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Application of Clean Dredged Material to Facilitate Contaminated Sediment Source Control

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Abstract

Navigation channels, turning basins, and other US Army Corps of Engineers (USACE)–managed navigation infrastructure often serve as repositories for contaminated sediment from off-site sources. As much as 10% of the material that USACE dredges on an annual basis is contaminated such that it requires additional and more costly management (for example, rehandling and placement in managed confined disposal facilities). Presence of contaminated sediments constrain potential management options resulting in additional costs and opportunity loss from the inability to beneficially use the material. One potential solution is applying clean dredged material to stabilize and isolate contaminated sediment sources, preventing further transport and introduction to USACE-managed infrastructure.

This document summarizes a comprehensive literature review of laboratory and field case studies relevant to using clean dredged material to isolate or stabilize contaminated sediments, focusing on the physical, chemical, and biological parameters critical to establishing its feasibility and long-term effectiveness. Potentially effective engineering control measures were also reviewed where erosion and site hydrodynamics are facilitating the transport of contaminated sediments to USACE-maintained navigation infrastructure. This literature review documents and summarizes those factors considered in establishing feasibility and long-term effectiveness of the approach as well as the applicable engineering tools employed and constraints encountered.

Contents

Preface

The literature review herein was compiled by the US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). Funding was provided by the Dredging Operations and Environmental Research Program (DOER). The Technical Monitor was Dr. Todd Bridges.

The work was performed by the Environmental Risk Assessment Branch and the Environmental Engineering Branch of the Environmental Processes and Engineering Division, ERDC-EL. At the time of publication, Dr. Michael Rowland, was Chief, Environmental Engineering Branch; Jay Lindsay was Chief, Environmental Risk Assessment Branch, ERDC-EL; and Warren Lorentz was Chief, Environmental Processes and Engineering Division, ERDC-EL. Dr. Brandon Lafferty was Deputy Director, ERDC-EL and Dr. Edmund Russo was Director, ERDC-EL.

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1 Introduction

This report describes a literature review and synthesis performed by the US Army Engineer Research and Development Center (ERDC). This work supports the Dredging Operations and Environmental Research (DOER) Program.

1.1 Background

Navigation channels, turning basins, and other US Army Corps of Engineers (USACE)–managed navigation infrastructure often serve as repositories for contaminated sediment originating from off-site sources. Approximately 10% of the sediment that the USACE dredges on an annual basis is contaminated to the extent that it requires additional handling and more costly management. The presence of contaminated sediments constrains potential management options, resulting in additional costs as well as opportunity loss resulting from the inability to beneficially use the material. Dredged material is being used as a beneficial resource for many civil engineering applications (Rakshith and Singh 2017; Zuliani et al. 2016). The purpose of this report is to explore the potential beneficial use of dredged material as a resource to stabilize or isolate contaminant sediment sources to prevent their introduction to navigation infrastructure (for example, channels and berth areas). This analysis assumes that the dredged material can be introduced in a way that maintains some level of order and structure rather than simply mixing with and diluting the existing contaminated sediment bed. Such an approach would facilitate an additional beneficial use of clean dredged material that might otherwise be disposed offshore, placed in confined disposal facilities (CDFs), or used for other civil engineering applications.

One potential application of clean dredged material is thin layer placement (TLP) on contaminated sediment deposits for source stabilization and isolation, reducing transport of contaminated sediments into USACE-managed navigation infrastructure (for example, channels, turning basins). Reduced channel dredge volumes classified as contaminated will increase management options and reduce maintenance dredging costs. In areas where erosion transport enhances translocation of contaminated material into USACE-maintained navigation channels, application of engineering controls may stabilize source areas to prevent further transport (for example, using dredged material to create nearshore berms [Beck, Rosati, and Rosati 2012], sediment mounds, or the use of geotubes filled with clean dredged material). USACE began constructing underwater berms in the mid-1930s with a 152,911m^3 berm off Santa Barbara, California in 6.1 m of water (Richardson 1988). Fine-grained material has typically been limited to the construction of stable berms in deep water (Williams and Prickett 1998), but recent work has shown that mixed material (sands, silts, and clays) can be strategically placed as feeder berms in nearshore applications, which are considered relatively higher energy environments (Brutsché and Pollock 2017). Additional benefits of dredged material berms that stabilize and isolate contaminated sediment deposits include reduced long-term environmental liability associated with contaminated storage in USACE owned CDFs, reduced exposure of aquatic habitat to contaminants, and dredged material associated with USACE operations and maintenance being suitable for beneficially use. An approach similar to TLP presently used in contaminated sediment management is enhanced monitored natural recovery (EMNR). EMNR is a hybrid remedy that relies on the combined effects of an engineered method of accelerating a natural recovery process and a monitoring plan that quantifies recovery and achievement of interim and final targets (Interstate Technology & Regulatory Council (ITRC) 2014; Magar et al. 2009; Merritt et al. 2010; Reible 2014; USEPA 2005). EMNR is designed to supplement natural depositional processes in depositional environments (that is, isolate contaminated material via natural deposition of cleaner material). The concept this report explores addresses contaminated sediment source material that by definition is not stable and as a consequence is being transported into adjacent navigation channels, turning basins, and berthing areas. However, the contaminated sediment source can be isolated in these dynamic environments by ongoing placement of cleaner dredged sediment. As the TLP dredged sediments are removed by hydrodynamic forces, additional dredged sediment can be added to nourish the isolation layer.

This document summarizes a comprehensive literature review of laboratory and field case studies relevant to the potential application of clean dredged material to isolate or stabilize contaminated sediments with a focus toward the physical, chemical, and biological parameters critical to establishing feasibility and long-term effectiveness of the approach. Potentially effective engineering control measures were also reviewed where erosion and site hydrodynamics are facilitating the transport of contaminated sediments to USACE-maintained navigation infrastructure.

1.2 Purpose

This report summarizes a comprehensive literature review of laboratory and field case studies relevant to the application of dredged material to stabilize or isolate contaminated sediment. Important physical, chemical, and biological parameters governing the use of clean dredged material for these purposes are identified along with engineering tools required for successful and cost effective implementation. Key parameters and critical data gaps identified in this review will inform development of guidance and future research needs.

2 Literature Review

2.1 Contaminated sediment isolation and stability

Many research studies have focused on using TLP as a capping method to remediate contaminated sites. The lessons learned from these studies are relevant to the use of clean dredged material for the control of contaminated sediment sources in dynamic environments near navigation infrastructure. For the purpose of this report *clean dredged material* is defined as the material that has been determined to be suitable for open-water disposal as defined in the Inland and Ocean Testing Manuals (ITM - USEPA/USACE 1998; OTM - USEPA/USACE 1991). TLP of clean dredged material has been used as an effective in situ risk-reduction method, low-cost source control measure, and as an alternative to conventional disposal of dredged material (Cornelissen et al. 2008; Wilber, Mogren, and Beeney 2016). Multiple laboratory tests and field case studies using sand, soils, dredged material, and amendments in thin layer caps have been identified in the literature (Wang et al. 1991; Talbert, Thibodeaux, and Valsaraj 2001; Simpson et al. 2002; Eek et al. 2007; Murphy et al. 2006; Josefsson et al. 2010, 2011; Josefsson et al. 2012; Lampert, Sarchet, and Reible 2011; Lin et al. 2014; Winther 2011). These studies typically evaluate contaminant flux, contaminant bioavailability, secondary impacts to benthic organisms, and physical stability in cases where TLP has been implemented as part of remediation, EMNR, or open-water disposal efforts. The certainty of the success of TLP for source control presumes that emerging contaminants (or what is not being measured) are not at higher levels in the donor material than the receiving sediment, that placement does not adversely affect important sensitive habitat or species, that placement does not produce unacceptable short-term water quality issues, and that placement does not result in an unacceptable increase in maintenance dredging frequency in nearby channels. Feasibility for implementing TLP of clean dredged material on a site for purposes of source control will depend on site-related conditions and the possible causes of bed shear stresses such as energy, flow conditions, bathymetry, water depth, currents, potential for storm-induced erosion, placement equipment, and placement techniques (Murphy et al. 2006; Walls et al. 1994). In each study reviewed, we focus on the physical, chemical, and biological characteristics of the site sediments and the placed dredged material.

2.2 Laboratory studies on contaminant isolation

Wang et al. (1991) studied thin caps with sediment from Tao River, China (0.26% TOC, 19% sand[1], 78.5% silt[2], 0.9% clay[3], porosity of 0.5, bulk density of 0.84 g/cm^3)[4], University Lake Sediment, Louisiana State University (1.73% TOC, 21.4% sand, 72.2% silt, 6.4% clay, porosity of 0.45, bulk density of 0.81 g/cm^3), and sand, in plexiglass simulator cells to understand the diffusion of the dissolved organic pollutant 2,4,6-trichlorophenol (TCP). The test showed that constructing the cap with sediment, which has a higher solid-water distribution coefficient (K_d) for TCP, delayed breakthrough relative to sand caps. However, once a steady state was reached, and all of the sorption sites on the cap were taken up, the diffusional flux was similar for all capping materials. At steady state, the porosity and thickness of the cap material were dominant parameters, and K_d was independent of flux.

Talbert, Thibodeaux, and Valsaraj (2001) used proof-of-concept experiments to show the effectiveness of very thin layers (1–8 mm) of sand, soil, and other materials at reducing the dissolution flux from a benzoic acid wafer. Thin layers were able to reduce flux by 81% to 96%. The results indicate that natural deposition of clean sediment is a significant part of natural recovery of contaminated sediment sites. The experiments suggested that the TLP technique could be engineered. Physical-chemical processes of diffusion were modeled to estimate flux. Physical experiments showed that, on average, flux was 1.7 times greater than model predictions. Surface-water flows induced advection in the upper layers of the cap and were the likely cause for the underprediction of the model. In the field, thin caps might create some temporary advection by consolidation as well. Thin layers with surface roughness element sizes (surface roughness) large in comparison to layer thickness displayed lowered effectiveness values. The roughness of the surface created advective flow in the cap porewater. Particle washout may also have been a minor factor affecting the experiments. Talbert, Thibodeaux, and Valsaraj

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[1] Particle size diameter larger than 50 µm.

[2] Particle size diameter between 2 and 50 µm.

[3] Particle size diameter smaller than 2 µm.

[4] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

(2001) concluded that engineered application of thin layers of soil or sand onto contaminated bed surfaces should be an aim in the remediation of contaminated sites.

Simpson et al. (2002) studied the flux of metals (by measuring dissolved Zn[5]) caused by recreated tides, bioturbating organisms, and periods of anoxia in corer reactors with different capping treatments. A clean sediment (particle sizes: 89.3% > 180 μm, 5% < 63 μm) layer of 5 mm thickness was the most effective capping material, as compared with sand and sand-zeolite mixtures, reducing flux to just ~0.01 mg m^{-2} day^{-1} for sediment-capped sediment from > 30 mg m^{-2} day^{-1} for uncapped sediment (>99.9% reduction). Capping with clean sediment was considered most effective because of its extremely high sorption capacity for most trace metal ions. The high number and variety of metal ion binding sites of natural sediments allow them to bind metals under a wide range of conditions. Metal sulfide formation, caused by anoxia below capping materials, is an important function of sediment caps. This should be applicable to all sulfide-forming metals, though Zn was the focus of Simpson et al. (2002). Even though 5 mm thickness showed high effectiveness in the laboratory experiments, Simpson et al. (2002) recommended that a layer thickness greater than 30 cm should be used to isolate the contaminated underlying sediment from bioturbating organisms. Atkinson, Jolley, and Simpson (2007) recommended the minimization of physical disturbances and biological disturbances (bioturbation) for controlling metal bioavailability in marine sediments. This is also important for Hg (Johnson, Reible, and Katz 2010), which is a common contaminant of concern due to the bioaccumulation potential of methylmercury.

Eek et al. (2007) performed laboratory tests to study compressive behavior of a 2 cm thick cap of crushed limestone and gneiss (sand size) placed on metal (Fe, Ca, Mn, Co, Ni, Cd, and Cu) contaminated sediment. They concluded that the most important functions of capping are the prevention of resuspension and oxidation of the sediment surface, which minimizes metal mobilization. They found that in the case of the gneiss, there was little or no acid volatile sulfide (AVS) and therefore simultaneously

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[5] For a full list of the spelled-out forms of the chemical elements used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 265, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

extracted metals (SEM) were greater than AVS. Metals in the gneiss were therefore more mobile than in the sediment, even though the sediment contained higher concentrations of metals than the gneiss. Conducting leaching tests of the capping materials, sediment, and mixtures of the two, in water similar to the site of interest, is important to obtain results that are accurate and representative of field conditions. Research by both Simpson et al. (2002) and Eek et al. (2007) indicate that clean local dredged sediment may be the safest do-no-harm thin layer capping material with regard to heavy metal contamination. Sediment often has some sorption capacity, making it perform better than sand, and sediment is less reactive (fewer unwanted secondary reactions or secondary environmental impacts than artificial or foreign materials).

A thin layer capping study evaluated the effectiveness of a 1.25 cm layer of coke, activated carbon (AC), and organic rich–soil to prevent PCB migration from sediments into the bioactive zone (Murphy et al. 2006). This study determined, through modeling, that isolation time increased with sorption capacity of the capping material. The amendment effective porosity, dispersivity, and bulk density had little effect on cap performance as compared to sorption capacity. Groundwater seepage had a strong impact on isolation time and amendment performance. In the absence of seepage, PCBs could be isolated for more than 100 years with all amendments, and in the presence of seepage, PCBs could be isolated for more than 60 years with AC. These findings suggest that in the presence of groundwater seepage, clean dredged material might not work for contaminant isolation, and active amendments should be used for contaminant isolation. Gidley et al. (2012) also showed in physical models that AC was a necessary amendment for controlling total porewater PAH flux in sand caps subjected to significant groundwater flow. Peat amendments showed moderate improvements, and a dredged material cap would likely perform similarly, chemically, to the peat-amended caps studied by Gidley et al. (2012).

Different materials including AC, Kraft lignin (LG), sand, clay, and three industrial by-products were considered for evaluating the ecosystem effects of TLP on contaminated sediments from Greenland fjords, Norway. The structural and functional effects on benthic communities were evaluated in the laboratory using sediment box-core samples. Community richness and abundance was significantly reduced with industrial products, whereas materials with similar characteristics to the site sediments such as sand and clay do not have a high impact on benthic communities (Näslund et al. 2012). Josefsson et al. (2012) conducted boxcosm experiments with bioturbating organisms to assess thin layer caps of sediment and limestone amended, and not amended, with active powder materials (AC and LG). The efficiency of the thin layer caps (as revealed by polychlorinated dibenzodioxin and dibenzofuran [PCDD/F], hexachlorobenzene [HCB] and octachlorostyrene [OCS] flux and bioaccumulation) improved with increasing thickness (up to 5 cm) and with the addition of active materials. AC was more efficient than LG at reducing flux. Increasing the cap thickness had a higher impact on reducing bioaccumulation in *Nassarius nitidus* (*N. nitidus*) than *Neries species* (*Neries spp*.). because the latter were deep burrowing and could reach the contaminated layer. The bioaccumulation in *Neries spp*. and the flux showed similar trends, with contaminant hydrophobicity suggesting that the two were influenced by a common factor—the levels of pollutants in the organism burrows. LG degraded and led to anoxic conditions in the caps, which affected organism survival, and was linked to contaminant flux. Josefsson et al. (2012) found through Hg tracer tests that increased flux with organism activity was attributed to more biorrigation and not particle mixing of sediment layers. Bioturbation compromises thin caps unless it improves contact between the contaminants and an active material that has not reached its sorption capacity. Bioavailability reductions were greater in the less hydrophobic (faster) compounds. If the experiments would have been extended for more than six months, Josefsson et al. (2012) hypothesized that greater bioavailability reductions would have occurred for the most hydrophobic compounds because of sorption kinetics between contaminants and AC.

Josefsson et al. (2010, 2011) conducted laboratory experiments with two organisms separately and buried layers of contaminants (PCBs and polybrominated diphenyl ethers [PBDEs]). Both organisms feed near the surface (surface-deposit feeders), but one was a polychaete that formed deep burrows while the other was a surface-dwelling amphipod. The bioaccumulation of buried contaminants decreased with increasing burial depth with both organisms. The polychaete had 12 times higher tissue concentrations than the amphipod. The ratio of concentration in the polychaete to concentration in the amphipod was higher for the more hydrophilic chemicals because these were transported better in the polychaete burrows via porewater. Though this was not a capping experiment, it does provide insight on the effect of contaminant burial depth related to biota with different functional traits.

Lampert, Sarchet, and Reible (2011) studied thin layer caps in laboratory microcosms that examined bioturbation as the primary contaminant transport mechanism for PAHs. The caps were made of sand but also had a thin layer of clean sediment at the cap–surface water interface. The results of the experiments showed that thin layer capping can be a useful sediment remediation technology as long as the cap thickness exceeds the depth of "rapid mixing" bioturbation. Successful remediation would also rely on the absence of erosion, groundwater advection, or other phenomena that may occur in addition to diffusion (Lampert, Sarchet, and Reible 2011).

Lin et al. (2014) studied the effectiveness of thin layers (0.5 cm) of clean sediment at reducing DDT flux and bioaccumulation in microcosm experiments with and without *Lumbriculus variegatus* (*L. variegatus*). In the absence of bioturbation caused by these worms, the thin layer of clean sediment reduced flux from about 3.5 to 0.1 µg ΣDDT m^{-2} day^{-1} (97% reduction). However, in the presence of bioturbation, the thin layer of clean sediment only reduced flux from about 5.4 to 4.5 µg ΣDDT m^{-2} day^{-1} (16.7% reduction). In addition to flux, DDT bioaccumulation did not reduce significantly with the addition of a thin layer of clean sediment. In freshwater systems with this species of worm, the thickness of the thin layer needs to be greater than the bioturbation layer unless the layer contains much greater sorption properties than the native sediment. Lin et al. (2014) showed that adding AC (75–150 µm particle size) as a thin 0.3 cm layer on top of contaminated sediment provided effective treatment. Winther (2011) conducted jar tests with PAH-contaminated marine sediment capped with a 1 cm layer of marine clay. Different types of biochars were mixed into the clay (0.05 g of biochar mixed into each gram of clay). The biochar amended caps showed reductions in flux for PAHs. Phenanthrene fluxes decreased by 77% for the biochar-amended cap as compared to the no cap control. More work should be done to test the effectiveness of sorptive materials mixed with dredged material and used as caps. Biochar functions similar to AC, but it is cheaper and more natural, potentially leading to fewer secondary effects. Furthermore, some dredged material contains native char–like materials, such as coal, charcoal, and other black carbons.

Fewer studies have looked at erosion of thin layers by shear stress. Graham, Hartman, and Droppo (2013) used an annular flume to conduct tests on sand and sand mixed with sediment from Hamilton Harbour, Lake Ontario, Canada, to determine the critical bed shear stresses for erosion of 18 cm thick caps. They then determined the conditions caused by ship traffic and weather events and compared them to the critical bed shear stresses. The test using sediment mixed with sand was conducted to simulate a condition where the sand mixes with the underlying sediment to some extent upon placement. Adding sediment to the sand increased the critical bed shear stress of the material from 0.13 Pa to more than 0.34 Pa (2.6 times greater). They concluded that in some areas, larger particle size material should be used to withstand propeller erosion. Larger particle sizes were not recommended for all areas, however, because finer material will create less resuspension of the pre-existing contaminated sediment bed during placement and provide better habitat for benthic re-colonization. Hamilton Harbour sediments were further studied in annular flumes by Droppo, Lau, and Mitchell (2001) to measure critical shear stresses. Droppo, Lau, and Mitchell (2001) found that the critical bed shear stress of sediment with a five-day-old biofilm (formed by the colonization of bacteria, fungi, or algae) was 1000% higher (0.325 Pa) than sediment without the biofilm (0.024 Pa) (growth inhibited by NaOCl). In marine and estuarine systems, extracellular polymeric substances are believed to provide greater stability than in freshwater systems (Spears et al. 2008).

2.3 Field studies on contaminant isolation

Cornelissen et al. (2011) studied thin layer caps of powdered activated carbon (PAC) mixed with clay, PAC alone, and PAC with a sand layer as a remediation strategy for PAH contaminated marine sediment. The site was in 4–6 m depth water with a tidal amplitude of 1–2 m and currents of up to 20 cm/s. The PAC slurries were made denser than surrounding water by soaking in a 10% w/w NaCl solution and were applied at a rate of 20 L/min using a flexible manually operated hose. Benthic flux chambers, 17 µm thick polyoxymethylene (POM) passive samplers, and grab samples were used to monitor effectiveness. PAC mixed with clay worked best for reducing contaminant flux (by a factor of 2–10) and minimizing adverse effects to benthic communities observed up to 12 months postplacement. Pore water reductions were most noticeable in the 0–5 cm bioactive layer of the sediments. The cost of PAC material was about $\$10/m^2$, and placement costs were on the same order of magnitude. Thin layer capping was recommended for systems with low hydrodynamic energy and an even surface. Both species abundance and richness decreased for all capping treatments compared to the reference site except for PAC mixed with clay, which only decreased in abundance. The PAC + clay treatment had the lowest impact on biotic indices. It was noted that, for this site, the PAH concentrations were low enough that the negative secondary effects of PAC on benthic habitat may outweigh the positive primary effect of PAH bioavailability reduction (Cornelissen et al. 2011).

A field experiment on thin layer capping conducted in Ormefjorden and Eidangerfjorden, Telemark, Norway, evaluated the functional response, bioavailability of dioxins, and benthic community response as part of a remediation effort that involved TLP of crushed limestone, clay dredged material, and a mixture of clay dredged material and AC, with a thickness ranging from 1.8 to 4.7 cm and an AC content of 2 kg/m^2. The placement sites were evaluated with a sediment profile imaging (SPI) camera every six months over three years. The benthic habitat quality index determined from image analyses indicated that the conditions significantly deteriorated at sites where the mixture of clay dredged material and AC was placed as compared to the reference sites (Schanning et al. 2011). Full macrofaunal analyses performed one month and two years after TLP implementation in some samples confirmed the results from the SPI analysis and indicted that the number of species, biomass, and the benthic quality index significantly depleted in the clay dredged material and AC sites as compared to the reference sites.

When the PAC content in sediment is ≤25%, there seems to be significantly less lethality caused by the PAC (Samuelsson 2013). The sites where coarse limestone material and clay dredged material with no AC was placed did not affect the number of species, biomass, or the benthic quality index. Long-term changes in the benthic communities and sediment characteristics are not likely to occur at the sites where clay dredged material was placed due to the similarities between the characteristics of the dredged material and the sediment located at the placement site pre-dredged material application (Schaanning et al. 2011). TLP did not significantly affect oxygen and nutrient fluxes for all treatments; however, a temporary uptake of phosphate and reduced release of silica nutrients from the sediment was experienced at the TLP sites that placed limestone (Schaanning and Allen 2012). Bioaccumulation and leakage of dioxins was 67–91% lower at the sites that used a mixture of clay dredged material and AC and 46% lower at the sites that used limestone and clay dredged material as compared to the reference sites. These results show that capping effectively reduced the flux of dioxins from the sediment as compared to the reference sites (Schaanning and Allen 2012).

Cornelissen et al. (2012) also studied the effectiveness of thin layers with a thickness of 5 cm of locally dredged clean clay to reduce PCDD/F contaminant fluxes over a two-year timeframe at Ormefjorden and Eidangerfjorden (same area described above). Diffusional fluxes were assessed primarily through measuring freely dissolved contaminants. The caps reduced contaminant fluxes by 50–70%. Freely dissolved concentrations were also monitored at 7–10 cm above the seafloor using POM passive samplers. This showed contaminant reduction of about 34% in freely dissolved surface water after capping. Mixing of the cap and bed sediments was observed, caused presumably by bioturbation. PAC with average particle size of 20 μm was also explored as an amendment to the dredged material cap (10 parts dredged material to 1 part PAC, on a dry-weight basis). Slurries were mixed for at least one hour in a hopper dredge tank prior to placement. During the time frame of this study, there was no benefit seen by adding the PAC. It was suspected that if monitoring was conducted for a longer period of time (dozens of years), that the benefits of adding PAC would be observed, due to AC-contaminant sorption kinetics, which are relatively slow. The results also showed that slightly thicker caps (5 cm vs. 2.5 cm) provide greater flux reductions in a two-year timeframe. To better understand the effect of time, Cornelissen et al. (2015) looked back at their 2010 study (Cornelissen et al. 2012) and re-examined the effectiveness of 5 cm thin layers over a three- to five-year time frame. Diffusional fluxes were assessed primarily by measuring freely dissolved contaminants in pore water and surface water. Compared to the effectiveness after just two years, the unamended caps decreased in effectiveness by a 20-60% flux. Compared to the two-year time frame, there was an increase in effectiveness (reduction in fluxes by 80–90%) seen in the caps amended with PAC. This indicates that unamended caps perform well initially but lose effectiveness over time while A- amended caps perform well over the long term (>5 years).

Other amendments that may have superior sorption capacity for metal constituents include steel slag and apatite. Kaplan and Knox (2014) conducted laboratory experiments to evaluate the influence of apatite on metals-contaminated sediment. Apatite addition resulted in significant reduction of pore water Cd, Co, Hg, Pb, and U concentrations; however, increases in pore water As and Se concentrations were observed as a result of phosphate competitive exchange. Both apatite and steel slag were superior at sorbing copper from copper-contaminated sediment obtained from Torch Lake in Michigan as compared to GAC on both batch sorption and column studies conducted at the ERDC.[6] Copper removal percentages were >90% for both apatite and steel slag.

A thin layer consisting of a sand and silt mixture was placed in multiple areas at Randle Reef, Hamilton Harbor, Lake Ontario (site material also discussed above in lab studies section) to enhance natural recovery adjacent to marine structures and in areas that will not be dredged (Kellems et al. 2013). The highest bottom shear stress induced by wind was then determined in the field, which was planned for future cap design and proper selection of sand size that will withstand the 0.5 Pa shear stress experienced in the area (He et al. 2014). The sediments at Randle Reef are highly contaminated with PAHs (average 5,000 mg/kg; max 73,755 mg/kg) (Graham et al. 2017). By applying a layer of clean dredged material on the site, the bacterial populations and production of extracellular polymeric substances may increase, which may improve sediment stabilization and resistance to erosion (Slater et al. 2008). In situ erosion flumes deployed at the site showed that erosion characteristics varied with sediment density, which, in turn, varied as a result of bioturbation, gas accumulation, and biofilm formation and degradation (Krishnappan and Droppo 2006).

A 15–30 cm layer of dredged material was placed in Ward Cove, Alaska, to reduce toxicity of sediments contaminated with ammonia, 4-methylphenol, and sulfide and to stimulate colonization of the remediated areas by benthic macroinvertebrates (Becker et al. 2009). The thin layer cap material was defined as fine-grained sand (particle diameter 0.08–0.43 mm) to medium grained sand (particle diameter 0.43–2.0 mm) with nonplastic silt (particle diameter 0.005–0.08 mm and plasticity index <4) (Hartman Consulting Corporation 2000). The material was placed with a derrick barge and modified cable arm rehandling bucket, which resulted in

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[6] Acevedo-Acevedo, D.; Ruiz, C.E.; Azhar, W.; Reible, D.; Lu, X. In review. *In-Situ Sediment Treatment: Laboratory Studies for the Evaluation of in-situ Sediment Amendments and Active Caps for Reducing Bioavailability of Sediment Contamination*. ERDC/EL TR-17-X. Vicksburg, MS: Engineer Research and Development Center.

the most consistent and uniform placement method in the deep water of the cove. The limiting factors for the TLP areas included bearing capacity of the sediment, the slope of the seafloor, and water depth. TLP was considered impractical in areas with a very high density of sunken logs (>200 logs/acre) that formed pyramids exceeding 10 ft high, water depth exceeding 120 ft, bottom slopes exceeding 40%, organic-rich sediment with bearing capacity smaller than 6 lbs/ft^2, and where routine maintenance dredging was required (Merritt et al. 2009). The results from monitoring efforts conducted three years after placement indicate that TLP improved the area significantly, thus reducing concentrations of the contaminants of concern and improving amphipod survival and benthic community colonization (Becker et al. 2009).

Geotechnical considerations are key for stability of the cap and underlying sediments, since underlying sediments can be very soft (Ebrahimi et al. 2016). Construction techniques such as placing thin lifts of cap materials in stages and allowing sufficient time between each lift for consolidation and strength gain are usually used to prevent cap failures (Ebrahimi et al. 2016; De Leeuw et al. 2002). This methodology was implemented for island creation in IJburg, Amsterdam, to prevent instability issues at the site, since the sediment was very soft. Ebrahimi et al. (2014) developed a methodology for evaluating geotechnical stability of a cap; this method considers the shear strength gain of sediments under loading from a cap.

Merritt et al. (2010) reviewed a range of thin layer capping sites from pilot to full scale. Thin layer capping was defined as a 15–30 cm cap of clean sand, sediment, or other material for enhancing monitored natural recovery (MNR). Most sites where thin layer capping has been employed have been moderately elevated in sediment contaminant concentration and dominated by quiescent near-bed processes with limited natural sedimentation. Thus, most thin layer capping evaluated to date has been intended to accelerate natural depositional processes. A review of thin layer capping sites shows that many practical issues can be overcome, such as deep water depth, steep slopes, and organic enrichment requirements (bearing capacity and habitat quality requirements) of the sediment. Monitoring tools, such as multibeam bathymetry, are still limited in their ability to assess caps thinner than 30 cm in thickness. However, multibeam technology is improving, and at some sites, simple visual (plan-view) inspection is enough to verify placement success. Further monitoring is needed to check for cap erosion. Though the sediment chemical concentrations goals can often be met through thin layer capping, this measure is not well correlated with bioaccumulation of contaminants in higher trophic level consumers (Merritt et al 2010).

2.4 Other field studies

Multiple field studies have evaluated the impact of open-water thin layer disposal of clean dredged material on benthic communities and water quality. While these studies were not designed to assess utility of TLP for purposes of contaminant isolation, their findings are relevant for identifying potential impacts that may result from TLP of dredged material for purposes of source control.

Dredged material was placed in a thin layer of 30 cm over three 300-acre disposal areas located in Mississippi Sound, a shallow coastal lagoon with a mean depth of -10 ft MLW and a tidal range of 1.5 ft. The sites were monitored prior to placement, during placement, and over a 16-month period postplacement, evaluating water quality and benthic community response. The results from water quality monitoring indicated that TLP did not consistently impact the water quality of the TLP areas and that any observed impacts were typically short term (Wilber, Mogren, and Beeney 2016; Rees and Wilber 1994). Total infaunal abundance at Mississippi Sound placement sites was similar to predisposal and reference conditions within 3 to 10 months after placement (Wilber, Mogren, and Beeney 2016).

In a TLP application in the Fowl River, located in Mobile, Alabama, an open-water area of 129 hectares, received 145,000 cubic yards of dredged material. The dredged material was placed as a layer of varying thickness over the project area (that is, 0–15 cm over 36% of the area, 16–30 cm over 48% of the area, and >30 cm over 16% of the area) (Wilber 1992). The site was monitored for water quality and infaunal abundance over a one-year period. Overall water quality was acceptable; total suspended solids (TSS) concentrations were elevated temporarily in the buffer areas and close to the discharge point during placement. Infaunal abundances approximated background levels within 2 weeks postplacement in areas that received less than 15 cm of dredged material and within 20 weeks in areas that received more than 15 cm of dredged material (Wilber 1992). Polychaetes, peracarid crustaceans, and bivalves dominated the infaunal community both in terms of numbers and species diversity (Wilber 1992).

Total fish abundances did not appear to be negatively affected by the dredging and placement operations.

Dredged material from the Pine Harbour Marina, Auckland, New Zealand, was placed in a thin layer over an area of similar sediment character in the adjacent embayment. Substantial monitoring efforts evaluated sediment transport and impacts to benthic organisms. Turbidity and suspended solids levels were elevated at a distance less than 250 m from the barge discharge point; however, levels were at approximately background levels at distances greater than 250 m (Healy et al. 1999). Data obtained through monitoring indicated that TLP did not cause adverse effects to the surrounding environment, sediment transport, or the benthic community.

TLP of dredged material with layer thickness smaller than 30 cm has also been implemented at multiple locations within Mobile Bay, Alabama (Parson et al. 2015). Data collected during monitoring efforts were used to assess the fate and transport of the placed material and to assess reintroduction of dredged material into the navigation channel. The LTFATE model was used to model the data, which indicated that TLP in Mobile Bay should have negligible impact on navigation channel infilling, TSS, and Mobile Bay bottom morphology (Gailani et al. (in preparation)).

Contaminated source areas may also be stabilized by increasing elevation and vegetation to create habitat less subject to erosional forces. TLP of dredged material has been used in multiple occasions as the major restoration technique in marshes (Cahoon and Cowan 1987; Cornu and Sadro 2002; Croft et al. 2006; DeLaune et al 1990; Ford et al. 1999; Mendelssohn and Kuhn 2003; Ray 2007; Schrift et al. 2008; Wigand et al. 2015; Wilber 1993) in different areas of the United States. Typically adding sediment to a coastal marsh raises its elevation, reducing anaerobic conditions (Mendelssohn and Kuhn 2003), promoting vegetation growth (Cornu and Sadro 2002; DeLaune et al. 1990; Schrift et al. 2008), and restoring a specific habitat or species (Borde et al. 2004). The thicknesses of dredged material used for marsh restoration typically ranges 10–30 cm, since revegetation via rhizomes occurs at thicknesses <30 cm (Ford et al. 1999; Schrift et al. 2008).

2.5 Utilizing clean dredged material to stabilize or isolate contaminated sediment sources

The above referenced research and demonstrations either (1) used sediment mined specifically for the purpose of isolating contaminated sediment deposits (that is, not the beneficial use of maintenance dredged sediment) or (2) demonstrated environmentally acceptable placement of dredged material using TLP in locations that were not contaminated. This effort proposes use of maintenance dredged material to reduce transport and flux from contaminated sediment deposits near navigation dredging projects. Dredged material is proposed to isolate contaminated sediment beds in active environments that include episodic erosion. The dredged material can either be applied as capping material on the contaminated bed or be applied to reduce wave energy that can resuspend the contaminated bed. Ongoing maintenance dredging then provides additional sediment for source control as originally placed dredged material erodes from the placement site. The use of TLP to cap contaminated sediments and renourish caps in dynamic environments has been discussed. Additional beneficial use of maintenance dredged material for source control include berms and mounds that dissipate wave energy or divert strong currents that would otherwise induce erosion from a nearby contaminated bed. These berms and TLP caps can also be used in conjunction with geotubes, coir logs, shell bags, or hay bales to further facilitate physical stabilization of contaminated sediment beds, TLP caps, or dredged sediment berms. Methods other than TLP that could be used in high energy environments with potential for erosion or bed shear stresses effects that may cause sediment transport include the use of dredged material to create nearshore berms and mounds or the use of dredged material in conjunction with geotubes, coir logs, shell bags, or hay bales to facilitate physical stabilization of placed material. This study considered whether dynamic berms will act as a wave buffer between the navigation channel and contaminated sediment deposit, typically in an estuarine environment. A feeder berm may also be strategically placed to supply sediment in an area that needs contaminant source control.

2.6 Berms and mounds

Nearshore berms have attenuated erosive wave energy on the coastline or increased the net volume of material in the sediment transport system (McLellan 1990). Different nearshore placement techniques can be considered depending on the sediment characteristics, hydrodynamic conditions, or main goals of a particular project. Alternatively, creation of more stable offshore berms can be considered when the wave climate and hydrodynamics need to be modified (McLellan 1990). Fine material has typically been limited for the construction of stable berms in deep water (Williams and Prickett 1998).

Berms have been used in the Great Lakes to decrease erosion by wave action and to supply sand to eroding beaches (USEPA/USACE 2007). Beck, Rosati, and Rosati (2012) discussed a recent study on nearshore berm placement and summarized information available in the literature. These studies discuss the Hallermeier index, which defines the active littoral zone where significant net transport occurs, referred to as the seaward limit of intense to intermediate bed activity. If the sediment is placed deeper than this limit, then it will not significantly affect wave energy. If sediment is placed shallower than this limit, it will be more mobile and transport more easily. Multiple case studies of nearshore placement were discussed, including projects on stable berms, which are not intended to migrate and may be a high or low relief (high- or low-energy attenuation), and feeder or active berms, which are higher relief and reduce wave energy and sediment transport. Multiple design aspects that are relevant to nearshore berms are discussed. Guidance required for nearshore berms can be separated into information pertinent to the dredging and placement of berms, and to cross-shore and alongshore design as a function of sediment size and distribution, forcing processes and conditions at the placement site. There are no monitoring protocols established, and USACE does not require monitoring of these projects; however, local sponsors may require monitoring efforts. Profile survey lines, mean grain size, lidar topographic and bathymetric data collection, and control profiles are suggested for monitoring at least annually or semiannually over a one-to-three-year period. Optimal monitoring program components are listed in table 1 of Beck, Rosati, and Rosati (2012) and include beach profile surveys, sediment sampling, sediment cores, waves and water levels, and aerial photography.

McLellan (1990) discussed aspects relevant to nearshore mound design and construction using dredged material. McLellan presents multiple case studies along with design and construction parameters. The material type typically used in these case studies consisted of sand; only two case studies used silt and clay in addition to sand. Water depths ranged 2–15 m, and mound height ranged 2–8 m. The higher mounds were associated with case studies in deeper water. McLellan indicated that factors such as sediment type, construction methodology, local wave and hydrological climate, depth, berm height, and orientation should all be considered to ensure that berms perform as intended (McLellan 1990). Engineering controls and considerations associated with each of these factors are also presented. Ludwick and Saumsiegle (1976) determined through numerical modeling of the Dam Neck disposal site that convergence of wave rays and an increase of wave height (up to 20%) may result from not mounding dredged material properly. Zwamborn, Fromme, and FitzPatrick (1970) explained the importance of designing a berm that will be stable under most wave conditions (erosive and nonerosive) with optimum dimensions that will provide effective beach protection through multiple studies and investigations conducted at beaches in Durban, South Africa. McLellan and Kraus (1991) presented a systematic method for design and evaluation of nearshore berm projects; both feeder and stable berms are discussed. According to McLellan and Kraus (1991) successful berm design and construction depend on the quantity and quality of material to be placed, availability of suitable equipment, local wave conditions, and the economics of berm construction versus other alternatives. Different criteria are presented for each of these considerations. The material quantity and quality will dictate the type of berm that can be constructed. The local wave conditions determine the depth of placement. Suitable equipment must be selected according to the designed depth and crest. Critical parameters and characteristics associated with location, timing of placement, depth of berm, berm height, width, length, and side slopes were presented. An example evaluation for a berm constructed at Bald Head Island, North Carolina, is presented.

Burt (1996) discussed three types of berms (feeder berms, hard berms, and soft berms) and the conditions under which each should be used. Hard and soft berms can reduce the wave force and vary its direction, thus reducing wave erosion. Feeder berms are dynamic berms designed to supply sediment and move onshore. Design parameters include alignment, height of the berm, and side slopes. A major distinction is made between hard and soft berms. Soft berms which are made of mud and silt and are designed to absorb wave energy. Hard berms are designed to cause the waves to steepen and break prematurely by increasing bottom friction by reducing water depth. Construction of berms is also discussed.

Natural mud banks off the southwest coast of India have been studied to better understand wave impact of nearshore berms (Mehta, Lee, and Li 1994; Mehta and Jiang 1993). Mud banks with typical thickness of 1 m and kilometers wide and long move onshore and offshore depending on the season in an otherwise sandy bottom area. Mud banks may cause wave energy reductions ranging 30–90%. During the fair weather season, the mud moves offshore and does not influence wave energy. During the monsoon season, the mud moves inshore and dissipates wave energy. As a result, the wave energy onshore is less during the monsoon season than during the fair weather season. Fine-grained material resulting from dredging navigation channels can be strategically placed by creating underwater “mud berms” to mitigate wave impact leeward of the berm (Mehta and Jiang 1993). A shallow-water, wave-mud interaction model, which assumes that water is inviscid and mud is highly viscid, was used to describe key parameters of berm design. This model determined the berm crest, elevation, and water depth using site conditions and dredged material properties. These design parameters significantly influence the degree of wave attenuation and impact. Other design parameters such as berm slope must be supplemented for implementation of berms in the field. Mehta and Jiang (1993) present a rheological constitutive model to account for the viscoelastic properties of mud at high forcing frequencies, which better represents coastal situations. The yield stress of dredged material was significant, since hydrodynamic stresses can exceed the yield stress of dredged material under some natural circumstances. When this occurs, the rigidity of dredged material drops, resulting in a more viscous response that could lead to a liquefied state under continuous wave action (Mehta and Jiang 1993; Feng et al. 1992). Another model presented in Mehta and Jiang (1993) consists of a finite amplitude wave-mud interaction model that accounts for the finite wave height of water waves (not restricted to shallow water) and treats dredged material as a viscoelastic material characterized by two moduli of elasticity and viscosity. This model was used to calculate wave attenuation over a nonsacrificial dredged material berm located near Dauphin Island, Alabama. This model could determine wave energy reduction before or after berm construction to better understand wave impacts leeward of the berm for cases where frequencies are smaller than 0.25 Hz.

3 Discussion

Principal means for the use of clean dredged material in contaminated sediment source control include: (1) TLP of clean DM alone or in combination with other materials (for example, PAC, biochar) to isolate or stabilize contaminant source areas, (2) use of clean DM alone or in combination with other engineering controls to create soft berms which reduce erosive forces on contaminated source areas, and (3) other structures that stabilize or isolate contaminated sediment source areas. As demonstrated in multiple field case studies (Mississippi Sound, Mobile Bay, Ormefjorden and Eidangerfjorden, Telemark, Ward Cove, and Pine Harbour Marina), application of clean dredged material alone via TLP allowed for establishment of a healthy benthic community within the first few years after material application. TLP allows benthic organisms to more easily burrow up through newly placed material, increases the rate of recolonization and recovery of the placement sites, and creates a smaller overall impact on benthic ecology than conventional capping (thicker caps) (Walls et al. 1994; USEPA/USACE 2004; USACE 2013). Implementation of a thin layer of clean dredged material provides a top layer of cleaner sediment, which reduces surface sediment chemical concentrations so that benthic organisms can colonize the sediment (ITRC 2014). TLP also alleviates concerns over burial of epibenthic species (for example, crab and bivalves) (Roegner and Fields 2014). Some studies have showed that TLP does not cause adverse effects to TSS, sediment transport, navigation channel infilling, and morphology (Healy et al. 1999; Gailani et al. (in preparation)). Clean dredged sediment regularly available during normal maintenance dredging cycles from an area near to the TLP project is often the cheapest, safest, and most effective material to use in thin layer caps. Sediment (for example, a mix of silt, clay, and sand with some organic content) has a higher sorption capacity relative to sand and therefore a greater capacity for sequestration of contaminants.

In general, the feasibility of implementing TLP of clean dredged material on a site depends on a number of factors, such as site energy, bearing capacity of the sediment, the slope of the sediment bed, flow conditions, site bathymetry, water depth, currents, potential for storm and vessel wake-induced erosion, physical characteristics of contaminated sediment and dredged material characteristics, and placement equipment and techniques (Murphy et al. 2006; Walls et al. 1994). TLP is generally preferable for lower energy environments (ITRC 2014); however, it can be implemented in a higher energy environments via periodic replacement or coupled with erosion protection. TLP may also be implemented to avoid potential navigational safety issues that might arise from construction of mounds or berms adjacent to a navigation channel (Welch, Mogren, and Beeney 2016). Sediment mounds can cause wave amplification and unpredictable currents (Welch, Mogren, and Beeney 2016). TLP is expected to reduce physical impacts to the receiving sediments (USEPA/USACE 2004) and accelerate the process of physical isolation due to natural sediment deposition occurring over time (ITRC 2014; Merritt et al. 2010).

Amendments in clean dredged material may also be considered for sites that require a reduction of risks and bioavailability that cannot be met with thin layer application of dredged material alone. In cases where groundwater seepage increases contaminant transport, the use of active amendments should be considered (Murphy et al. 2006; Gidley et al. 2012). Also, in the presence of bioturbation, the use of active amendments should be considered in cases that require significant reductions of contaminant flux and biouptake (Lin et al. 2014). The active capping technologies promise to be a permanent and cost-efficient solution to contaminated sediments when necessary (Zhang et al. 2016).

Different placement techniques should be considered depending on the site conditions and volumes of dredged material to be placed. For relatively small volumes of dredged material, high-pressure spray equipment is recommended, whereas for large volumes of dredged material, conventional hydraulic equipment is recommended (USEPA/USACE 2004). Geotechnical considerations such as shear stress and slope stability must be considered for TLP implementation. Slope stability calculations are recommended when the slope is >5% or when the sediment shear strength is less than 1 kPa on a slope (ITRC 2014). Geotechnical stability of a cap can be evaluated through a method that considers the shear strength gain of sediments under loading from a cap (Ebrahimi et al. 2014). TLP may require special design and placement methods when the slope is greater than 15% (ITRC 2014). Construction techniques such as placement in thin lifts to allow sufficient time for consolidation and strength gain help prevent cap failures (Ebrahimi et al. 2016; De Leeuw et al. 2002).

Nearshore berms canreduce erosive energy or increase the net volume of material in the sediment transport system (McLellan 1990). Depending on the goals of a project, different placement techniques or types of berms will be most effective. The Hallermeier index defines whether berm placement will have a significant impact on wave energy and sediment transport; if sediment is placed deeper than this limit, no significant impact is expected, and if it is placed shallower than this limit, then significant impact is expected. One of the main aspects that should be considered for berm design is the stability of the berm under both erosive and nonerosive conditions. The local wave conditions will dictate optimum berm dimensions and depth of placement, which in turn are used for selection of suitable equipment for placement. The characteristics and parameters critical for implementing a berm placement project include location, timing of placement, alignment, depth of berm, berm height, width, length, and side slopes. Parameters suggested for monitoring berms at least annually or semiannually over a one-to-three-year period include profile surveys, mean grain size, lidar topography, bathymetry, control profiles, and sediment sampling including cores, waves and water level, and aerial photography.

Mudbanks have also been studied to better understand wave impacts of nearshore berms (Mehta, Lee, and Li et al. 1994; Mehta and Jiang 1993); these may reduce wave energy 30–90%. Fine-grained material resulting from dredging navigation channels can be strategically placed by creating underwater mud berms to mitigate wave impact leeward of the berm (Mehta and Jiang 1993). Multiple models used for mudbanks have been used to determine berm design parameters using site conditions and dredged material properties, evaluate dredged material yield stress under hydrodynamic conditions, and analyze wave energy reduction before or after berm construction.

4 Conclusions

From the perspective of contaminant source control, TLP with clean dredged material should, in most cases, have a positive effect (source reduction) or, in the worst case, no effect (that is, no effect on source inputs). The success of TLP for source control depends on many factors including, but not limited to local site hydrodynamic characteristics, stability of donor material, the ability to effectively place the material—thus not resulting in unacceptable impacts to water quality or sensitive habitat and species that might be present. Ideally, TLP should isolate and stabilize contaminated source areas; therefore, a successful TLP application should cause increased maintenance dredging frequency. Source control goals must be considered before choosing materials for a TLP effort, since a cap with clean dredged material may not provide sufficient flux reductions; in some cases the addition of amendments (AC, apatite) may be necessary. In addition to TLP, clean dredged material can also be used to build berms or mounds to shield contaminant source areas from sediment transport processes that would otherwise result in movement of the contaminated material into adjacent navigation channels or berth areas. Berms can be dynamic (that is, the material is periodically replaced to maintain an effective barrier or used to feed material onto contaminated source areas via natural processes to ultimately isolate and stabilize these areas). Alternatively, berms and mounds can provide a more permanent or stable barrier using engineering technologies such as geotubes, geogrids, geocells, or other technologies. Ultimately the approach or combination of approaches used to prevent transport of sediment of contaminant source areas to adjacent navigation infrastructure depends on specific site conditions and the desired performance goals for the source control measures. While numerous studies have been conducted both in the lab and field, which serve to inform the potential application of clean dredged material for purposes of source control, important knowledge gaps remain: physical and chemical performance evaluation of thin layer caps with similar sorption properties and different physical characteristics (for example, comparison of a thin layer sand cap amended with AC vs. a clean dredged material thin layer cap amended with AC); a better understanding of the sorption capacity of the sorption capacity and breakthrough potential of dredged materials with different grain size and organic composition; (1) improved understanding of the predictive performance and placement requirements of dredged material for source control according to physical characteristics of the dredged material; (2) an evaluation of innovative placement technologies (pneumatic flow tube mixing) that may facilitate consolidation and improve long-term resiliency; (3) effectiveness of low-cost amendments (biochar, biopolymers) to improve sorptive capacity or stimulate microbial activity and formation of stabilizing biofilms. Finally, innovative engineering control, such as the use of geocells to improve stability of placed material, should also be evaluated.

References

Atkinson, C.A.; Jolley, D.F.; Simpson, S.L. 2007. “Effect of Overlying Water Ph, Dissolved Oxygen, Salinity and Sediment Disturbances on Metal Release and Sequestration from Metal Contaminated Marine Sediments.” *Chemosphere* 69, 1428-1437.

Beck, T.M.; Rosati, J.D.; Rosati, J. 2012. *An Update on Nearshore Berms in the Corps of Engineers: Recent Projects and Future Needs*. ERDC/CHL CHETN-XIV-10. Vicksburg, MS: Engineer Research and Development Center.

Becker, D.S.; Sexton, J.E.; Jacobs, L.A.; Hogarty, B.; Keeley, K. 2009. “Biological Responses to Sediment Remediation Based on Thin Layer Placement near a Former Pulp Mill in Ward Cove, AK (USA).” *Environ. Monit. Assess*. 154: 427-438.

Brutsché, K.E. and Pollock, C.E. 2017. *Strategic Placement of Mixed Sediment in the Form of Nearshore Berms along Fort Myers Beach, Florida*. ERDC-TN-EWN-17-1. Vicksburg, MS: Engineer Research and Development Center.

Brutsché, K.E.; Wang, P.; Beck, T.M.; Rosati, J.D.; Legault, K.R. 2014. “Morphological Evolution of a Submerged Artificial Nearshore Berm along a Low-Wave Microtidal Coast, Fort Myers Beach, west-central Florida, USA.” *Coastal Engineering* 91: 29-44.

Burt, T.N. 1996. Guidelines for the Beneficial Use of Dredged Material. HR Wallingford - SR 488.

Cornelissen, Gerard; Schaanning, Morten; Gunnarsson, Jonas S.; Eek, Espen. 2015. “A Large-Scale Field Trial of Thin-Layer Capping of PCDD/F-Contaminated Sediments: Sediment-to-Water Fluxes up to 5 Years Post-Amendment.” *Integrated Environmental Assessment and Management* 12 (2): 216-221.

Cornelissen, Gerard; Amstaetter, Katja; Hauge, Audun; Schaanning, Morten; Beylich, Bjørnar; Gunnarsson, Jonas S.; Breedveld, Gijs D.; Oen, Amy M.P.; Eek, Espen. 2012. “Large-Scale Field Study on Thin-Layer Capping of Marine PCDD/FContaminated Sediments in Grenlandfjords, Norway: Physicochemical Effects." *Environmental Science and Technology* 46:12030-12037.

Cornelissen, G.; Oen, A.M.P.; Brändli, R.; Eek, E.; Breedveld, G.D. 2008. Opticap, Thin Layer Capping of Sediments Using Reactive and Non-Reactive Materials, Field Studies. SEDNET.

De Leeuw, H.A.; Smits, E.P.T.; Mathijssen, F.A.J.M.; Estourgie, A.L.Ph. 2002. “Reclamation on Soft Subsoil by Spraying Thin Layers of Sand: The "Ijburg" Project near Amsterdam.” *Terra et Aqua* 89.

Droppo, I.G.; Lau, Y.L.; Mitchell, C. 2001. “The Effect of Depositional History on Contaminated Bed Sediment Stability.” *The Science of the Total Environment* 266: 7-13.

Ebrahimi, A., Viswanath, M., Zhu, M. and Beech, J.F. 2014. “Methodology to Evaluate the Geotechnical Stability of a Subaqueous Cap Placed on Soft Sediments.” In *Geo-Congress 2014: Geo-characterization and Modeling for Sustainability*, pp 1910-1918.

Ebrahimi, A., Erten, M.B., Carlson, C., Coraspe, T., Zhu, M. and Beech, J.F. 2016. “An Integrated Subsurface Investigation for Sediment Capping Projects.” In *Geo-Chicago* 2016: 459-470.

Gailani, J., E. Hayter, R. Chapman, J. Smith, M. Taylor, D. Perkey, N. Lovelace, and E. Godsey. In preparation. *Modeling of thin layer placement of dredged material in Mobile Bay, Alabama*. ERDC/CHL TR- In preparation. Vicksburg, MS: US Army Engineer Research and Development Center.

Gidley, P. T.; Kwon, S.; Yakirevich, A.; Magar, V.; Ghosh, U. 2012. “Advection Dominated Transport of Polycyclic Aromatic Hydrocarbons in Amended Sediment Caps.” *Environ. Sci. Technol.* 46: 5032-5039.

Graham, M.; Hartman, E.; Joyner, R.; Kim, K.; Santiago, R. 2017. “Environmental Monitoring to Guide and Assess the Effectiveness of Randle Reef Sediment Remediation on the Recovery of Hamilton Harbor.” *Aquatic Ecosystem Health & Management*. 20:3, 308-318, DOI: 10.1080/14634988.2017.1316658.

Graham, M.; Hartman, E.; He, C.; Droppo, I.G. 2013. “Examining Thin-Layer Cap Behaviour in a Freshwater Industrial Harbor.” *J Soils Sediments* 13: 1515-1526.

Hartman Consulting Corporation. 2000. “Ward Cove Sediment Remediation Project Design Analysis Report for the Marine Operable Unit of the Ketchikan Pulp Company Site.” Seattle, WA: Hartman Consulting Corporation.

He, C., Scott, E., Graham, M. and Binns, A. 2014. “Measurement and Numerical Modeling Studies of the Highest Bottom Shear Stress in the Randle Reef Area.” *Canadian Journal of Civil Engineering* 41(9): 828-838.

Healy, T.; Mehta, A.; Rodríguez, H.; Tian, F. 1999. “Bypassing of Dredged Littoral Muddy Sediments Using a Thin Layer Dispersal Technique.” *Journal of Coastal Research* 15(4): 1119-1131.

Interstate Technology and Regulatory Council (ITRC). 2014. Contaminated Sediments Remediation, CS-2. Washington, DC: ITRC Contaminated Sediments Team. http://www.itrcweb.org/contseds_remedy-selection.

Johnson, N.W.; Reible, D.D.; Katz, L.E. 2010. “Biogeochemical Changes and Mercury Methylation beneath an In-Situ Sediment Cap.” *Environ. Sci. Technol.* 44(19): 7280-7286.

Josefsson, S.; Schaanning, M.; Samuelsson, G.S.; Gunnarsson, J.S.; Olofsson, I.; Eek, E.; Wilberg, K. 2012. “Capping Efficiency of Various Carbonaceous and Mineral Materials for In Situ Remediation of Polychlorinated Dibenzo-p-dioxin and Dibenzofuran Contaminated Marine Sediments: Sediment-to-Water Fluxes and Bioaccumulation in Boxcosm Tests.” *Environ. Sci. Technol.* 46: 3343-3351.

Josefsson, S.; Leonardsson, K.; Gunnarsson, J.S.; Wiberg, K. 2011. “Influence of Contaminant Burial Depth on the Bioaccumulation of PCBs and PBDEs by Two Benthic Invertebrates (*Monoporeia affinis* and *Marenzelleria spp.*).” *Chemosphere* 85: 1444-1451.

Josefsson, S.; Leonardsson, K.; Gunnarsson, J.S.; Wiberg, K. 2010. “Bioturbation-Driven Release of Buried PCBs and PBDEs from Different Depths in Contaminated Sediments.” *Environ. Sci. Technol.* 44(19): 7456-7464.

Kaplan, D.I. and Knox, A.S. 2004. “Enhanced Contaminant Desorption Induced by Phosphate Mineral Additions to Sediment.” *Environmental Science & Technology* 38(11):.3153-3160.

Kellems, B., Fabian, K., Orchard, B., Parmelee, R., Bonkoski, B., Spadaro, P., Beaver, J., Fitzgerald, W.P., Santiago, R. and Rozenberg, W. 2013. “Randle Reef Sediment Remediation Project.” In *Ports 2013: Success through Diversification*, pp 70-79.

Krishnappan, B.G. and Droppo, I.G. 2006. “Use of an in situ erosion flume for measuring stability of sediment deposits in Hamilton Harbour, Canada.” *Water, Air, and Soil Pollution: Focus* 6: 557-567.

Lampert, D.J.; Sarchet, W.V.; Reible, D.D. 2011. “Assessing the Effectiveness of Thin-Layer Sand Caps for Contaminated Sediment Management through Passive Sampling.” *Envion. Sci. Technol.* 45: 8437-8443.

Lin, D.; Cho, Y-M; Werner, D. Luthy, R.G. 2014. “Bioturbation Delays Attenuation of DDT by Clean Sediment Cap but Promotes Sequestration by Thin-Layered Activated Carbon.” *Environ. Sci. Technol.* 48: 1175-1183.

Ludwick, J.C. and Saumsiegle, W.J. 1976. *Sediment Stability at the Dam Neck Disposal Site*. Virginia Tech. Rep. 27. Norfolk, VA: Old Dominion University, Institute of Oceanography.

Magar, V.S.; Chadwick, D.B.; Bridges, T.S.; Fuchsman, P.C.; Conder, J.M.; Dekker, T.J.; Steevens, J.A.; Gustavson, K.E.; Mills, M.A. 2009. *Technical Guide: Monitored Natural Recovery at Contaminated Sediment Sites*. ESTCP-ER-0622. Arlington, VA: Environmental Security Technology Certification Program (ESTCP).

McLellan, T.N. 1990. “Nearshore mound construction using dredged material.” *Journal of Coastal Research,* 99-107.

McLellan, T.N. and Kraus, N.C. 1991. Design Guidance for Nearshore Berm Construction. In *Proceedings of Coastal Sediments*, Volume 91, pp 2000-2011.

Mehta, A.J. and Jiang, F. 1993. *Some Observations on Water Wave Attenuation Over Nearshore Underwater Mudbanks and Mudberms*. Technical Report UFL/COEL/MP-93/01. Gainesville, FL: University of Florida, Coastal and Oceanographic Engineering Department.

Mehta, A.J.; Lee, S-C.; Li, Y. 1994. *Fluid Mud and Water Waves: A Brief Review of Interactive Processes and Simple Modeling Approaches*. Dredging Research Program. Final Contract Report DRP-94-4, July 1994. Vicksburg, MS: US Army Corps of Engineers Waterways Experiment Station.

Merritt, K.A.; Conder, J.; Kirtay, V.; Chadwick, B.; Magar, V. 2010. "Review of Thin-Layer Placement Applications to Enhance Natural Recovery of Contaminated Sediment." *Integrated Environ. Assessment and Management* 6(4): 749-760.

Merritt, K.; Conder, J.; Magar, V.; Kirtay, V.J.; Chadwick, D.B. 2009. Enhanced Monitored Natural Recovery (EMNR) Case Studies Review. SPAWAR Systems Center Pacific.

Murphy, P., Marquette, A., Reible, D., and Lowry, G. 2006. "Predicting the Performance of Activated Carbon-, Coke-, and Soil-Amended Thin Layer Sediment Caps." *J. Environ. Eng.* 132(7): 787–794.

Näslund, J.; Samuelsson, G.S.; Gunnarsson, J.S.; Nascimento, F. J. A.; Nilsson, H. C.; Cornelissen, G.; Schaanning, M. T. 2012. "Ecosystem effects of materials proposed for thin-layer capping of contaminated sediments." *Marine Ecology Progress Series* 449: 27-39.

Parson, L., N. Lovelace, E. Godsey, K. Reine, and J. Gailani. 2015. "Regional sediment management (RSM) strategy for Mobile Bay, Alabama." ERDC/CHL CHETN-XIV-41. Vicksburg, MS: US Army Engineer Research and Development Center.

Rakshith, S. and Singh, D.N. 2017. "Utilization of Dredged Sediments: Contemporary Issues." *J. Waterway, Port, Coastal, Ocean Eng.* 143(3): 04016025.

Rees, S.I. and Wilber, P. 1994. "Effects from Thin-Layer Disposal of Dredged Material on Water Quality in Mississippi Sound." Proceedings of the Second International Conference on Dredging and Dredged Material Placement, Dredging '94, 2: 1481-1489.

Reible, D.D. ed., 2014. Processes, assessment and remediation of contaminated sediments (pp. 365-391). Springer.

Richardson, T.W. 1988. "Overview of Beneficial Uses of Berms." In: *Beneficial Uses of Dredged Material*. Proceedings of the Gulf Coast Regional Workshop 1988. Ed. R.L. Lazor. Technical Report D-90-3. Galveston, TX: Environmental Laboratory.

Roegner, C. and Fields, S. 2014. Mouth of the Columbia River: Beneficial Sediment Deposition Project Benthic Impact Study 2014. Portland District, Northwestern Division, U.S. Army Corps of Engineers

Samuelsson, G. 2013. In situ remediation of contaminated sediment using thin-layer capping – efficiency in contaminant retention and ecological implication. Stockholm, Sweden: Stockholm University. Printed by US-AB, distributed by Department of Ecology, Environment and Plant Science (DEEP).

Schaanning, M.T.; Allan, I. 2012. *Field Experiment on Thin-Layer Capping in Ormefjorden and Eidangerfjorden, Telemark Functional Response and Bioavailability of Dioxins 2009-2011*. Report no. 6285-2012. NIVA, Norwegian Institute for Water Research.

Schaanning, M.T.; Beylich, B.; Samuelsson, G.; Raymond, C.; Gunnarsson, J.; Agrenius, S. 2011. *Field Experiment on Thin-Layer Capping in Ormefjorden and Eidangerfjorden; Benthic Community Analyses 2009-2011*. Report no. 6257-2011. NIVA, Norwegian Institute for Water Research.

Simpson, S.L.; Pryor, I.D.; Mewburn, B.R.; Batley, G.E.; Jolley, D. 2002. "Considerations for Capping Metal-Contaminated Sediments in Dynamic Estuarine Environments." *Environ. Sci. Technol.* 36: 3772-3778.

Slater, G.F.; Cowie, B.R.; Harper, N.; Droppo, I.G. 2008. Variation in PAH inputs and microbial community in surface sediments of Hamilton Harbour: Implications to remediation and monitoring. 153: 60-70. Environmental Pollution.

Spears, B.M.; Saunders, J.E.; Davidson, I.; Paterson, D.M. 2008. "Microalgal sediment biostabilization along a salinity gradient in the Eden Estuary, Scotland: unravelling a paradox." *Marine and Freshwater Research* 59: 313-321.

Talbert, B.; Thibodeaux, L.J.; Valsaraj, K.T. 2001. "Effectiveness of Very Thin Soil Layers in Chemical Release from Bed Sediment." *Environ. Progress* 20(2): 103-107.

US Army Corps of Engineers (USACE). 2013. Memorandum for record: Mobile Harbor beneficial use. Interagency working group meeting. Mobile, AL: US Army Corps of Engineers, Mobile District.

US Environmental Protection Agency and US Army Corps of Engineers (USEPA/USACE). 1991. *Evaluation of Dredged Material for Ocean Disposal* (The Ocean Testing Manual, OTM) EPA-503/8-91/001. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

US Environmental Protection Agency and US Army Corps of Engineers (USEPA/USACE). 1998. *Evaluation of Dredged Material Proposed for Discharge in Waters of the US - Testing Manual* (The Inland Testing Manual, ITM). EPA-823-B-98-004. Washington, DC: USACE.

US Environmental Protection Agency and US Army Corps of Engineers (USEPA/USACE). 2004. Evaluating Environmental Effects of Dredged Material Management Alternatives - A Technical Frame-work. EPA842-B-92-008. Washington, DC: USACE.

US Environmental Protection Agency (USEPA). 2005. Contaminated Sediment Remediation Guidance for Hazardous Waste Sites. EPA-540-R-05-012. Washington, DC: USEPA Office of Solid Waste and Emergency Response.

US Environmental Protection Agency and US Army Corps of Engineers (USEPA/USACE). 2007. Identifying, planning, and financing beneficial use projects using dredge materials. EPA842-B-07-001 Walls, B.E.; Lemlich, S.K.; Wright, T.D.; Clausner, J.E.; Mathis, D.B. 1994. *Open-Water Placement of Dredged Sediment: A Framework for Site Management*. DRP-5-10. Vicksburg, MS: US Army Waterways Experiment Station.

Wang, X.Q.; Thibodeaux, L.J.; Valsaraj, K.T.; Reible, D.D. 1991. "Efficiency of Capping Contaminated Bed Sediments In Situ. 1. Laboratory-Scale Experiments on Diffusion-Adsorption in the Capping Layer." *Environ. Sci. Technol.* 25(9): 1578-1584.

Welch, M.; Mogren, E.T.; Beeney, L. 2016. *A Literature Review of the Beneficial Use of Dredged Material and Sediment Management Plans and Strategies*. Portland, OR: Portland State University, Center for Public Service Publications and Reports. 34.

Wilber, P. 1992. “Case Studies of the Thin-layer Disposal of Dredged Material – Fowl River, Alabama.” *Environmental Effects of Dredging*, Volume D-92-5, pp 1-5. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Wilber, D.H.; Clarke; D.G.; Rees, S.I. 2007. “Responses of Benthic Macroinvertebrates to Thin-layer Disposal of Dredged Material in Mississippi Sound, USA.” *Marine Pollution Bulletin* 54: 42-52.

Williams, G. L., and T. L. Prickett. 1998. *Planning considerations for near-shore placement of mixed dredged sediments*. DOER Technical Notes Collection TNDOER-N3. Vicksburg, MS: US Army Engineer Research and Development Center. https://el.erdc.dren.mil/elpubs/pdf/doern3.pdf

Winther, Aina 2011. *Thin Layer Capping with Biochar on Marine Sediments Contaminated With Pahs, and the Effect of Different Caps on Marine Sediment Contaminated With Dioxins*. Thesis, Norwegian University of Life Sciences.

Wright, S.J.; Mohan, R.K.; Brown, M.P.; Kim, C.C. 2001. “Filter Design Criteria for Sediment Caps in Rivers and Harbors.” *J. of Coastal Research* 17(2): 353-362.

Zhang, C., Zhu, M.Y., Zeng, G.M., Yu, Z.G., Cui, F., Yang, Z.Z. and Shen, L.Q. 2016. “Active Capping Technology: A New Environmental Remediation of Contaminated Sediment.” *Environmental Science and Pollution Research* 23(5):4370-4386.

Zuliani, T.; Mladenovič, A.; Ščančar, J.; Milačič, R. 2016. “Chemical Characterization of Dredged Sediments in Relation to Their Potential Use in Civil Engineering.” *Environ. Monit. Assess.* 188:234.

Zwamborn, J.A., Fromme, G.A.W. and FitzPatrick, J.B., 1970. “Underwater Mound for the Protection of Durban's Beaches.” *Coastal Engineeing* 975-994.

Acronyms

AC – activated carbon

AVS – acid volatile sulfide

CDFs – confined disposal facilities

DOER – Dredging Operations and Environmental Research Program

EMNR – enhanced monitored natural recovery

ERDC – US Army Engineer Research and Development Center

ITRC – Interstate Technology & Regulatory Council

MNR – monitored natural recovery

POM – polyoxymethylene

PBDE – polybrominated diphenyl ethers

SEM – simultaneously extracted metals

SPI – sediment profile imaging

TCP – trichlorophenol

TLP – thin layer placement

TSS – total suspended solids

USACE – US Army Corps of Engineers

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14. ABSTRACT

Navigation channels, turning basins, and other US Army Corps of Engineers (USACE)–managed navigation infrastructure often serve as repositories for contaminated sediment from off-site sources. As much as 10% of the material that USACE dredges on an annual basis is contaminated such that it requires additional and more costly management (for example, rehandling and placement in managed confined disposal facilities). Presence of contaminated sediments constrain potential management options resulting in additional costs and opportunity loss from the inability to beneficially use the material. One potential solution is applying clean dredged material to stabilize and isolate contaminated sediment sources, preventing further transport and introduction to USACE-managed infrastructure.

This document summarizes a comprehensive literature review of laboratory and field case studies relevant to using clean dredged material to isolate or stabilize contaminated sediments, focusing on the physical, chemical, and biological parameters critical to establishing its feasibility and long-term effectiveness. Potentially effective engineering control measures were also reviewed where erosion and site hydrodynamics are facilitating the transport of contaminated sediments to USACE-maintained navigation infrastructure. This literature review documents and summarizes those factors considered in establishing feasibility and long-term effectiveness of the approach as well as the applicable engineering tools employed and constraints encountered.

15. SUBJECT TERMS

Dredging	Contaminated sediments – Stabilization
Dredging spoil	Contaminated sediments – Management

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