load of sand or rocks. Such a challenge was for example raised in the scope of the remediation of Gunneklevfjord, and studies concluded that covering is possible at the condition that the capping is thin and the material used is not too dense (NGI, 2015).

Sediment capping with "only" a thin reactive barrier (5 cm) on top of the sea-bottom is an approach that is relevant in environments where accumulation conditions prevail. However, in areas prone to erosion or in cases where spatially uniform application is more challenging, the long-term effectiveness of biochar capping is uncertain. But when designed correctly to address site-specific conditions, controlled (accurate and spatially uniform) placement of activated carbon bearing treatment materials has been demonstrated using a range of conventional construction equipment and delivery mechanisms and in a wide range of aquatic environments (Table 4), including wetlands (Patmont et al., 2015). When highly contaminated sediments are present in unstable environments, traditional capping or dredging remedies might be the preferred option (Patmont et al., 2015).

In addition, a limitation to sediment capping with activated carbon is the deleterious effects of powdered AC on benthic fauna. Recent studies suggest that sediment capping with fine-grained activated carbon, even though most effective chemically, can have negative impact on benthic populations (Abel et al., 2017; Samuelsson et al., 2017; Trannum et al., 2021). The most likely mechanism for the deleterious effects of powdered AC on biota is that microvilli in the gut, where uptake of food takes place across the gut epithelium, are getting clogged by below-50 µm AC particles, as shown by SEM-evidence by Abel et al (2017). In the field, even as long as 10 years after placement of the cap, negative effects of the powdered AC on the benthic population were observed (Eek and Schaanning, 2012; Samuelsson et al., 2017), especially impacting larger species, and leading to a semi-permanent shift in the composition of the population. Granular AC, with particles above 100 µm, is less effective chemically, but more benign to the organisms living in the sediments. Granular AC in the order of 100-300 µm has been shown to be very effective for PCBs in the Grasse River, Upstate New York (Beckingham et al., 2011). A knowledge gap currently addressed at Stockholm University (Gunarsson group) is finding the optimal balance between chemical effectiveness (small AC particles) while limiting deleterious effects on benthic organisms (larger AC particles). Knowledge is lacking on the effect of sediment capping with activated biochar, which could be more benign than fossil-based AC, as it stems from plant materials and as it has positive effects on plant growth.

In addition, care should be taken in the case of sediments contaminated with both compounds that activated carbon sorbs efficiently (like PAH) and elements that are more mobile or toxic in local environments enriched in activated carbon. For example, a recent study warns that when considering remediation of organic-rich and Hg-contaminated sediments with activated carbon, caution is warranted, as the overall effect of reducing Hg-transport out of the sediment could partly be offset by an increased formation of

MeHg in the sediment under the influence of the activated biochar (Sørmo et al., 2021). Other studies predict a poor efficiency of sediment capping for limiting arsenic diffusion, because 1) a cap favors the reduced form of arsenic, As(III), which is more mobile than theoxidized form As(V), and 2) the cap limits the diffusion of Fe and the precipitation of Fe oxides which normally sorb As at the surface of sediments (Bessinger et al., 2012). Recent studies proposed to design capping materials specifically for arsenic remediation, based either on oxidizing materials (Gao et al., 2021) or on sorbants with very high affinity for As such as zirconium-loaded lanthanium-modified bentonite (Wang et al., 2022).

Another disadvantage of activated carbon and activated biochar is that the sorbents can get "fouled" – oil and natural organic matter clog their pore systems and the sorbents become less effective in binding contaminants. Also, high concentrations of contaminants can saturate the sorption sites on the sorbents (so-called nonlinear sorption), rendering the sorbents less effective at very high pollutant concentrations. Under such "hot-spot" conditions, dredging or conventional capping with a thicker layer is often recommended.

Thin-layer capping with activated biochar is probably the most sustainable sediment remediation in an overall perspective. Sparrevik et al. (2011) showed that activated biochar was much more benign in an overall life-cycle perspective than AC from fossil coal sources, since coal mining is a relatively polluting process, and the AC needs to be transported over long distances. The most significant advantage of activated biochar is that its carbon originates from biological sources, and thus is originally CO_2 removed from the atmosphere and stored safely and stably in the sediment as activated biochar.

Other sustainability advantages of thin-layer capping with activated biochar include the relatively limited amount of material needed, and relatively small fossil fuel use for transportation and deposition of capping materials compared to conventional capping practices. Also, dredging and landfilling requires more (fossil) energy than thin-layer capping. In addition, landfilling on land requires valuable land areas, and often negatively impacts biodiversity and ecotoxicological conditions. Landfilling under water has lower impacts on biodiversity than land deposition, but it needs continuous monitoring of potential emissions via leachate water.

As a conclusion, sediment thin-layer capping, including using activated carbon or activated biochar, is an approach that was tested in a significant number of instances. The success of this approach depends on site-specific conditions and the types of contaminants present (Table 2; Table 5). Depending on sediment and site conditions, using activated carbon/biochar can achieve short-term risk reduction similar to conventional capping and better overall risk reduction than environmental dredging, with lower costs and environmental impacts than traditional sediment cleanup technologies (Sparrevik et al., 2011; Patmont et al., 2015). The most important drawback is the negative impact on sediment biota of powdered AC – research is underway to find out the optimal balance between chemical effectiveness and limited deleterious effects on biota.

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