Swedish Geotechnical Institute

# *In-situ* capping of contaminated sediments

## Sediment remediation technologies:
## A general overview

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**SGI Swedish Geotechnical Institute**

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## Abbreviations for key terms used herein are as follows:

| | |
|---|---|
| **AC** | Activated carbon. |
| **BAZ** | Biologically active zone. |
| **EMNR** | Enhanced monitored natural recovery. |
| **GAC** | Granular activated carbon. |
| **MNR** | Monitored natural recovery. |
| **PAC** | Powdered activated carbon. |
| **USEPA** | United States Environmental Protection Agency. |
| **USACE** | United States Army Corps of Engineers. |

## The entire SGI Publication 30 set includes the following independent parts:

SGI Publication 30-1, Huvuddokument. *In-situ* övertäckning av förorenade sediment. Metodöversikt. (In Swedish)

SGI Publication 30-1E, Main text. *In-situ* capping of contaminated sediments. Method overview.

SGI Publication 30-2E. *In-situ* capping of contaminated sediments. Contaminated sediments in Sweden: A preliminary review.

SGI Publication 30-3E. *In-situ* capping of contaminated sediments. Established *ex-situ* and *in-situ* sediment remediation technologies: A general overview.

SGI Publication 30-4E. *In-situ* capping of contaminated sediments. Remedial sediment capping projects, worldwide: A preliminary overview.

SGI Publication 30-5E. *In-situ* capping of contaminated sediments. Capping Sweden's contaminated fiberbank sediments: A unique challenge.

SGI Publication 30-6E. *In-situ* capping of contaminated sediments. An extensive, up-to-date collection of relevant technical and other international references.

SGI Publication 30-7. *In-situ* övertäckning av förorenade sediment. Övergripande sammanfattning. (In Swedish)

SGI Publication 30-7E. *In-situ* capping of contaminated sediments. Overall summary.

Fact sheet. *In-situ* capping of contaminated sediments. Method overview.

# 1. Introduction

The problem of contaminated sediments and risks they can pose to the environment and humans is not unique to Sweden. Contaminated sediments occur in nearly all countries to some extent. And, like Sweden, most sediment contamination in most countries results from historical releases, when regulatory controls were lacking or minimal.

National responses to the problem of contaminated sediments have varied greatly from country-to-country, for various reasons. Some countries have done little to address the problem, including not even developing or increasing regulatory controls on ongoing releases from land-based sources into surface waters. Other countries have fully acknowledged the problem. Most notably, the U.S. and Norway have made considerable investments over the last decades to actively address contaminated sediments.

National investments in managing (remediating) contaminated sediments have resulted in development and refinement of a relatively small number of proven-effective technologies for sediment remediation. These globally-accepted technologies rely on either removing contaminated sediment, then managing it *ex-situ*, or remediating sediment contamination in-place (*in-situ*).

Provided in this publication is a general overview of proven-effective and globally-accepted, *ex-situ* and *in-situ* technologies for sediment remediation.

To underscore: This is only a general overview of the multiple *ex-situ* and *in-situ* sediment remediation technologies available for use, and is not intended to function as a guidance document. There is a clear need, for a number of reasons, in conducting follow-up, technology-specific reviews (as we have attempted to provide for capping-based technologies in the current project). Each such technology-specific review can and should: (a) be much more expansive and detailed than addressed herein, (b) include up-to-date project examples and profiles, (c) incorporate input from multiple informed parties – with special emphasis from the Swedish perspective, and (d) serve as the basis for a detailed, technology-specific guidance document. Furthermore, there will also be the need for additional documentation that focuses on, compares, and balances the relative advantages and limitations of using different remedial technologies at representative or “typical” contaminated sediment sites, not just from the economic perspective, but also in terms of possible long-term impacts to the environment and society in general.

# 2. *Ex-situ* sediment remediation technologies

## 2.1 Removal (dredging and excavation)

*Ex-situ* sediment remediation by more-or-less conventional means typically involves the following steps: (1) physically removing contaminated sediments from the aquatic environment by dredging (surface water present) or excavation (surface water absent), (2) removing porewater from the sediment, (3) treating the separated solid and/or porewater phases, and (4) transporting and disposing of the sediment solids. Note, a so-called “treatment-train” approach may be used to address one or more of the middle steps combined.

*Ex-situ* sediment remediation could instead be accomplished using the much newer and non-conventional technique of freeze dredging (e.g. Eriksson, 2014).

Of all the sediment remediation technologies available, removal-based technologies have been in existence the longest, and are thus the most well-known. The first removal-based projects completed for environmental (rather than navigational) purposes took place decades ago in the U.S.

As summarized mainly in USEPA (2005), conditions especially conducive to the use of removal-based remedial technologies include:

- A suitable disposal site is available nearby.
- A suitable area is available for staging and handling dredged material.
- Existing shoreline areas and infrastructure can accommodate dredging or excavation. That is, maneuverability and access are not significantly impeded by piers, buried cables, or other structures.
- Navigational dredging is scheduled or planned.
- Water depth is adequate to accommodate dredging, but not so great as to be infeasible.
- Dry excavation of sediment (no surface water present) is feasible.
- Long-term risk reduction by removal outweighs sediment disturbance and habitat disruption.
- Water diversion is practical, or flow velocities are low or can be minimized to reduce re-suspension and downstream transport of contaminated sediments during dredging operations.
- Contaminated sediment overlies not contaminated sediment, so over-dredging is feasible.
- Sediment contains relatively low amounts of debris (e.g., logs, boulders, scrap material) or is amenable to effective debris removal prior to dredging or excavation.
- Relatively high contaminant concentrations cover discrete site areas.
- Contaminant concentrations are highly correlated with sediment grain size, to facilitate grain-size separation and minimize disposal costs.

As also discussed in USEPA (2005) and elsewhere (Palermo et al., 2008; CCMS, 1997; ITRC, 2014), relative advantages and limitations are recognized for removal-based technologies. These are summarized in Table 1.

**Table 1** Remediating contaminated sediments by removal: Relative advantages and limitations.

| Advantages | Limitations |
|---|---|
| • Contaminants removed from the aquatic environment.<br>• Can be used to remediate a wide variety of dissolved-phase contaminant types and concentrations, multiple contaminants, and non-aqueous phase liquids (NAPLs).<br>• Can sometimes quickly reduce contaminant exposure and related risks.<br>• Greater certainty of long-term effectiveness.<br>• Typically few to no restrictions on site use after removal.<br>• Offers potential for beneficial re-use of removed sediment material. | • Often more complex, slower to implement.<br>• Contaminants often not destroyed, rather they are moved from one location to another.<br>• Adequate nearby disposal options may be limited.<br>• At least some residual sediment contamination always remains after removal.<br>• During removal, more disruptive to humans and the environment.<br>• After removal, more disruptive to benthic and/or aquatic habitats.<br>• Typically more costly than other remedial technologies. |

Internationally, removal-based technologies continue to be widely used, and it is expected this trend will continue. However, despite significant advances in equipment design and techniques over the last couple decades, challenges remain. In addition to being relatively costly to implement, continuing technical challenges associated with removal-based technologies include sediment re-suspension and residual contaminated sediments remaining after removal (ITRC, 2014; Patmont and Palermo, 2007; Bridges et al., 2010; Bridges et al., 2008; Reible, 2016). Anywhere from approx. 1 up to 10% of sediment contamination can remain after dredging, with much of this residual contamination occurring at the sediment surface, where it is most bioavailable.

Many regulatory and related guidance documents have been published on removal-based technologies for sediment remediation. Much guidance originates from the U.S., but some also comes from other countries. Some guidance and related documents focus exclusively on removal-based technologies (Palermo et al., 2008; Bridges et al., 2008; Naturvårdsverket, 2010; NRC, 2007; Hammar et al., 2009). Other guidance includes technical discussions on removal-based technologies along with discussions of *in-situ* remediation technologies (USEPA, 2005; ITRC, 2014; NAVFAC, 2003; ASTSWMO, 2007; CCMS, 1997; USEPA, 1994; COWI, 2013; Klif, 2012; SFT, 2004).

Also, many papers addressing various aspects of removal-based sediment remediation have been published over the years in peer-reviewed scientific journals. Such journals include (but are not limited to) Integrated Environmental Assessment and Management, Environmental Science and Technology, and Journal of Soil and Sediments.

Additionally, a great number of papers addressing various aspects of removal-based sediment remediation have been presented at international conferences by researchers, consultants, and regulatory representatives. Some of the more high-profile international conferences include:

- Battelle (primary sponsor) – http://www.battelle.org/media/conferences/sedimentscon
- SedNet, a European Sediment Network – http://www.sednet.org.
- NORDROCS, Nordic Remediation of Contaminated Sites – http://nordrocs.org.

# 3. *In-situ* sediment remediation technologies

Several *in-situ* sediment remediation technologies are globally recognized and accepted:

- Monitored Natural Recovery (MNR).
- Enhanced MNR (EMNR).
- *In-situ* capping.
- *In-situ* treatment.

## 3.1 Monitored natural recovery (MNR)

Monitored Natural Recovery (MNR) involves allowing contaminated sediments to remain in place and letting ongoing, naturally occurring recovery processes (chemical, biological, and/or physical) to naturally contain, destroy, and/or reduce bioavailability and/or toxicity of contaminants over time, eventually to acceptable levels.

Compared to other remedial technologies, MNR is less of an active *technology* and more of a *risk-management approach*. It should be underscored that given the substantial pre- and post-remedy monitoring requirements associated with MNR, this is not a "do-nothing" approach, as some consider it to be.

As summarized mainly in USEPA (2005), some conditions especially conducive to MNR include:

- Anticipated land uses or new structures are compatible with natural recovery.
- Natural recovery processes have a reasonable degree of certainty to continue at rates that will contain, destroy, or reduce the bioavailability or toxicity of contaminants within an acceptable time frame.
- Expected human exposure is low and/or can be adequately managed by institutional controls.
- The site is generally low-energy and depositional, i.e. sediments tend to naturally accumulate over time.
- The sediment bed is reasonably stable, and likely to remain so.
- The sediment bed is resistant to re-suspension, e.g. cohesive or well-armored sediment predominates.
- Contaminant concentrations in biota and the sediment's biologically active zone are already trending towards risk-based cleanup goals.
- Contaminants are readily biodegrade or transform to lower-toxicity forms.
- Contaminant concentrations are relatively low and cover diffuse areas.
- Contaminants have a low ability to bio-accumulate.

As also discussed in USEPA (2005) and elsewhere (including Magar et al., 2009; ITRC, 2014), relative advantages and limitations are recognized for MNR. These are summarized in Table 2.

**Table 2** Managing contaminated sediments by MNR: Relative advantages and limitations.

| Advantages | Limitations |
|---|---|
| • Least invasive and disruptive to aquatic and benthic habitats.<br>• Least complex, quickest to implement.<br>• Can be used to remediate a variety of dissolved-phase contaminants, including presence of multiple contaminants.<br>• No infrastructure or space required for staging equipment and/or materials.<br>• Typically least costly overall, compared to other remedial technologies. | • Sediment contaminants remain in place, often for an extended period of time.<br>• More time may be required to reduce exposure and risks to adequate levels (e.g. contaminants may have extended chemical and/or biological half-lives).<br>• Disturbances can cause increased exposure and risks.<br>• Monitoring costs can add up significantly over time.<br>• Incompatible with some waterway uses, e.g. navigational dredging.<br>• Institutional controls required.<br>• Uncertain of long-term effectiveness. |

Few guidance and related documents exclusively focusing on MNR have been published to-date, worldwide (Magar et al., 2009; USEPA, 2010). However, MNR has been discussed in detail in guidance addressing other *ex-situ* and *in-situ* remedial technologies (CCMS, 1997; ITRC, 2014; USEPA, 2005; COWI, 2013; Klif, 2012; NAVFAC, 2003; ASTSWMO, 2007).

## 3.2 Enhanced MNR (EMNR)

Enhanced Monitored Natural Recovery (EMNR) is very similar to MNR. However, EMNR additionally involves applying a thin layer of sediment or sand to the contaminated sediment surface to enhance or “fast-forward” chemical, biological, and/or physical processes of natural recovery. Although thin compared to many isolation caps, placed material thickness for EMNR projects can vary significantly, often between 10 to 30 cm, and even up to 45 cm (Colton, 2010; Merritt et al., 2009, 2010a).

Layers of sediment or sand placed at such thicknesses are often referred to as “thin-layer caps” (Merritt et al., 2009, 2010a; Magar et al., 2009). In general, EMNR is considered the same as thin-layer capping using conventional (non-sorptive) materials, assuming the layer thickness placed is greater than the depth of the well-mixed biotubation zone.

Since EMNR is based on MNR, site conditions especially conducive to EMNR should generally be the same as those for MNR. However, EMNR should be more widely applicable at a larger number of sites than MNR since natural deposition of sediment is not required for EMNR. Furthermore, since EMNR involves capping, the relative advantages and limitations of EMNR are generally the same as those for *in-situ* capping, especially *thin-layer* capping (next section).

As for MNR, few guidance and related documents exclusively or mainly focusing on EMNR have been published to-date, worldwide (Magar et al., 2009). Regardless, like MNR, EMNR has been discussed in guidance documents, or addressed in detail for specific projects or case-study reviews (ITRC, 2014; Merritt et al., 2009; Merritt et al., 2010a; Colton, 2010).

## 3.3 *In-situ* capping

The remedial practice of *in-situ* capping contaminated sediments is the focus of the capping overview document to which this publication is attached. A brief summary of capping is also provided herein.

In general, capping involves placing cap material overtop the surface of contaminated sediment to create new bottom substrate and to meet pre-defined objectives for cap performance.

Subaqueous contaminated sediments can either be capped *in-situ* (where they naturally deposit and build up over time) or after contaminated sediment has been removed from one location and re-deposited in another location. Both capping practices have basically the same objectives for cap performance.

Capping re-deposited contaminated sediments is often (but not always) done in conjunction with navigational dredging. This type of capping occurred before *in-situ* capping. The first capped marine sediment-disposal sites were established by the U.S. Army Corps of Engineers (USACE) starting in the late 1970s. Examples include the New York Mud Dump and Central Long Island Sound disposal sites (SGI Publication 30-4E, Appendix). The remedial practice of *in-situ* capping evolved from that of capping re-deposited contaminated sediments. Some of the first *in-situ* capping projects were completed in the U.S. in the early 1980s (SGI Publication 30-4E, Appendix).

Discussions in this publication and in the capping overview document focus on *in-situ* capping, mainly because subaqueous capping of re-deposited contaminated sediments is not expected to be a common practice in the future in Sweden. Regardless, most of these discussions also apply to capping re-deposited sediments as well.

The remedial technology of *in-situ* capping has evolved significantly over the last few decades, both in the U.S. and internationally. Much of this evolution has been motivated by, and has resulted in, addressing many of the technology limitations identified during *in-situ* capping's earlier years (see below).

Nowadays, a distinction is made between **isolation capping** and **thin-layer capping**. These two major sediment capping "strategies" differ mainly in terms of respective objectives for cap performance, as discussed in the capping overview document. In practice, project-specific sediment caps are often hybrids which fall somewhere along the isolation ↔ thin-layer spectrum, both in terms of cap design and performance objectives. As noted in Section 3.2, thin-layer capping with conventional materials is generally considered the same as EMNR, although remedial objectives may be somewhat different.

A wide variety of natural and/or man-made materials can be used in isolation and thin-layer capping. Material types generally fall under two categories: Either "inert" conventional materials or "active" materials, including active amendments. Conventional and active capping materials are discussed in detail in the capping overview document.

As summarized mainly in USEPA (2005), some conditions particularly conducive to capping, and especially conventional isolation capping, include:

- Suitable types and quantities of cap material are readily available, and at reasonable delivered cost.
- Anticipated infrastructure needs (e.g., piers, pilings, buried cables) are compatible with capping.

- Water depth is adequate for capping given anticipated site uses (e.g. navigation or flood control).
- The incidence of cap-disrupting human behavior, like boat anchoring, is low or controllable.
- Long-term risk reduction outweighs habitat disruption, and habitat improvements may be provided by the cap.
- Natural and/or man-made erosive conditions (currents, ice scour, boat propwash, flooding, etc.) are not likely to damage a cap, or can be addressed in cap design.
- Rates of upwelling groundwater through the cap are low and not likely to create unacceptable contaminant releases.
- The capped sediment has sufficient physical strength (bearing capacity) to support a cap's weight.
- Contaminants are expected to have low rates of transfer up through the cap.
- Sediment contamination covers larger, contiguous areas rather than smaller, discrete areas.

**Table 3** Remediating contaminated sediments by *in-situ* capping: Relative advantages and limitations.

| Advantages | Limitations |
|---|---|
| • Less complex, quicker to implement than removal-based remedies.<br>• Quickly reduces exposure and related risks.<br>• Little to no residual contaminants involved.<br>• Typically easy to construct.<br>• Can be used to remediate a wide variety of dissolved-phase contaminant types and concentrations, including multiple contaminants and NAPLs.<br>• Can be applicable to a variety of aquatic environments, e.g. lakes, rivers, harbors, wetlands, etc.<br>• Provides clean and perhaps also unique habitat for floral and faunal benthic communities.<br>• During capping, less disruptive to humans and the environment.<br>• After capping, less disturbance to habitat than removal (with time).<br>• Typically less costly than removal-based remedial technologies. | • Most contaminants remain in-place long-term (they do not degrade significantly).<br>• Potential for post-cap disruption and sediment exposure (if not designed and/or constructed properly).<br>• Institutional controls often required after capping.<br>• Some approaches inappropriate when significant erosive forces.<br>• Some approaches inappropriate when significant groundwater upwelling.<br>• Cap material may not be preferred habitat for some floral and/or faunal communities.<br>• Could adversely affect hydrology and/or ecology of a site.<br>• May be incompatible with some waterway uses, e.g. when regular navigational dredging occurs.<br>• May be inappropriate where water depths are already shallow, and a thick cap would further decrease water depths to the point of interfering with boat traffic.<br>• Protected floral and/or faunal species occur in abundance.<br>• Concerns exist for potential effects from a thick (and heavy) cap overtop archeological artifacts occurring at the sea bottom, as in Bergen Harbor (Vågen), Norway (e.g. Stern, 2012).<br>• Long-term monitoring and perhaps also maintenance and repair required. |

Many of the above limitations apply specifically to conventional isolation capping. Other capping approaches (active isolation, conventional thin-layer, and/or active thin-layer) can adequately address many of these limitations, but not all of them at all sites.

As discussed for removal-based sediment remediation technologies:

- Many regulatory and related guidance documents have been published for capping-based technologies.
- Most guidance originates from the U.S., but some also comes from other countries.
- Some guidance focuses exclusively on capping (SFT, 2002; USEPA, 2013; Palermo et al., 1998a, 1998b; Truitt, 1987; Palermo, 1991a, b, c; Bailey and Palermo, 2005). Other guidance includes detailed discussions on capping together with discussions of other sediment remediation technologies (USEPA, 2005; ITRC, 2014; NAVFAC, 2003; ASTSWMO, 2007; CCMS, 1997; USEPA, 1994; COWI, 2013; Klif, 2012; SFT, 2004).
- Many papers addressing various aspects of capping have been published in scientific journals and presented at international conferences like Battelle, SedNet, and NORDROCS (see Section 2.1).

## 3.4 *In-situ* treatment

*In-situ* treatment of contaminated sediment involves placing different types of active treatment agents either: (A) directly *into* the sediment, or (B) *overtop* the sediment surface, each for the purpose of accomplishing one or more remedial objectives. Remedial objectives for *in-situ* treatment typically include: reducing contaminant mass, toxicity, and/or bioavailability within the sediment's biologically active zone (BAZ).

Different treatment agents are "active" in different ways, and the specific type of agent used depends on the organic, metallic, and/or organometallic contaminant(s) targeted for treatment, and also to some degree on which treatment method is considered, A or B.

**Method A** involves using specially designed field equipment to mechanically inject-plus-mix flowable (usually water-based) treatment agents directly into the BAZ. **Method B** involves placing settleable treatment agents overtop the sediment surface, then allowing benthic burrowing organisms to naturally mix the agent into the BAZ by bioturbation processes over time.

Note, references herein to Method A or B for *in-situ* sediment treatment are not recognized and accepted nomenclature amongst sediment remediation practitioners. Rather, the distinction is only made herein to clarify discussions in the current context.

Published summaries or listings of conditions especially conducive to *in-situ* treatment are not readily available. Regardless, many conditions listed above for MNR, EMNR, and capping should also be at least generally applicable to *in-situ* treatment. The applicability of some conditions depends in part on which treatment method is considered, A or B.

Furthermore, relative advantages and limitations are recognized for *in-situ* treatment (ITRC, 2014; CCMS, 1997; Chapman, 2011; Ghosh, 2012; Renholds, 1998; Kupryianchyk et al., 2015**)**. These are summarized in Table 4. Again, applicability of each advantage or limitation depends in part on which treatment method is considered.

**Table 4** Remediating contaminated sediments by *in-situ* treatment: Relative advantages and limitations.

| Advantages | Limitations |
|---|---|
| • Less costly than some other technologies.<br>• Could eliminate need for contaminant removal.<br>• Concept of *in-situ* treatment may be attractive to regulatory authorities and other stakeholders.<br>• Can be used to remediate a wide variety of dissolved-phase contaminant types and concentrations (although multiple treatment agents may be needed).<br>• Could reduce or eliminate the need for long-term monitoring, maintenance, and repair. | • Some approaches still in process of developing, including gaining international acceptance.<br>• Challenges with effective and controlled delivery of treatment agents (especially for Method A).<br>• Challenges with effective and controlled treatment-agent delivery in deeper-water environments (especially for Method A).<br>• Not usually appropriate for treating NAPLs.<br>• May be incompatible with some waterway uses, e.g. regular navigational dredging.<br>• Disruptions to the benthic ecosystem (especially for Method A). |

Method A for *in-situ* sediment treatment existed before Method B. Some of the first Method A projects involved injecting aqueous solutions of calcium nitrate into the BAZ to reduce sulfide odors (Golder, 2003; Sullivan et al., 2005).

A different type of Method-A treatment involves injecting aqueous suspensions of activated carbon (AC) into the BAZ. This is done to promote strong binding (sorption) of organic sediment contaminants, like PCBs, onto and into AC particles (Luthy et al., 2004; ESTCP, 2008; Ghosh et al., 2011; Patmont et al., 2014). Strong sorption of organic contaminants to the AC significantly reduces their dissolved concentrations in the BAZ's porewater phase. This treatment approach can significantly reduce contaminant exposure to and bioaccumulation by benthic organisms since it is generally recognized dissolved-phase contaminants are the most bioavailable (e.g. ITRC, 2011; NYDEC, 2014).

Method B for *in-situ* sediment treatment basically evolved from Method A. Similar to evolution of *in-situ* capping (Section 3.3), evolution of *in-situ* treatment over the past decade or so has been motivated by, and has resulted in, addressing a number of the technology limitations identified during *in-situ* treatment's earlier years (Table 4).

Nowadays, *in-situ* treatment using Method B seems to be more widely used internationally than Method A, probably for a number of reasons. Furthermore, AC – either in powdered (PAC) or granular (GAC) form – clearly remains the most frequently used treatment agent, worldwide, for *in-situ* sediment treatment using both treatment Methods A and B (USEPA, 2013; Kupryianchyk et al., 2015; Patmont et al., 2014; Collins et al., 2012; Ghosh et al., 2011; Sun and Ghosh, 2007).

It should be noted secondary effects from AC amendments on some species of benthic organisms have been reported, including some negative impacts on certain ecotoxicological endpoints like organism survival, growth, lipid content, and/or behavior (Kupryianchyk et al., 2015; Janssen and Beckingham, 2013; Janssen et al., 2012; Jonker et al., 2009). More research is needed to evaluate these secondary effects, including under what species-, sediment-, and AC-specific conditions such effects may be more likely to occur (e.g. Janssen and Beckingham, 2013; Nybom et al., 2016). Practically speaking, secondary negative effects from AC amendments will need to be balanced and weighed against AC's clearly demonstrated effectiveness in significantly reducing bioavailability of sediment contaminants to benthic organisms (e.g. Kupryianchyk et al., 2012 a).

Few regulatory and related guidance documents have been published to-date exclusively focused on *in-situ* sediment treatment (USEPA, 2013). Regardless, this remediation technology, and especially Method B it appears, is receiving increased international attention in guidance documents addressing multiple sediment remediation technologies (e.g. ITRC, 2014). Furthermore, *in-situ* sediment treatment using AC has been the subject of a growing list of papers published in scientific journals and presented at international conferences.

For clarification, the Method B type of *in-situ* sediment treatment is generally considered the same as thin-layer capping with active (sorptive) materials like AC. Additional discussions of active thin-layer capping are provided in the capping overview document.

# 4. Combination of remediation technologies

Multiple sediment remediation technologies can often be combined at a given site, spatially and/or sequentially.

A **spatial** remedy combination could involve dredging or capping in river-area X (which is more-highly contaminated and erosional) plus MNR or EMNR at river-area Y positioned downstream. In general, such spatial combinations of remedies are usually a requirement at larger sites, across which a wide variety of conditions often occur.

A **sequential** remedy combination could involve first removing contaminated sediment from lake-area Z, then placing a cap over the same area to physically and chemically isolate residual contamination remaining after removal. Capping re-deposited contaminated sediment is another obvious way in which removal- and capping-based remedies are combined (SGI Publication 30-4E, Appendix).

Combinations of sediment remediation technologies are becoming common practice in established sediment markets like the U.S. (USEPA, 2005, 2013; Ells, 2012; Zeller and Cushing, 2006; Palermo et al., 2008; Patmont and Palermo, 2007). Remedy combinations are typically most appropriate and practical at larger and/or more complicated sites, e.g. sites displaying a variety of contaminant types and/or concentrations, water depths, surface- and groundwater flow regimes, physical sediment characteristics, etc.

Natural recovery is almost always a final, or finishing, step to all site-specific sediment remediation efforts, regardless of whether or not MNR is actively implemented.

# 5. Costs

Despite the fact many of the above sediment remediation technologies have been in existence and use for decades, locating readily available and up-to-date, published summaries in which costs for the different technologies are presented and compared – including in a clear and concise manner – is a challenge. There are likely a number of reasons for this.

When project-specific and/or general overview-level cost information *is* available, it is often unclear exactly what costing components are and are not included. There are many costing components to consider, depending on the specific technology considered, including: permitting, design, equipment, materials, labor, post-removal treatment and disposal, and post-remedy monitoring.

Regardless, when considering cost information from numerous published and non-published sources (Mohan et al., 2008; DNV, 2011; Palermo et al., 2002; Palermo et al., 1999; Ghosh et al., 2008; Patmont, 2008; Magar et al., 2009; Naturvårdsverket, 2003 and other sources), the following can generally be said regarding costs for the three major remediation technologies: removal (dredging), capping, and MNR:

In **relative terms**, most references agree costs for dredging-based removal > *in-situ* capping >> MNR (CCMS, 1997; ITRC, 2014; Chapman and Smith, 2012; USEPA, 2005; NAVFAC, 2003).

In **approximately quantitative terms**, costs for international sediment remediation projects and Norway-specific projects are as shown in Table 5.

**Table 5** Approximate costs for sediment remediation, internationally and in Norway.

| | **Removal (dredging) (SEK / $m^3$)** | ***In-situ* capping (SEK / $m^2$)** | | **MNR (SEK / $m^2$ / yr)** |
|---|---|---|---|---|
| | | Conventional isolation | Thin-layer reactive (Using AC) | |
| **Inter-national** | Removal: 60 - 1,200<br>Treatment: 30 - 10,500<br>Disposal: 40 - 2,300<br>**Total: 130 - 14,000** | 15 - 1,400 | 85 - 265 | << 1 - 4 |
| **Norway** | Dredging: 110 - 220<br>Disposal: 170 - 790<br>**“Rule of thumb” for dredge + dispose: 850** | 135 | ----- | ----- |

Footnotes:

1. Norway-specific projects are presented separately since relatively more cost information is readily available for Norway than for any other country, other than the U.S.
2. The primary source for cost information for Norwegian projects is DNV (2011).
3. Assumed currency exchange rates of approx. 1 USD = 6.7 SEK and 1 NOK = 1.1 SEK.

Also, according to Naturvårdsverket (2003), costs for two Swedish capping projects – Vansbro and Turingen (thin-layer) – were reported at 1,400 SEK/$m^2$ and 25 SEK/$m^2$, respectively (SGI Publication 30-4E, Table 1).

As shown in Table 5, there is clearly a very wide range in costs, especially for removal/dredging-based remedies, where multiple steps and related costing components are involved. The international cost range for conventional isolation capping is also quite broad. However, this is because the exceptionally high unit cost for the Vansbro capping project is also included. Based on information for other international projects, maximum unit costs for conventional isolation capping are typically far lower, on the order of around 500 SEK/$m^2$ or much less.

Significant variability in costs for any particular remediation technology is not surprising, since each project is unique in multiple respects (variable project size, contaminants and contaminant concentrations, site conditions, physical sediment characteristics, targets for risk reduction, etc.).

# 6. Summary

- Proven-effective and internationally-accepted, *ex-situ* and *in-situ* technologies are available for remediating contaminated sediments. These include: removal (dredging), MNR, EMNR, *in-situ* capping, and *in-situ* treatment.
- Relative advantages and limitations are recognized for each remediation technology. One limitation common to all *in-situ* technologies (MNR, EMNR, capping and treatment) is that sediment contamination remains in place, at least to some degree and for some period of time. Significant limitations of removal-based technologies is they are typically more (to much more) costly to fully implement than *in-situ* technologies, and residual contamination often remains (usually at the sediment surface, where it is most bioavailable).
- No "one-size-fits-all" sediment remediation technology is appropriate for all sites. Also, there should not be a pre-conceived notion (based on little to no site-specific evaluation) a particular technology, like dredging or capping, is most appropriate for a given site. Objectively and systematically selecting which remediation technology or technology combination is both most technically appropriate and most cost-effective is a site- and project-specific process.
- The remedy-selection process should consider and balance multiple and sometimes conflicting factors including: rate and degree of risk-reduction required, contaminant type(s) and concentration(s), site conditions, sediment characteristics, future anticipated site uses, and costs for all remedy components.
- Regulatory guidance and other technical documentation has been published in a number of countries, including in Sweden and Norway, describing: (a) each of the *ex-situ* and *in-situ* sediment remediation technologies in detail (see technology-specific discussions and references above), and (b) procedures for systematically working through and selecting the most appropriate remediation technology or technology combination for a given site and project (Naturvårdsverket, 2009a; Rosen et al., 2009; Holm et al., 2013; Linkov et al., 2006; Bates et al., 2014).
- Prior to sediment remediation at a site, a risk assessment should be done in order to: (a) document sediment contamination indeed poses unacceptable current and/or future risks to the environment and/or human health, risks that have to somehow be managed, and (b) identify specifically what sediment contaminant(s) are driving risk at the site. Presence of measureable sediment contamination does not necessarily mean the contamination poses, or could pose, unacceptable risks. Furthermore, even though most *ex-situ* and *in-situ* remediation technologies can be appropriate for a variety of contaminant types and concentrations, the specific sediment contaminant(s) driving risk at a site can dictate not only the best remedial approach in general, but also specific designs for a particular remedial approach, like certain types of capping.

**To emphasis:** identification and control of ongoing sources of contamination into a site – *before* site remediation, if at all possible – is critical to insure long-term success of any remedial approach. Contaminant sources can be primary (from land), secondary (from adjacent sediment areas), or both. It is possible to do an excellent job of designing and executing a sediment cleanup remedy, but if significant contaminant inputs continue after remedy implementation, the remedy will have likely done little to reduce long-term contaminant exposure and related risks. Numerous project examples exist where post-remedy re-contamination has been documented (ASTSWMO, 2013; Nadeau and Skaggs, 2008; Dalton, 2007).

# 7. References

For all references cited herein, please see SGI-Publication 30-6E.

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