Beneficial Use of Contaminated Sediments

The State of Treatment Technologies

Prepared for
Sediment Management Work Group
660 Woodward Avenue
2290 First National Building
Detroit, MI 48226-3506

Prepared by

integral consulting inc.
45 Exchange Street
Suite 200
Portland, ME 04101

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CONTENTS

ACRONYMS AND ABBREVIATIONS

AAM	alkali-activated material
AI	artificial intelligence
CSA	calcium sulfoaluminate cement
DOI	digital object identifier
EDTA	ethylene diamine tetraacetic acid
EKR	electrokinetic remediation
EPA	U.S. Environmental Protection Agency
GGBS	ground granulated blast furnace slag
Integral	Integral Consulting Inc.
LCA	life cycle analysis
MC	magnesia-based cements
MCDA	multi-criteria decision analysis
nZVI	nanoscale zerovalent iron
OPC	ordinary Portland cement
PAH	polycyclic aromatic hydrocarbon
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyl
PFAS	per- and polyfluoroalkyl substances
S/S	stabilization/solidification
SCM	supplementary cementitious material
SMWG	Sediment Management Work Group
TCLP	toxicity characteristic leaching procedure
URL	uniform resource locator

EXECUTIVE SUMMARY

Integral Consulting Inc. (Integral) prepared this white paper on behalf of the Sediment Management Work Group (SMWG) with the goal of describing the state of the science of treatment technologies for contaminated sediments following dredging, particularly as they apply to beneficial use of those materials. Specifically, this white paper evaluates the recent literature available on (mostly) *ex situ* treatment technologies for dredged materials. The literature review focused on existing and emerging treatment technologies and the factors that influence their selection, success, and risks for subsequent beneficial use of dredged material. The white paper discusses common themes of recent research on this topic, including data gaps, uncertainties, and recommendations for future research.

This white paper is designed as a companion piece to the white paper prepared by Barr et al. (2023), also on behalf of SMWG, on beneficial use of contaminated sediments in North America and Europe. That white paper described the history of beneficial use of contaminated sediments, applicable regulatory programs, management techniques, and roadblocks and opportunities to advance the practice and the science. Efforts are made here to avoid repeating content covered in the earlier white paper, though there are some cases where summaries of its findings add context to material presented in this white paper.

Integral conducted the literature review using a variety of traditional, open source, and artificial intelligence (AI)-powered research tools for scientific literature, including Web of Science, Science Direct, Google Scholar, and Elicit, among others. Searches were conducted based on favored phrases of "beneficial use" and "contaminated sediment" and specific treatment technologies. From 2,937 sources identified, 85 references were found to meet the project criteria for inclusion. Sources from the last 10 to 20 years were reviewed and relevant studies published in the last 5 years were preferentially considered to capture the latest technical advances and recommendations for future research that remain relevant.

Integral identified several review papers that specifically addressed the topic of recent advances of *ex situ* treatment technologies to support beneficial uses. From these review papers, primary research publications were identified and reviewed. Most references presented primary research findings focused on individual or multiple treatment technologies. Few references described the full life cycle of a project, costs and benefits, timelines and durations, contaminant concentrations in dredged and treated materials, regulatory thresholds and acceptance, or the basis for selecting beneficial use applications.

Studies were available for three general types of treatment technologies: solidification/ stabilization (S/S; including sequestration), extraction treatments, and bioremediation. Based on our review, the number of studies on treatment technologies increased two- to three-fold in the last 5 years, and qualitatively, the greatest number of studies addressed the use of S/S as a treatment for dredged materials to support beneficial use applications. This white paper summarizes recent technological advances for each treatment type. It also presents factors that influence the success or failure of stabilizing or removing contamination in the dredged materials and the risks associated with use of treated materials in construction or other beneficial use.

The white paper details the following data gaps and research needs:

- Most investigations of treatment technologies have been conducted at the laboratory- or pilot-scale. Full-scale studies are needed, particularly using field installations that allow adjustment of parameters from laboratory- or pilot-scale studies.
- For most technologies, sediment heterogeneity affects treatment effectiveness, efficiency, and timelines and duration. Research is needed to understand how sediment heterogeneity can be managed in the treatment approaches.
- Long-term studies on the stability of treated sediments and/or S/S products are needed. Related topics include durability, costs and/or marketability, legal implications of the S/S product, leachability, and the effects of environmental factors like pH on the integrity of S/S products.
- Because no single treatment technology will work in all situations, research is needed on the adaptability of treatment technologies and approaches for specific beneficial use applications.
- To achieve long-term management of dredged contaminated sediments, research is needed on the environmental impacts of treatment technologies (e.g., energy consumption, carbon emissions).
- Emerging and novel treatments, such as nanotechnologies for PAHs and ionic liquids, offer promising results, but their high costs greatly limit large-scale application. Research is needed to develop these treatments into practical options.
- There is a need to optimize decision tool frameworks to support the identification of preferred treatment technologies and beneficial uses, while considering environmental, economic, and social benefits.
- Where contaminated dredged sediment has been beneficially used, there is often limited information available describing the complete project life cycle, costs and benefits, timelines and durations, contaminant concentrations in dredged and treated materials, regulatory thresholds and acceptance, or the basis for selecting beneficial use applications.

In conclusion, we recommend exploring the opportunities to develop a platform for sharing information about treatment technologies and promote knowledge and data sharing of the salient details noted in the final bullet above including:

- Creating and maintaining a data repository or clearinghouse for data compilation on treatment technologies and beneficial use applications
- Providing broad access to the clearinghouse to allow for easy data entry by project proponents
- Establishing data quality rules to ensure consistency among data entries and to allow meaningful comparisons among projects (i.e., apples-to-apples comparisons)
- Investigating opportunities to partner with permitting agencies to capture project details
- Incentivizing knowledge and/or data sharing through partnerships with practitioners who are implementing current projects.

1 INTRODUCTION

Integral Consulting Inc. (Integral) prepared this white paper on behalf of the Sediment Management Work Group (SMWG) with the goal of describing the state of the science of treatment technologies for dredged contaminated sediments,[1] particularly as they apply to beneficial use of those materials. The literature review that underpins this work focused on existing and emerging technologies for treating contaminated sediments, factors that influence selection and success of treatment technologies, and risks associated with treating contaminated sediments for subsequent beneficial use. This white paper focuses on the successes and failures of treatability studies undertaken to support beneficial uses of dredged materials. For each treatment technology and beneficial use, this white paper discusses the common themes of lessons learned, data gaps, uncertainties, and recommendations for future research.

This white paper is intended as a companion paper to Barr et al.'s (2023) white paper on beneficial use of contaminated sediments in North America and Europe, which SMWG also commissioned. Barr et al. (2023) describe the history of beneficial use of contaminated sediments, applicable regulatory programs, management techniques, and roadblocks and opportunities to advance the practice and the science. Key terms defined by Barr et al. (2023)—such as beneficial use, contamination, sediment, and treatment—are also used in this white paper. Efforts are made here to avoid repeating content covered in the earlier white paper, though there are some cases where summaries of its findings add context to material presented in this white paper.

Section 2 describes the methods used to conduct the literature search and review. Section 3 presents the state of the science on treatment technologies. Section 4 discusses factors influencing the selection of appropriate treatments and beneficial use applications. Section 5 describes risks associated with treatment of contaminated sediments and/or types of beneficial uses, and Section 6 presents a summary and recommendations for further investigations. References are listed in Section 7 and are tabulated with greater detail in a database provided as Appendix A. Appendix B presents representative case studies identified from the literature and from practitioners.

[1] Also referred to herein as "dredged materials" or "materials." Though the technologies described in this paper may also be applicable to dredged materials that are not contaminated, the focus of the white paper is on beneficial use of contaminated sediments.

2 LITERATURE SEARCH AND REVIEW METHODS

This white paper reflects findings from a detailed literature search of peer-reviewed and gray literature, including published studies and documents or reports that are not published commercially, on available and emerging treatment technologies for dredged materials. The search focused on treatment technologies applied to sediment, rather than to other environmental media. Because this white paper is focused on beneficial use of dredged materials, the literature search focused on *ex situ* treatment technologies. *In situ* treatment technologies were considered in few cases (e.g., electrokinetic remediation [EKR]) where the technology is expected to perform similarly both *ex situ* and *in situ*.

Integral conducted the literature search and review using traditional, open source, and artificial intelligence (AI)-powered research tools for scientific literature. Integral first applied authoritative databases known for peer-review, reference tracing, and citation reporting (Web of Science, Science Direct, Wiley, and ProQuest) with the goal of prioritizing retrieval of the most "important" papers. The search expanded to open source scholarly literature indexes (PubMed, Google Scholar, Semantic Scholar, and Elicit), some of which use AI, to identify a broader range of sources covering all aspects of beneficial uses of contaminated sediments.

The keywords were based on the favored phrases of "beneficial use*" and "contaminated sediment*." Additional searches were conducted using specific keywords for each treatment technology (e.g., "electrokinetic remediation," "EKR," "sediment washing." Synonyms were also reviewed, particularly for the concept of "beneficial use," to include "reuse," "recycl*," and "reclamation." Natural language scientific literature search systems (Semantic Scholar and Elicit) were used because they have greater flexibility for keywords with multiple synonyms or meaning.

Though many relevant studies were published in the last 5 years, the literature search covered the last 20 years. The more recent sources were preferentially considered with respect to the latest advances and recommendations for future research. The literature review process also covered gray literature such as reports, documents, and conference proceedings retrieved from internet searching, scholarly paper references, and peer recommendations.

In total, a master corpus of 2,937 sources was compiled and then screened in a reference management system, based on the abstracts and other bibliographic metadata. A total of 85 references were identified that met the project criteria for inclusion. Figure 2-1 illustrates the timeline over which the references were published in the master corpus and the final 85 references. From 2003 to 2015, a steady rate of 50 to 100 studies per year were published on this topic. From 2016 to 2022, the number of publications increased by two- to three-fold, particularly in the last 5 years.

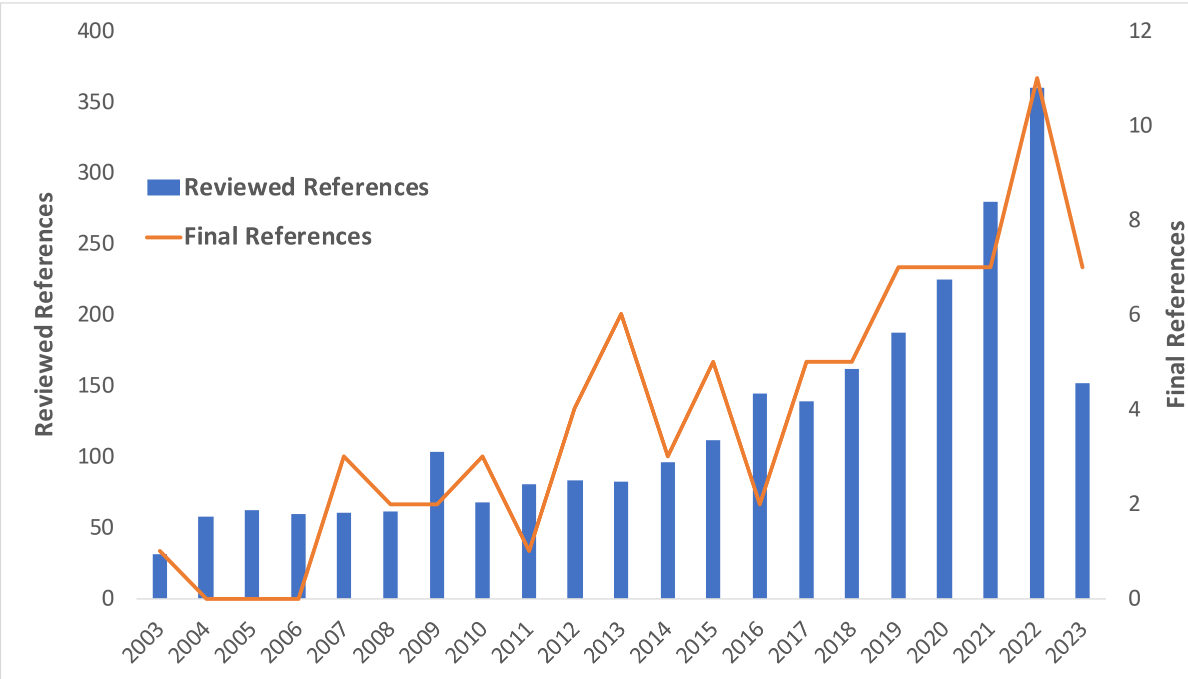

Figure 2-1. Number of references reviewed in total (approximately 2,900) from the 20-year period and number of final references selected for the white paper (85[2])

The final 85 references are documented in a database (Appendix A), which provides detailed information for each reference on document type and title, publication year and title, author, digital object identifier (DOI), publication page uniform resource locator (URL), and abstract or summary. When available, the following information is also presented:

- Treatment technology
- Scale of tested treatment (i.e., laboratory- or bench-, pilot-, or full-scale)[3]
- Beneficial use

[2] Four references from 1998 and 2002 are not included in this figure because they fall outside of the 20-year period that was the focus of the literature review.
[3] Typically, the scale was defined by the author(s) of the study. If not, the scale was roughly estimated based on the guidelines available from the Technology Readiness Assessment (GAO-16-410G, Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects) in which laboratory-scale refers to testing in a laboratory environment, pilot-scale refers to testing at a smaller scale than full in a relevant environment, and full-scale refers to a full-sized demonstration in a relevant environment.

- Sediment type and volume
- Contaminants (type and concentration)
- Duration of treatment
- Location
- Sustainability/environmental impacts/risk assessment[4]
- Decision framework
- Regulatory acceptance
- Reported or estimated costs
- Abstract or summary.

[4] Sustainability or environmental impacts as defined by the authors.

3 STATE OF SCIENCE ON TREATMENT TECHNOLOGIES

This section describes the current science of treatment technologies, beginning with summaries of several recent reviews on this topic, often in the context of beneficial use applications. It then individually discusses physical, chemical, biological, and thermal treatments organized into three general types of technologies: solidification/stabilization (S/S), extraction treatments, and bioremediation. Because most studies involved more than one treatment type, there is overlap among these three categories. The discussion reflects an assumption that dredged materials undergo thorough chemical and physical characterization, as this information is crucial for designing an effective treatment strategy.

3.1 REVIEWS OF TREATMENT TECHNOLOGIES TO SUPPORT BENEFICIAL USES

Several review papers evaluate treatment technologies for contaminated sediments in support of beneficial uses. This section provides an overview of the review literature with a focus on treatment technologies and approaches used to support beneficial uses. The scope of each review paper is presented in this subsection, whereas key information pertaining to treatment technologies is presented in Section 3.2.

Zhang et al. (2021) review *ex situ* treatment technologies for contaminated sediments, with the goal of identifying a suitable approach in support of beneficial uses. The authors consider costs, potential risks to the environment, readiness, and effectiveness of the technologies for multiple contaminants. The authors note that, compared to *in situ* treatment, *ex situ* treatment is often more efficient and more easily controlled, though its implementation may be complicated and expensive. Zhang et al. (2021) summarize recent advances for several *ex situ* treatment technologies, including physical treatment (e.g., sediment washing), chemical treatment (e.g., electrochemical remediation, chemical extraction, S/S), biological treatment (e.g., bioslurry reactor), and thermal treatment (e.g., thermal desorption, incineration, and vitrification). The authors evaluate S/S as a source for construction materials—for example, conversion of sediment into ceramsite, supplementary cementitious materials, fill materials, paving blocks, partition blocks, ready-mix concrete, and foamed concrete.

Xu and Wu (2023) review *ex situ* treatment of metal-contaminated sediments to support beneficial uses. Most treatment technologies for metals involve either mobilizing or immobilizing metals to reduce the toxicity and/or bioavailability. These authors evaluate advantages and disadvantages of many of the same technologies evaluated by Zhang et al. (2021). Xu and Wu (2023) highlight factors warranting consideration during the selection of treatment technologies, such as sediment physical characteristics and financial and environmental costs. Their review also examines beneficial use applications including ecosystem restoration, construction materials, and agricultural activities.

Crocetti et al. (2022) review *ex situ* technologies for reducing toxicity of contaminated sediments, including sediment washing, chemical treatments like S/S, thermal methods including desorption, oxidation and immobilization, and biological methods using microorganisms or plants. The authors compare the different treatment technologies' effectiveness in contaminant removal, efficiency in limiting costs, environmental impacts, and production of waste. The authors note that hybrid approaches (using more than one treatment) often offer greater flexibility and efficiency than single approaches. Crocetti et al. (2022) also evaluate the management and recycling of sediment-based resources for beneficial uses such as through the production of construction and road materials.

Alvarez-Guerra et al. (2008) examine treatment options for dredged materials, considering biological treatments such as bioleaching and bioslurry systems and solid-phase treatments such as land farming and composting. The authors note that most *ex situ* treatments require pretreatment (e.g., dewatering, physical grain size separation) to prepare the sediment for treatment and to reduce the volume and/or mass of sediment that requires transport and/or treatment. The waste residues produced during pretreatment must also be treated appropriately for contamination (Alvarez-Guerra et al. 2008).

Pal and Hogland (2022) review physical separation, sediment washing, and thermal, electrochemical, and biological extraction techniques. Pal and Hogland (2022) observe that few cost-effective extraction techniques are available and more research is required. The authors compare treatment technologies in terms of effectiveness of reducing chemical concentrations and/or bioavailability, cost efficiencies of treatment and monitoring, and time efficiencies of methods and sustainability, which is defined as "transforming renewable materials into useful products".

Like Xu and Wu (2023), which focuses on treatment of metal-contaminated sediments, several reviews focus on select types of contamination. Peng et al. (2018) also summarize physical-chemical and biological approaches for remediating metal-contaminated sediments and highlight factors that warrant consideration in the selection of appropriate methods. The efficacy of combined approaches such as physical-chemical process with phytoremediation or microorganisms and "group technology" (a combination of three or more remediation methods) is also evaluated for metals. Peng et al. (2018) also discuss emerging technologies, such as microorganism immobilization by sulfur-reducing bacteria. Also focusing on metal-contaminated sediments, Kumar et al. (2020) discuss biosorption using algae, bacteria, and fungi as biosorbents, as well as the use of nano-carbonaceous materials.

For sediments contaminated with polycyclic aromatic hydrocarbons (PAHs), Bianco et al. (2023) review *ex situ* treatments including bioremediation (bioaugmentation, biostimulation, anaerobic digestion), physical-chemical methods (adsorption, sediment washing), and thermal desorption methods. The authors report that, compared to bioremediation, physical-chemical and thermal processes have higher removal efficiencies and lower treatment times, but often at higher environmental (e.g., waste production) and financial costs. Bianco et al. (2021) and Li et al. (2020) review carbonaceous adsorbents for treatment of PAH-contaminated sediments, concluding that such amendments can be cost-effective and efficient. Maletić et al. (2019) review *in situ* remediation techniques for PAHs including bioremediation (bioaugmentation, biostimulation, phytoremediation), EKR, surfactant addition, and carbonaceous amendments.

Two papers review treatment technologies for sediments contaminated with polychlorinated biphenyls (PCBs): Fan et al. (2016) and Jing et al. (2018). Fan et al. (2016) review recent developments in chemical and EKR technologies. Examples of technologies considered include sediment washing and extraction methods using surfactants followed by treatment of washing eluate by ultraviolet photodegradation and TiO_2 photocatalytic technologies. Jing et al. (2018) review PCB remediation approaches including traditional technologies, such as bioremediation using plants and microbes, chemical dehalogenation of PCBs, and reduction of PCB bioavailability through carbon amendments. Jing et al. (2018) discuss the emerging technologies of bimetallic systems, nanoscale zero-valent iron (nZVI)-based reductive dechlorination, and supercritical water oxidation. The authors evaluate the technologies using a framework that considers costs, removal efficiency, treatment duration, and environmental impacts.

Reviews of treatment technologies for per- and polyfluoroalkyl substances (PFAS) mostly focus on contaminated water and soil, though three also address sediments. Mahinroosta and Senevirathana (2020) evaluate the following existing and emerging technologies for remediating PFAS-contaminated soils and sediments: immobilization, washing, thermal treatment, chemical oxidation, ball milling (physical method to reduce particle size), and electron beams (advanced oxidation-reduction process by irradiation). Kucharzyk et al. (2017) review several novel and promising technologies, including sonochemistry, bioremediation, and photolysis. Xu et al. (2023) review biodegradation treatments of PCBs, polybrominated diphenyl ethers (PBDEs), and PFAS compounds using microbes and evaluating the availability of tools like biomolecular modeling to optimize the approach.

3.2 TREATMENT TECHNOLOGIES

This section reviews the recent science available on S/S treatment, biological treatment, extraction methods, and hybrid treatments.

3.2.1 Solidification/Stabilization Treatment

For the last few decades, S/S treatment has been used extensively for the management of contaminated sediments. S/S treatment involves adding binding materials in sediments to immobilize or stabilize contaminants and to reduce their potential for release into the environment. Solidification processes physically bind contaminants within a stabilized mass. Stabilization processes reduce the mobility of contaminants through chemical reactions with a stabilizing agent. The primary goal of S/S is to transform dredged materials into a solid and stable material that can be safely used due to reduced leachability and mobility of the contaminants (Elghali et al. 2022).

The effectiveness of S/S depends on several factors, including the types and concentrations of contaminants present, the type and amount of binder used, and the curing conditions. Following sediment characterization, S/S typically involves the following steps:

1. Selection and addition of reagents: Suitable additives or reagents are chosen based on the contaminants present and physical character of the sediments. Those reagents are mixed with sediment by mechanical mixing, pug milling, or other methods.

2. Chemical reaction: During and after mixing, the reagents interact with contaminants through physical and chemical processes. Depending on the reagents used and contaminants present, those processes may involve precipitation, chemical immobilization, adsorption, or ion exchange. Metals are typically immobilized, whereas organic contaminants may require a pretreatment to alter or break down the compound before immobilization (Conner and Hoeffner 1998).

3. Solidification: The mixture of additives and sediments undergoes a solidification process that immobilizes the contaminants and prevents their leaching or release.

4. Curing and stabilization: The solidified sediments are allowed to cure or harden, which strengthens the matrix and enhances its stability. This curing period can range from a few days to several weeks, depending on the specific treatment and the desired level of stabilization.

5. Testing and quality control: The treated sediments are tested to assess the effectiveness of the S/S treatment and to verify compliance with regulatory standards. Testing may involve leaching tests, strength tests, and chemical analysis.

Each of the five steps offers opportunities to improve efficiency and effectiveness of S/S treatment. The selection of binders is particularly important in immobilizing contaminants, which occurs as uptake during cement hydration or precipitation of low-solubility secondary products (Elghali et al. 2022). Binders or additives—including cements, cement/soluble silicate, limes, fly ash, kiln dust, phosphate, pozzolans, thermoplastics, clays, and silicates—physically alter, encapsulate, or chemically react with contaminants by reducing access to water (Alvarez-Guerra et al. 2008; Conner and Hoeffner 1998; Zhang et al. 2021; Svensson et al. 2022). Cement-based materials are common in these applications, and recent research on cementitious materials has focused on making those materials more efficient and cost-effective (further discussed in Section 3.2.1.1).

Metals in sediment are typically immobilized by the strength of the bound material and resultant decreased leachability, thereby creating a matrix that mitigates the risk of release of metals to the air, water, or soil (Crocetti et al. 2022). The mobility of metals in sediment is controlled by pH buffering capacity, chemical speciation, and redox potential (Conner and Hoeffner 1998; Alvarez-Guerra et al. 2008); thus, chemical immobilization requires consideration of these characteristics. As discussed by Wang et al. (2015a), additional factors that affect the ability of reagents to immobilize metals include organic matter enhanced calcium complexation (Dubois et al. 2009) and soluble chloride and sulfate salts in marine sediments (Zentar et al. 2012; Zhao et al. 2013). Matrix solidification can be delayed or reduced by the presence of metals that can disrupt the formation and growth of the crystalline phases that contribute to the strength of cementitious materials (Wang et al. 2015a; Gollmann et al. 2010; Pandey et al. 2012; Navarro-Blasco et al. 2013).

Immobilization processes for organic compounds may be categorized as (a) reactions that destroy or alter the compounds or (b) physical processes such as adsorption and encapsulation (Conner and Hoeffner 1998). Like metals, organic compounds can interfere with binder hydration reactions and the strength of the solidified product (Wang et al. 2018; De Gisi et al. 2020). Such limitations can be mitigated through the selection of the binder, mixture design, and manufacturing methods. Wang et al. (2018) describe the successful creation of paving blocks from sediments contaminated by metals, PAHs, and PCBs by optimizing the binder mixture design to reduce the leachability to levels below the regulatory criteria. Likewise, De Gisi et al. (2020) illustrate that S/S treatments involving lime, organoclay, and activated carbon successfully produced fill material from sediments contaminated by metals, PAHs, and PCBs. In this case, organic compounds slowed the process of metals stabilization and hardening.

The heterogeneity of the physical characteristics of the sediment and the contaminants present may necessitate pretreatment, such that successful creation of S/S products requires longer treatment times (Xu and Wu 2023). Prewashing can effectively remove excessive water, soluble salts, chlorides, or sulphates, but also increases overall water consumption, which in turn increases costs and treatment duration (Wang et al. 2015a). Additional pretreatment options include thermal treatment processes, including vitrification and thermal desorption. Vitrification involves heating sediment to very high temperatures (>1,600 °C), which melts metals and destroys organic contaminants, yielding a slag product that can be used in cement products (Alvarez-Guerra et al. 2008). Thermal desorption involves heating the sediment to temperatures at which contaminants condense and can be collected in a liquid, captured on activated carbon, or destroyed in an afterburner (Zhang et al. 2021).

Several studies investigated the leachability of contaminants following S/S treatments to evaluate the effectiveness of different combinations of binding materials and methods (Xu and Wu 2023). Remobilization of heavy metals can occur by dissolution of precipitated contaminants or altered physical states of the solidified materials due to changes in climate (Elghali et al. 2022). Wang et al. (2015a,b, 2018) used the toxicity characteristic leaching procedure (TCLP; U.S. Environmental Protection Agency [EPA] Method 1311; USEPA 1992) to evaluate the potential leachability of metals from untreated contaminated sediment and from S/S-treated materials. De Gisi et al. (2020) used leachability as a measure of success, defining optimal conditions as those that limited release of metals after contact with deionized water. De Gisi et al. (2020) found that the mobility of copper was influenced by pH and the addition of lime. Zhang et al. (2020) relied on Dutch tank leaching tests to evaluate marine sediment under S/S treatments with different binder combinations to identify the impacts of temperature and pH on leaching of metals.

Elghali et al. (2022) identify topics warranting further research. These authors raise the possibility of climate change causing the remobilization of metals due to dissolution of precipitated contaminants or altered physical states of the solidified materials. They also note that most studies on S/S treatments have been conducted only at the laboratory- or pilot-scale; the effectiveness and efficiency of S/S technologies are expected to vary between the laboratory- and field-scale (Elghali et al. 2022). De Gisi et al. (2020) note that scaling up to a full implementation will require consideration of materials handling. Zhang et al. (2021) note that additional research is needed on the long-term stability of contaminated sediments treated by S/S methods, particularly in the context of full-scale implementation.

The following sections present a more detailed review of two types of S/S technologies. First, a discussion of the cement-based technologies is presented with a focus on recent advances to produce more stable and sustainable, which is defined as a lower carbon footprint, products. Second, the use of sequestration treatment technologies to improve the stabilization of contaminants in S/S products is presented.

3.2.1.1 Cementitious Materials

Following S/S treatment, the stabilized and/or solidified materials may be beneficially used for a variety of purposes, such as construction materials, fill material for land reclamation projects, roadbed material, or material for engineered caps or covers for landfills or contaminated land. The potential use of treated dredged materials as raw materials for construction or fill has long been recognized (PIANC 2023; Bailey 2014). Due to relatively low disposal costs, however, this method has not yet been widely used for sediments (Svensson et al. 2022). Stabilization using a cementitious or pozzolanic binder to encapsulate contaminated sediment is a common and practical solution over other more expensive treatment options (Zhang et al. 2018). Cement-based technologies typically involve cements such as ordinary Portland cement (OPC), calcium sulfoaluminate cement (CSA), magnesia-based cements (MC), and alkali-activated materials (AAMs) to bind the sediments and form a solid mass (Xu and Wu 2023).

Though OPC is cost-effective, it contributes high greenhouse gas emissions (Zhang et al. 2021), has high porosity, and has elevated potential for pollutant leaching (Zhang et al. 2018). Recently, low-carbon cements have been pursued by replacing cement clinker (i.e., the solid material produced as an intermediary product) with supplementary cementing materials, yielding end products with a lower carbon footprint and improved durability suitable to a variety of applications (Khessaimi et al. 2022). Ground granulated blast furnace slag (GGBS) is a by-product of steel manufacturing that is widely used as a partial replacement for OPC in concrete. The low pH of GGBS limits the leaching potential of metals and mitigates emissions and the end product's carbon footprint (Zhang et al. 2018). Though limestone calcined clay cement is considered a durable S/S binder, research is needed to evaluate its ability to stabilize sediment contaminants (Khessaimi et al. 2022).

Xu and Wu (2023) describe CSA, MC, and AAMs as effective and sustainable (i.e., lower carbon footprint) alternatives to OPC. The crystal structure of CSA enables it to support binding sites for many metals, while minimizing interference by metals on the hydration process. CSA is considered a low-carbon, low-alkaline product with good early strength and durability. MC can physically fix and stabilize metals through physical encapsulation and chemisorption and is considered superior to OPC in terms of curing metals with a smaller solidified body. AAMs are derived from the reaction of an aluminosilicate precursor such as slag or fly ash with an alkali binder, which provides a geopolymer matrix to physically encapsulate heavy metals. AAMs are a low-carbon alternative to OPC that offer better temperature and chemical resistance.

As summarized below, Zhang et al. (2021) discuss research needs and the following S/S products created from contaminated sediments: ceramsite, supplementary cementitious materials, fill materials, paving blocks, partition blocks, ready-made concrete, and foamed concrete.

- Ceramsite—This low bulk, high porosity material uses sediment in place of clay as a raw material. It may be used in construction or water treatment. Contaminants in sediment used to create ceramsite are immobilized or volatilized during the manufacturing process. Research is needed on how the quality and performance of ceramsite are influenced by different kinds of sediment contaminants and the high salinity of marine sediment.
- Supplementary cementitious materials (SCMs)—Sediment with high clay content (>30 percent) can be used as a clay substitute for manufacturing SCMs. Flash calcination is an energy-efficient approach to deriving calcined sediment, in which sediment is exposed to high temperatures for short periods. Calcined sediment has been used to manufacture mortars, concrete, and bricks. The high temperatures of the calcination process decompose organic contaminants, but the metals may interfere with cement hydration. Further research is needed on the use of calcined contaminated sediment as an SCM.
- Fill materials—Combining contaminated sediments with other types of wastes such as coal fly ash, sewage sludge, or glass powder can be cost-effective. Addition of activated carbon materials can enhance the immobilization of contaminants in sediment.

- Blocks—Sediment, particularly marine sediment, can be recycled into concrete blocks for use in construction. Pretreatment, such as calcination and addition of biochar, can improve the strength and thermal insulation properties of the blocks.
- Foamed concrete—A porous construction material can be made of cementitious materials, admixtures, and foaming agents. This approach has not been widely applied with dredged sediment. Further research is needed on the influence of sediment on the physical and chemical properties of foamed concrete.

Several authors offer examples of the use of dredged materials in the S/S products discussed above. Dang et al. (2013) describe the use of dredged materials in the production of cement in which a thermal treatment was applied, heating sediment at high temperatures (650 °C and 850 °C) to destroy PAHs and PCBs. The authors found that, compared to OPC, the lower temperature tested produced an acceptable blended cement at lower costs but required longer curing time to develop necessary mechanical strength. Further research was recommended on a cost–benefit analysis and durability of the product.

Wang et al. (2015a,b, 2018, 2022a) investigated the use of dredged marine sediments contaminated with metals, PAHs, and PCBs to produce concrete materials for construction. Wang et al. (2015a) evaluated the use of metal-contaminated sediments and waste materials (e.g., fly ash) in S/S products for construction (load- or non-load-bearing blocks). The authors report that the replacement of aggregate by sediment increased the porosity and decreased the compressive strength of the blocks. The reduced compressive strength could be offset by the addition of waste materials, including bottom ash or crushed glass. Wang et al. (2015a) concluded that up to 80 percent of sediment/waste could be used in the production of blocks, while reducing the leachability of metals through the cement calcination and hydration process. They report that this process is cost-effective relative to the market value of comparable materials. Similar investigations were conducted by Wang et al. (2015b, 2018) using dredged materials contaminated with metals, PAHs, and PCBs. The authors report optimal combinations of binders and aggregate materials for concrete block production by S/S, yielding an end product with low toxicity and high cost-efficiency. In comparing the various end products, Wang et al. (2018) note that building materials like paving blocks offer the highest potential profits, whereas fill material precludes disposal fees. Further research is needed on S/S treated sediments to determine the impact of environmental factors like pH, which based on modeled long-term exposures, may compromise the integrity of the product (Wang et al. 2022a).

In conclusion, the end products discussed above are alternatives to disposal of dredged materials and, compared to landfilling, are attractive from a cost–benefit standpoint. That said, the long-term performance of these potential beneficial uses warrants additional investigation. For example, Amar et al. (2021) review experimental tests of the durability and performance of cementitious materials containing sediments and conclude that most durability tests for common mortar or concrete also can be applied to sediment-based materials. Svensson et al.

(2022) describe a life cycle assessment of the management of contaminated dredged materials for the port of Gothenburg, Sweden, illustrating that the production of construction materials using S/S-treated material is cost-effective but contributes high greenhouse gas emissions. Further research is necessary to assess the durability, costs, and environmental impact of these S/S materials and the treatments applied to ameliorate the contamination.

3.2.1.2 Sequestration Treatments

Contaminants in dredged materials can be sequestered through treatment with carbonaceous materials (e.g., activated carbon, biochar[5]) and other materials (e.g., zeolites[6]). Carbonaceous materials have high surface areas and strong adsorption capacities, which allow them to bind to and immobilize contaminants (Li et al. 2020). Activated carbon additions are common *in situ* treatments that reduce the bioavailability of organic contaminants like PCBs and PAHs (Alvarez-Guerra et al. 2008). For *ex situ* treatment, carbonaceous materials can be used in combination with other treatments, such as S/S.

Li et al. (2020) report that activated carbon and biochar are the most used adsorbents for sediment that is contaminated with organic compounds, such as PAHs. Bianco et al. (2021) demonstrated that the use of biochar to adsorb PAHs in contaminated sediments reduced bioavailability and toxicity to aquatic organisms. The authors summarize several applications of biochar for remediation of PAHs in sediment. Remediation times ranged from 1 to 100 days, and bioavailable PAHs were reduced by 11 to 99 percent. Biochar can reduce the effectiveness of bioaugmentation and phytoremediation treatments due to decreased PAH bioavailability and increased pH. Resultant water or nutrient retention can lead to toxicity to plants or aquatic organisms. Bianco et al. (2021) recommend further research on biochar sources, the influence of electron acceptors (e.g., sulfate) and pH on biostimulation, and potential for toxicity to aquatic organisms and plants. Li et al. (2020) also recommend evaluating strategies for increasing the adsorption kinetics of biochar and reducing interference by natural organic carbon in sediment.

Mamindy-Pajany et al. (2012) review non-carbon sequestration options, including iron-based additives such as hematite or zero-valent iron. Such amendments have been shown to be effective in metal-contaminated soils in which the charge on the surface of hydroxide particles is controlled by pH to create iron hydroxides, which are amphoteric[7] and form complexes with metals. Similarly, zeolites are a low-cost material that can reduce leaching of metals from soils. These additives can reduce ecotoxicity by decreasing mobility of contaminants in liquid phase. Some mineral additives, however, can increase sediment toxicity due to the need for preparation methods that can alter the contaminant bioavailability (e.g., increased shaking

[5] Biochar is a porous carbonaceous material produced by thermochemical decomposition of biomass under anaerobic or limited oxygen conditions,
[6] Zeolites are aluminosilicate mineral with tetrahedral pore structure, high surface area, and strong capability of ion exchange and adsorption.
[7] Possesses the characteristics of both an acid and a base and capable of chemically reacting as either.

times relative to higher sediment concentrations) and the presence of more sensitive microbial species (Mamindy-Pajany et al. 2010, 2012).

Several studies report successful sequestration treatments in combination with other treatments for other organic and inorganic contaminants. Sörengård et al. (2019) demonstrate the use of activated carbon, zeolite, and bentonite to stabilize PFAS contaminated soils using an S/S approach. Xing et al. (2021) applied a washing treatment with a biosurfactant (high concentration humic substance from green waste compost) followed by zeolite stabilization, to increase microbial activity in cadmium-contaminated sediment and reduce the bioavailability of cadmium. Popov et al. (2021) evaluated a combined treatment of EKR followed by S/S with activated carbon to effectively immobilize metals-contaminated sediments.

3.2.1.3 Summary of S/S Treatment

The status of S/S to treat contaminated dredged materials for beneficial uses is as follows:

- **Status of Treatment Development**: Most investigations of S/S were at the laboratory or pilot scale, with a few examples of full-scale applications.
- **Recent Advances:**
  - Researchers have evaluated different binders to increase the efficiency and effectiveness of immobilizing contaminants. Pretreatment methods (e.g., sediment washing, thermal treatments) decrease the contaminant load requiring immobilization in the S/S product.
  - Recent studies on cementitious materials employ products comparable to OPC but with lower greenhouse gas emissions and leaching potential of metals. Researchers replaced aggregate with contaminated dredged materials to cost-effectively produce concrete materials for construction.
  - Researchers report that the addition of biochar, activated carbon, or other non-carbon additives (e.g., iron-based hematite) can decrease mobility of contaminants in treated dredged materials, enhancing the stability of the contaminants for S/S products.
- **Research Needs:**
  - Improved understanding is needed on the long-term stability of contaminants bound in S/S products, and the binder's influence on stability under varying climate conditions.
  - Research is needed into ways to increase the durability and lower carbon footprint of cementitious materials.

– Recommended studies include methods of optimizing sequestration treatments that are used in concert with S/S and other treatments, to increase adsorption of contaminants and to reduce toxicity to plants and animals.

3.2.2 Biological Treatments

Biological treatments are primarily applied to sediments contaminated with organic compounds. This category of treatments spans bioleaching, composting, and use of plants or microorganisms. Alvarez-Guerra et al. (2008) describe four categories of biological treatment:

- Bioleaching uses bacteria to oxidize sulfur and enhance the solubility of metals. This treatment can be performed in a slurry system or by heap leaching. With heap leaching, metals are mobilized by acidophilic bacteria that oxidize reduced sulfur compounds to sulfuric acid. These bacteria typically require an external source of reduced sulfur and preliminary conditioning. Löser and Zehnsdorf (2002) provide an example of preconditioning prior to a bioleaching treatment by reed canary grass (*Phalaris arundinacea*); here, the permeability of dredged sediment was increased by the plants' root growth, growth of microbes stimulated by oxygen and exudates from the roots, and reduced sediment moisture caused by plant transpiration.
- Bioslurry systems treat organic contaminants in a reactor, wherein sediment is mixed with water and native or introduced microorganisms biodegrade the contaminants. This method requires treatment of wastewater.
- Solid-phase biological treatments, such as land farming, involves spreading partially dewatered sediment over an area (e.g., land-based treatment cells) and increasing nutrients and aeration to promote microorganism growth. Similarly, composting entails mixing partially dewatered sediments with bulky organic materials to improve the permeability of the sediment and to stimulate microorganism growth. The goal of both methods is to promote aerobic biodegradation of contaminants. These methods require a large area for processing, as well as long treatment durations.
- Phytoremediation methods are used to transfer, stabilize, concentrate, or destroy contaminants from sediment. Phytostabilization limits sediment mobility and immobilizes contaminants. Phytoextraction removes contaminants (including metals) from sediments by plant uptake into plant roots and/or shoots. Phytodegradation occurs in plant tissues. Phytostimulation uses symbiotic microbes on plant roots. Phytovolatilization transforms contaminants into volatile compounds and releases them to the atmosphere. These methods are typically not sufficient as a singular treatment and are commonly used in combination with other treatments.

Though bioleaching has largely been tested only at the laboratory scale, Xu and Wu (2023) describe it as promising; in the absence of field studies, uncertainty in remediation efficiencies remain. High metals recoveries (> 90 percent) were reported for bioleaching of sediments in two studies—one used acidophilic sulfur-oxidizing bacteria and the other used filamentous fungi and lithotrophic bacteria (Chen et al. 2022; Sabra et al. 2011). Akcil et al. (2015) summarize several recent laboratory or pilot studies on bioleaching for removal of metals, most of which were conducted in a reactor with acidophilic or sulfur-oxidizing bacteria, with treatment durations ranging from 5 hours to 48 days and removal efficiencies up to 99 percent. Some of those studies were based on spiked synthetic sediment, however, and few presented feasibility assessments of the approach.

Fonti et al. (2016) review several laboratory- and pilot-scale bioleaching studies using acidophilic bacterial strains for metal-contaminated sediments. The authors note that factors that influence the success of bioleaching processes include geochemical properties of the sediment, moisture content, type of metal, presence of key growth substrates, and preconditioning of bacteria to sediment. Fonti et al. (2016) recommend using other treatment options under certain conditions, such as when the sediment has a high acid-neutralizing power, lead or chromium are the main contaminants, metals have low solubility, or high amounts of sulfur, iron, or acids are required.

Zhang et al. (2021) describe bioslurry reactor treatment as a fast and safe method that may be scaled to full application more easily than conventional bioremediation technologies. A laboratory-scale study investigating the effectiveness of using both free and immobilized indigenous and exogenous bacteria in a bioslurry treatment illustrated faster degradation of PAH compounds (phenanthrene and fluoranthene) using the Ca-alginate-immobilized bacteria to enhance removal efficiencies by up to 63.2 percent (Wang et al. 2019). Pino-Herrara et al. (2017) review this technology and the factors that influence successful removal of organic contaminants. These authors suggest several areas of future research for this treatment, including further investigation of the microbial diversity required for an optimized approach, properties of mixed sediment mineral-microbial bioflocs, treatment of wastewater, and use of remediated sediment following treatment.

Gomes et al. (2013) describe landfarming in which PCB-contaminated sediments were added to soil in biotreatment cells and mixed frequently to increase aeration. Pilot studies illustrate that PCBs were degraded by photolysis, volatilization, and biodegradation. This method was effective when PCBs (and PAHs) could be desorbed from sediment particles, but not when they were sequestered.

Xu and Wu (2023) also highlight phytoremediation examples, including studies of tropical mangroves remediating metals in sediments by root uptake. Bert et al. (2009) review several studies on phytoremediation and report that various types of vegetation (e.g., trees, high-biomass crops, and graminaceous species) can grow and develop on contaminated dredged sediment and both degrade organic contaminants and extract or stabilize inorganic contaminants. In some cases, metal-induced oxidative stress can reduce plant growth, limiting the effectiveness of this method (Bert et al. 2009). Adding biochar can ameliorate oxidative stress and promote removal efficiencies, in that it can change the speciation of metals in sediment and increase their accumulation and mobility in plant tissues (Gong et al. 2019).

Pal and Hogland (2022) review the biological extraction methods for inorganic-contaminated sediments using plants or microbes. Through phytoremediation, a variety of hydrophytes can uptake multiple metals from sediment. For microbial remediation, metals can be immobilized on microbial cells, which occurs through biosorption, bioaccumulation, and biotransformation. Compost can be used to biologically immobilize heavy metals, which suggests that a plant-growing medium holds promise as a beneficial use (Peng et al. 2018).

Phytoremediation can remove PAHs and PCBs from contaminated sediments through biodegradation in the root-zone (Bianco et al. 2021, Smith et al. 2008). Adding biochar to enhance phytoremediation of PAHs can decrease the bioavailability of PAHs, thereby reducing the ecological risks but also reducing the efficiency of bioremediation. As such, this method is not effective for organic contaminants like PAHs, in that high pyrolysis biochars can increase pH and decrease PAH bioavailability. Smith et al. (2008) illustrate that wetland plant species including *Carex aquatalis* and *Spartina pectinate* enhance reductive dechlorination of PCBs (reductions up to 21 percent for PCB congeners based on a starting total PCB concentration of 20 mg/kg) under anaerobic conditions in an 18-month greenhouse study. While these approaches are generally cost-effective, they can be time-consuming and difficult to control during remediation.

The status of biological treatments to address contaminated dredged materials for beneficial uses is as follows:

- **Status of Treatment Development**: Most investigations of bioremediation are at the laboratory or pilot scale.
- **Recent Advances:** Bioleaching and bioslurry reactor treatments and phyto- or microbial remediation were investigated for inorganic and organic contaminants, some of which included other types of treatments (e.g., sequestration) to enhance removal efficiencies.
- **Research Needs:**
  - Several bioleaching studies were conducted on spiked synthetic sediment, which limits the applicability of the findings to field settings. In addition to feasibility studies using field-condition sediment, research is needed on optimizing microbial diversity for these treatments.
  - Several bioremediation approaches including phytoremediation require long durations (months to years). Research is needed on increasing the efficiencies and decreasing duration through, for example, the application of biochars, compost or other additives to enhance phytoremediation.

3.2.3 Extraction Methods

This section describes three methods tested or used to extract contaminants from sediments: sediment washing, EKR, and chemical extraction. As detailed in the following subsections, sediment washing may employ inorganic acids, chelators, or surfactants to extract contaminants from the dredged materials. Types of chemical extraction include flotation, microwave, and ultrasonic-assisted extractions.

3.2.3.1 Sediment Washing

Sediment washing uses solutions to wash the sediment and separate the contaminants from sediment particles. Contaminants are removed by dissolution or suspension in washing solution or by concentrating contaminants via particle size separation and gravity (Akcil et al. 2015; Zhang et al. 2021). Although water is typically used as the washing solution, removal efficiency may be enhanced with chemical agents such as inorganic acids (nitric, sulphuric, and hydrochloric acids), ethylene diamine tetraacetic acid (EDTA), and surfactants (Akcil et al. 2015; Xu and Wu 2023). Acidic agents degrade metal compounds, whereas EDTA and activated carbon act as chelators to increase the solubility of metals (Xu and Wu 2023). Surfactants (e.g., rhamnolipid) form complexes with metals and transfer the aggregated complexes in solution (Xu and Wu 2023). Humic substances extracted from compost are effective in removing some metals and have little impact on sediment properties that are desired for beneficial uses (Zhang et al. 2021).

Akcil et al. (2015) review sediment washing studies for removal of metals using a variety of chemical agents. The highest removal efficiencies (up to 100 percent) were reported for copper, lead, and zinc with lower efficiencies for cadmium and nickel. The authors note that this treatment is best suited for metals with weak associations with sediment and for sediments dominated by coarse particles. The acid neutralizing capacity of sediment can otherwise limit removal efficiencies. Pal and Hogland (2022) note that soil washing is costly for metals and a full-scale application would require a large washing installation. As such, they propose that the technology may be more suitable when combined with other treatments. Lumia et al. (2020) demonstrate an optimized approach with high removal efficiencies (>80 percent) using citric acid and EDTA to remove metals and total petroleum hydrocarbon from marine sediment. The process was optimized, in part, by treating coarse and fine sediments separately.

Sediment washing with surfactants and organic solvents has successfully removed PCBs; however, as noted above for metals, additional treatment (e.g., ultraviolet photodegradation) of the washing and extraction solutions is necessary (Fan et al. 2016). Bianco et al. (2023) review sediment washing for PAH-contaminated sediments and report that surfactants and organic solvents (e.g., ethanol, humic acid, vegetable oil) remove PAHs by desorption. The authors note that removal efficiencies for PAHs are influenced by the organic fraction of sediment. The duration of treatment is often tied to the type and quantity of extraction agent applied and the solid-to-liquid ratio. A low solid-to-liquid ratio typically requires less time to reach equilibrium. Agarwal et al. (2015) report that sediment washing is less effective than flotation separation for oil-contaminated sediment. The effectiveness of sediment washing is limited by small sediment particle sizes (i.e., clay or silt). Limitations like those listed above for other contaminants also were noted for PFAS, particularly the persistence of low concentrations in leachate following treatment (Mahinroosta and Senevirathna 2020).

3.2.3.2 Electrokinetic Remediation

EKR involves the application of a direct current through the sediment using electrodes that cause charged contaminants to migrate towards the electrodes (Xu and Wu 2023). An electrical gradient causes the movement of charged particles, fluids, and chemical reactions, resulting in the concentration and removal of contaminants near the electrodes (Alvarez-Guerra et al. 2008). Metals and other positively charged contaminants move towards the cathode (i.e., negative electrode), while anions and other negatively charged contaminants move towards the anode (positive electrode). The three main transport mechanisms are electromigration, electroosmosis, and electrophoresis (Masi et al. 2017). Enhancing agents may be used to improve metals removal and reduce the treatment duration by controlling the pH and promoting electromigration of metals in the system (Colacicco et al. 2010; Rozas and Castellote 2012).

The effectiveness of electrochemical remediation treatments can vary depending on the types and concentrations of contaminants, sediment characteristics, treatment duration, and applied current density. EKR is particularly effective in treating fine and low-permeability materials (Benamar et al. 2020; Xu and Wu 2023). It also can achieve consolidation, dewatering, and removal of salts and inorganic contaminants in a single stage. Zhang et al. (2021) note that advantages of EKR include high removal rates (e.g., up to 96 percent removal of PCBs [Gomes et al. 2014]) in fine-grained sediment with no or minimal byproducts. On the other hand, EKR often requires a long duration, and financial and environmental costs may increase if chemicals are added to enhance the selectivity of target contaminants.

Xu and Wu (2023) present several examples of EKR as a singular treatment or combined with other treatments (e.g., biosurfactants or citric acid enhancement) and reported variable recoveries for metals ranging up to 73 percent. The addition of a chelating agent can improve recovery, though it can introduce an additional source of toxicity and there is no universally favorable enhancing solution for metals (Rozas and Castellote 2012). Wen et al. (2023) report removal efficiencies up to 88 percent for lead using electroosmosis with EDTA as a washing reagent following 13 days of EKR. Colacicco et al (2010) report that the addition of EDTA as a chelating agent improved the treatment's energy efficiency and the mobilization of metals from marine sediments, yielding removal efficiencies up to 84 percent. Because EDTA is ecotoxic, the authors recommend researching nontoxic and biodegradable extracting agents.

Tian et al. (2017) report that enhancing agents with low toxicity, including citric acid and biosurfactants, did not significantly increase the toxicity of the sediment but also did not substantially remove metals, PAHs, or PCBs. The authors attribute these results to low mobility of contaminants in sediment due to the age of contamination and the sediment's high buffering capacity, low hydraulic permeability, and high organic content. Stronger acids and/or higher (or continuous) voltage gradients were suggested for potential future scenarios that may result in higher removal efficiencies, though they would increase energy use (Tian et al. 2017).

Several studies report increased removal efficiencies of organic contaminants when EKR is combined with bioremediation or dechlorination using nanoparticles. In a mesocosm-scale study, Cappello et al. (2019) report that PAHs were removed from oil-contaminated sediments by electroosmosis and biodegradation, with minimal maintenance and low carbon costs. Chun et al. (2013) illustrate up to 60 percent reduction in PCB concentrations in sediment by combining *in situ* EKR with PCB-dechlorinating microorganisms. Fan et al. (2016) note that the efficiency of *in situ* EKR in removing PCBs from sediment or soil are improved when combined with chemical oxidation, nZVI dechlorination, and bioremediation. Field testing of this technology has been limited, however, and the practicalities of EKR are hindered by its high costs and the long durations required for PCB remediation (Fan et al. 2016). Jing et al. (2018) review EKR technologies in combination with other technologies for the remediation of PCBs and note that approaches using EKR and nZVI dehalogenation or nano Pd/Fe particles offer promising advances, though recoveries are variable. One example (Gomes et al. 2014) combined electrodechlorination with surfactants (saponin and Tween 80) and nZVI to enhance PCB desorption, which resulted in removal efficiencies of both lower and higher chlorinated PCB congeners ranging from 9 to 96 percent.

One drawback of EKR has been the lack of field-scale application. Benamar et al. (2020) evaluated a scale-up involving sediment contaminated with both inorganic and organic compounds and reported favorable results on a large scale using a mixture of chelating agent (citric acid) and nonionic surfactant (Tween 20) for sediments impacted by metals, PAHs, and PCBs. However, field-scale effectiveness was limited by sediment heterogeneity, inertial effects, and the poor ability for the electrical field to control the migration process (Benamar et al. 2020). Masi et al. (2017) present a model-based approach for field-scale application of EKR for the treatment of lead-contaminated marine sediments with a targeted removal of 70 percent. They note improved correlation of modeled and validated results when sediment heterogeneity is low.

Drawbacks of EKR include high energy consumption and related high costs, but these factors can be mitigated by selecting appropriate parameters (e.g., electrodes, voltage gradient, electrolytes) or by combining EKR with other approaches (Xu and Wu 2023). Additional research is needed at the field-scale to optimize parameters and to identify opportunities to reduce costs (Zhang et al. 2021).

3.2.3.3 Chemical Extraction

Chemical extraction uses chemical agents that interact with contaminants, facilitating their separation from the sediment matrix. Chemical extraction is like sediment washing, except that an organic solvent (e.g., methanol) is used instead of water (Alvarez-Guerra et al. 2008). The preferred chemical agent and treatment approach vary with the contaminants' nature, extent, and properties. Types of chemical agents include solvents, chelating agents, oxidizing agents, reducing agents, or pH-adjusting agents.

A typical chemical extraction approach may involve the following steps:

- Sediment preparation: Large debris and stones are removed, and the sediment is dried to reduce its volume.
- Chemical agent application: The selected chemical agents are applied to the sediment via spraying, mixing, or immersing. The chemicals are thoroughly mixed with the sediment to ensure contact with the contaminants.
- Contaminant extraction: Depending on the contaminants present and the treatment approach, contaminants may be extracted from the sediment matrix through dissolution, complexation, oxidation, reduction, and/or pH adjustment.
- Separation and treatment: Contaminants are removed by subjecting the sediment and chemical agent mixture to separation techniques, such as sedimentation, filtration, centrifugation, and flotation. When contaminants are removed by wet classification, sediments are mixed to break up particle agglomerates and contaminated and non-contaminated particles are mechanically separated by centrifugation, up flow column, or other means (Alvarez-Guerra et al. 2008). The separated contaminants are then either disposed of safely or are further treated to minimize environmental impact.
- Post-treatment assessment: Following treatment, both the sediment and wastewater are assessed to ensure that contaminant concentrations meet regulatory criteria (Alvarez-Guerra et al. 2008).

Zhang et al. (2021) describe using ionic liquids (i.e., liquids formed from organic cation and inorganic anion as typical salts) to recover oil from sediments. The strong dipole moment of ionic liquid 1-ethyl-3-methylimidazolium tosylate makes it particularly effective at enhancing recovery of oil from sediments and ionic groups (Agarwal and Liu 2015). Ionic liquids have also been used in combination with nonpolar solvents, such as acetone and toluene, to enhance removal of organic contaminants from oil-contaminated sediments (Agarwal and Liu 2015). Álvarez et al. (2017) report that combining the chelating agent EDTA with the ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate for the extraction of metals in an ultrasonic bath reduced the treatment duration from 6 hours (for EDTA alone, the more traditional approach) to 7 minutes. Ionic liquids are also considered to be treatment options with high recovery and recyclability, though aquatic toxicity is a concern, and the large-scale application of these liquids is constrained by high costs (Agarwal and Liu 2015).

Flotation is another method frequently combined with chemical extraction. After sediment is mixed with a chemical agent, sediment particles are separated based on differences in densities and surface properties that control whether particles float or sink (Xu and Wu 2023; Alvarez-Guerra et al. 2008). For metals, chemical pretreatment can be applied to generate metal sulfides for separation from sediment particles (Xu and Wu 2023). Cauwenberg et al. (1998) report up to 80 percent removal efficiencies of metals using a combined chemical extraction and flotation process.

Xu and Wu (2023) present examples of microwave- and ultrasonic-assisted chemical extractions for metals with recoveries exceeding 77 percent. These methods are reported to be cost- and time-efficient with fewer chemicals involved and greater efficiencies in contaminant removal. Alvarez-Guerra et al. (2008) report that this technology was used at the laboratory scale in combination with vacuum pressure for treatment of sediments dredged from New York/New Jersey Harbor (Meegoda and Veerawat 2002). Meegoda (2008) illustrates how this method could be used on a dredge vessel in a two-step process, in which coarse sediments are first decontaminated using ultrasound, after which fines and bulk dredged suspension are treated with ultrasound and acoustic and flow fields. Xu and Wu (2023) note that microwave- and ultrasonic-assisted treatments are rarely applied in practice. Further research is needed to apply these methods on a field-scale.

Alvarez-Guerra et al. (2008) describe the following additional examples of chemical extraction methods:

- Supercritical extraction can be used to extract volatile organic compounds and persistent organic pollutants. pH-adjusted sediments are placed under pressure and contaminants are extracted with recirculated steam of carbon dioxide and water.
- Dechlorination can be used for PCBs, chlorobenzenes, and dioxins by mixing the contaminated sediments with chemical reagents (potassium or sodium hydroxide) in a batch reactor to dehalogenate the contaminants into less toxic glycol ethers and water-soluble chloride compounds. The authors note that this method is not effective when concentrations of contaminants are high, water content exceeds 20 percent, or pH is less than 2.
- Chemical oxidation/reduction processes can be used to degrade recalcitrant organic compounds into immobile or less toxic forms using chlorination combined with either ozonation or photolysis. This treatment can be augmented with ultraviolet radiation for some contaminants (e.g., PCBs or dioxins). This treatment can generate toxic by-products through incomplete oxidation (Eldos et al. 2022).

3.2.3.4 Summary of Extraction Treatment

The following summarizes the current status of extraction methods to treat contaminated dredged materials for beneficial uses:

- **Status of Treatment Development**: Most investigations of extraction treatments are at the laboratory- or pilot-scale.
- **Recent Advances:**
  - Surfactants (e.g., EDTA, acidic agents, activated carbon, and humic substances) are effective in removing contaminants through sediment washing treatments.
  - The addition of strong acids agents, bioremediation or nZVI dechlorination methods, or higher voltage can increase the efficiency of EKR, albeit while also increasing energy use and overall cost for implementation.
  - At the laboratory scale, ionic liquids are effective in rapidly removing oil and metals (e.g., 7 minutes to 6 hours). Flotation, microwave-, or ultrasonic-assisted chemical extractions also offer promising results at the laboratory-scale.
- **Research Needs:**
  - Further investigation is needed to optimize sediment washing approaches and increase removal efficiencies. For example, research is needed to characterize the influence of the organic fraction and particle size range of sediments on the solid-to-liquid ratio and the duration required for treatment.
  - To date, there is little evidence of successful, cost-effective applications of EKR beyond the laboratory- or pilot-scale. Given the challenges posed by sediment heterogeneity, more investigation is needed to optimize EKR and chemical extraction methods at full scale.

3.2.4 Hybrid Treatments

The literature on *ex situ* treatment technologies consistently reports that removal efficiencies for singular treatment technologies often are improved by (or require) pretreatment and/or a combined approach. Combined treatments can condition the sediment, such as through physically sorting coarse and fine materials, removing excess water, or preparing sediment contaminants for removal (e.g., a pretreatment with a chelating agent to improve solubility of metals). Several examples of hybrid treatments are discussed above in the context of individual treatments, including sequestration (Sörengård et al. 2019; Xing et al. 2021; Popov et al. 2021), sediment washing (Pal and Hogland 2022; Agarwal et al. 2015), EKR (Colacicco et al. 2010; Rozas and Castellote 2012; Gomes et al. 2014; Fan et al. 2016; Yang 2019), chemical extraction (Meegoda and Veerawat 2002; Alvarez-Guerra et al. 2008), and bioremediation (Löser and

Zehnsdorf 2002). Examples of projects involving combined treatments are described in Appendix B.

4 FACTORS WARRANTING CONSIDERATION IN SELECTING TREATMENT AND BENEFICIAL USE APPLICATIONS

Many factors can influence the success of treatment technologies and beneficial use applications. This section discusses factors most pertinent to remedy selection.

4.1 FACTORS PERTINENT TO TREATMENT TECHNOLOGIES

The success of treatment technologies is primarily influenced by sediment contaminant properties and physical characteristics of sediment, both of which influence fate and transport processes. Other factors warranting consideration include the scale of treatment applications, efficiency of contaminant removal, duration of the treatment period, risk management, and environmental impacts of the treatment process. While marketability, costs, and regulatory approval are important considerations, they are discussed in the context of the beneficial uses (Section 4.2).

Characteristics of the primary contaminant(s) are fundamental to the selection of treatment technologies. Metals accumulate in sediments through adsorption and precipitation (Peng et al. 2018; Akcil et al. 2015) and are typically bound by carbonates, iron-manganese oxides, or organic matter. Alternatively, metals may be present in residual, extractable, or exchangeable forms (Xu and Wu 2023). Because metals cannot be degraded, immobilization is typically the main treatment objective, though removal of metals from sediment has also been investigated (Akcil et al. 2015).

Organic contaminants, such as PAHs and PCBs, are adsorbed to sediments through electrostatic interaction with charged clay and organic matter surfaces or hydrophobic interaction with organic matter (Bianco et al. 2023; Kewalramani et al. 2022). Treatment for organic contaminants typically focuses on desorption from sediment and degradation of the contaminants to nontoxic constituents. Overall, the effectiveness of treatment technologies is site-specific and related to the mix of inorganic and organic contaminants, the age of the contamination, and the physical characteristics of the sediment (Gomes et al. 2013).

Several authors (Zhang et al. 2021; Xu and Wu 2023; Crocetti et al. 2022) compare advantages and disadvantages of various *ex situ* treatment technologies, as summarized here:

- Sediment washing is recommended for sediments with coarse particles. Sediments with a high acid-neutralizing capacity can diminish the effectiveness of a sediment washing treatment. Wastewater from the washing process will require treatment (Zhang et al. 2021).
- High removal efficiencies can be achieved with chemical extraction but can be costly to implement on a large scale. The resulting waste likely requires treatment (Zhang et al.

2021; Xu and Wu 2023; Gomes et al. 2013). This technology typically requires large quantities of chemical agents and moderate energy consumption (Crocetti et al. 2022).

- EKR is effective for inorganic contaminants (Xu and Wu 2023) and can be combined with other treatments to address organic contaminants (Fan et al. 2016; Cappello et al. 2019; Gomes et al. 2014). A potential benefit of EKR technologies is the recovery of valuable metals from contaminated sediments, though that practice is not broadly applied and further investigation is needed (Gomes et al. 2013). EKR treatments require high energy use (Xu and Wu 2023) and additional investigation is needed on large-scale application (Benamar et al. 2020) and long-term effectiveness.
- Though rapid, bioslurry reactors and thermal treatments are energy-intensive and contribute greenhouse gas emissions, they have not been extensively applied at large scales (Zhang et al. 2021; Crocetti et al. 2022).
- Biological treatments can be cost-effective options but may require long treatment durations to yield sufficient removal efficiencies (Xu and Wu 2023; Pal and Hogland 2018; Peng et al. 2018). Some biological treatments require large land areas for application (Crocetti et al. 2022).
- S/S approaches are well suited to beneficial use as construction materials or fill. The frequent need for pretreatment can increase costs and treatment durations (Xu and Wu 2023). Immobilization treatments are effective for metals but require continuous monitoring (Pal and Hogland 2022).
- Hybrid or combined approaches are typically more efficient and effective than individual technologies. Hybrid methods may first involve physical treatments as a pretreatment to remove water, reduce salinity or contaminant levels, and/or separate sediment fractions, followed by chemical, biological, or thermal treatment (Crocetti et al. 2022; Peng et al. 2018). Peng et al. (2018) note that a single method often cannot address the heterogeneity and complexity of contaminated sediments.

Overall, the literature consistently reports that, while several promising treatment technologies exist, more research is needed to make the various treatment approaches feasible, cost-effective, and applicable at the field scale.

4.2 FACTORS PERTINENT TO BENEFICIAL USE APPLICATIONS

Most applications that are considered a beneficial use of treated sediments yield building or construction materials prepared with S/S treatments (Section 3.2.1). Increasingly, the benefits of applications like the production of cementitious materials can outweigh the costs of more traditional management approaches, such as disposal on land or at sea. This is particularly true in locations with high disposal costs and limited disposal capacities (Bell et al. 2021). Disposal costs and capacity constraints have prompted investigation of S/S applications (Zhang et al. 2020).

The Central Dredging Association defines dredged sediment as a resource with many potential uses, including raw materials for construction or fill or cover materials for upland applications (CEDA 2019a). CEDA (2019a) identifies programs in the U.S. and internationally, presenting more than 30 case studies of beneficial use applications for contaminated sediments. The World Association for Waterborne Transport Infrastructure published a report summarizing the findings of workshops conducted in 2019 and 2020 on beneficial use applications (PIANC 2023). Both CEDA (2019b[8]) and PIANC (2023) present many case studies involving contaminated sediments. Although most examples presented in both reports use sediment as a resource for construction materials and fill, they also describe other beneficial use applications such as materials for ecosystem restoration or supplemental agricultural soil.

Bell et al. (2021) discuss technical, economic, and institutional barriers to beneficial use applications. Among the technical barriers identified are high heterogeneity and inconsistency of sediment physical characteristics. These characteristics challenge the design of many beneficial use applications. Other technical barriers include variability in dredged sediment volumes and timing, as well as uncertainties associated with treatment technologies. Such factors can increase project planning costs, such as those related to the need for temporary storage of dredged sediments or facilities for treatment implementation.

Economic barriers relate to the direct costs of beneficial use applications for treatment, permitting, risk assessment, and liability. When employing a traditional economic analysis that does not consider social or ecological service benefits, such costs typically exceed traditional disposal costs. Finally, Bell et al. (2021) note that institutional barriers include compliance with established regulatory guidance and approaches for evaluating the acceptability of a beneficial use application. Bell et al. (2021) conclude that, despite these barriers, partnerships among stakeholders are prioritizing beneficial use applications. The case studies generated from these partnerships will likely demonstrate feasible paths forward and best practices.

Barr et al. (2023) describe various applications of beneficial uses of contaminated sediments, noting that most applications are in upland rather than aquatic environments. The authors summarize the factors that impact the successful implementation of beneficial use applications, with a focus on regulatory and community acceptance. They note that, compared to historical practices, sustainability metrics, or metrics that account for balancing the uses of resources, costs, and social acceptance, have been more widely applied in the decision-making process in the last 5 years. Decision frameworks are increasingly used in sediment remediation management. Several example frameworks and tools are highlighted, including those presented in EPA and U.S. Army Corps of Engineers guidance documents (EPA and USACE

[8] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies. Accessed on August 16, 2023.

2007a,b; Williams et al. 2020; Estes et al. 2014) and examples from the New York/New Jersey Harbor and other U.S. and international locations. Barr et al. (2023) note that life cycle assessment (LCA) and other decision frameworks allow projects to be viewed through a broad lens spanning potential social, environmental, and economic impacts.

Several articles also discuss decision tools that could aid selection of treatments and optimization of beneficial use applications for contaminated sediments, as summarized below:

- Zhang et al. (2021) present criteria for evaluating sediment remediation technologies that consider costs, safety, technological readiness level (laboratory-scale versus full-scale), efficacy, maintenance and monitoring requirements, environmental impacts, and acceptability. This approach employs multi-criteria decision analysis (MCDA) and can be coupled with LCA to determine the best option for a beneficial use application relative to environmental, economic, and social benefits.
- Crocetti et al. (2022) review several studies that conducted circular economic analyses of construction materials from dredged sediment and incorporated the S/S treatment processes (including binders), end product characteristics, positive impacts, and costs of the product. Several other studies used LCA and other tools to compare S/S products based on partial substitution of calcined sediments as alternatives for construction materials (Hadj Sadok et al. 2022; Barjoveanu et al. 2018; Zhou et al. 2021, 2023).
- Zheng et al. (2019) describe a decision framework based on the green and sustainable remediation strategy developed by ITRC (2011) that incorporates LCA, cost-effectiveness analysis, human health risk assessment, and MCDA. The authors apply the framework to a case study in Taiwan, demonstrating that the approach is flexible and transparent. Drawbacks of the approach include limited risk assessment conclusions (due to the high variability in sediment contamination) and lack of local reference data on remediation techniques.
- Svensson et al. (2022) present an LCA for construction of a port in Gothenburg, Sweden, considering several scenarios of treatment and beneficial use applications of the contaminated sediments. The authors discuss greenhouse gas emissions, other short and long-term environmental impacts, and relative costs for each approach. The analysis concludes with a summary of those treatments offering the greatest benefits in terms of environmental and economic costs. Like Zheng et al. (2019), these authors conclude that variability in sediment contamination is the greatest uncertainty in this analysis.
- Jing et al. (2018) use a streamlined approach to evaluate PCB treatment technologies in a matrix that considered costs, removal efficiency, time duration, and environmental impacts.
- Williams et al. (2020) developed a decision tool framework for the Great Lakes that includes environmental, economic, and social impacts for decisions regarding management of dredged contaminated sediments. This framework provides a

transparent structure that can be used by stakeholders to compare treatment and beneficial use applications. Such a use is important, in that both Barr et al. (2023) and Williams et al. (2020) note that a major limitation to beneficial use is broad acceptance and consideration of dredged sediments as a useful, commodified resource by stakeholders.

5 RISKS ASSOCIATED WITH TREATMENT TECHNOLOGIES AND BENEFICIAL USES

Barr et al. (2023) discuss potential risks in the context of the regulatory programs that guide decision-making for contaminated sediment beneficial uses. Two key risks associated with the application of treatment technologies for beneficial use of contaminated sediments are potential structural failure and chemical release, both of which could lead to adverse effects on human health and the environment. Because Section 3 of this white paper details which treatment technologies are most and least vulnerable to these risks, this section succinctly summarizes those earlier observations in order to minimize redundancy.

An additional risk is the presence of emerging contaminants, which ideally would also be addressed by the applied treatment(s), but in reality, has the potential to challenge the treated dredged materials used in beneficial use applications.

5.1 PHYSICAL/STRUCTURAL INTEGRITY

The ability for treated sediment to be beneficially used as a structural or fill material requires predictable structural properties that ensure safety and proper performance. Compared to other treatment technologies, S/S provides the greatest structural integrity. Within a given site, dredged material may be heterogenous, and multiple end uses may be desired. Consequently, multiple types of amendments may be required to achieve the required structural integrity. Summarized below are physical/structural integrity risks associated with each treatment technology category.

S/S treatment methods add binding materials to sediments, a process that improves control over the physical properties of the final material. The success of the technology depends, however, on the means of accounting for the heterogeneity of the contaminated material. To ensure the stability of the material before use, it may be necessary to segregate materials before treatment and to frequently conduct performance testing of the treated material. The final use of the material influences stability requirements and risks of failure. Compared to roads, for example, sidewalks have lower stability requirements and lower risks of failure. Beneficial use of S/S treated sediments as fill for ecosystem restoration or agricultural activities may offer alternatives to their use as construction materials due to the reduced strength required to support plant growth. Further research is needed to assess the durability, costs, and environmental impact of these S/S materials and the treatments applied to ameliorate the contamination.

Sediment treated with biological treatments and extraction methods are not amended in a manner that increases structural integrity. Therefore, end uses of materials treated with such technologies are more limited than those treated with S/S. Materials treated with biological and extraction methods are suitable for non-loading uses. If a structural use is required, additional treatment with an S/S agent likely will be needed to achieve structural integrity.

5.2 CHEMICAL STABILITY/SEQUESTRATION

The ability for treated sediment to remain inert and safe is critical to the successful beneficial use of sediment. In addition to the treatment technology applied, the safety of the end product is influenced by the end use and relevant exposure pathways. Bailey et al. (2014) discuss risks associated with exposure and bioavailability of contaminants in treated sediments that have been used beneficially. The potential for human and ecological exposures to contaminants in dredged materials that have been used beneficially will vary depending on the contaminants and their mobility, the treated sediment matrix, and the location of beneficial use. Human and ecological exposures can be limited through engineering controls that prevent contact (e.g., covering dredged sediment that is used as fill with clean soil, asphalt, or structures). Summarized below are chemical stability/sequestration risks associated with each treatment technology category.

S/S is generally expected to sequester contaminants, particularly when tested for leachability prior to use. There is some risk, however, exposure to acidic rain or an altered physical state due to climate conditions could remobilize contaminants immobilized in an S/S matrix (Elghali et al. 2022). The leachability of metals has been evaluated for the initial S/S product (Wang et al. 2015, 2018; Zhang et al. 2020), but the risks of leaching from long-term climatic exposure of S/S products is less well understood.

EKR can increase the bioavailability of metals, which can become mobile through a change in speciation (Tian et al. 2017). That risk can be mitigated by using alternative chemical agents or by combining EKR with other treatments (Tian et al. 2017). Thermal desorption can treat PAHs but can significantly alter the physical/chemical properties and biological characteristics of the sediment, thereby affecting the biological production of plants, microbial populations, and options for beneficial uses after treatment (Bianco et al. 2023).

Ortega-Calvo et al. (2012) review approaches for bioremediation of PAHs by increasing the bioaccessible fraction of PAHs (i.e., the fraction of biodegradable PAHs), while minimizing the potential for environmental risks. Such approaches require monitoring to limit the potential for risks related to residual contamination.

6 SUMMARY AND RECOMMENDATIONS

This review evaluates the recent literature available on (mostly) *ex situ* treatment technologies for dredged contaminated sediments and the subsequent beneficial use of treated sediments. The literature available on *ex situ* treatment technologies spans simple to complex approaches, ranging from sediment washing or S/S to EKR. A common theme throughout the literature is the advantage of using a combined approach of multiple technologies to achieve the highest remediation efficiencies. Sediment management decision-making benefits from consideration of many factors related to selecting treatments and beneficial use applications. Existing decision-making tools and frameworks can help optimize decisions and simultaneously manage costs, remediation time, and future environmental risks.

The literature offers the following recommendations for future research:

- Most investigations of treatment technologies have been conducted at the laboratory- or pilot-scale. Full-scale studies are needed, particularly using field installations that allow adjustment of parameters from laboratory- or pilot-scale studies. Given the heterogeneity of sediment contamination, field-scale investigations will provide valuable information regarding remediation effectiveness and efficiencies, costs, and duration.
- For most technologies, sediment heterogeneity affects treatment effectiveness, efficiency, and timelines and duration. Research is needed to understand how sediment heterogeneity can be managed in the treatment approaches.
- Because individual treatment technologies are unlikely to work in all situations, research is needed on the adaptability of treatment technologies and approaches for beneficial use applications.
- Long-term studies on the stability of treated sediments and/or S/S products are needed. Related topics include durability, costs and/or marketability, legal implications of the S/S product, leachability, and the effects of environmental factors like pH on the integrity of S/S products.
- Additional research is needed on bioremediation approaches (e.g., bioleaching, phytoremediation) to reduce duration of the treatment and improve the effectiveness of contaminant removal.
- Further research is needed to improve the effectiveness of treatment methods, such as sediment washing and chemical extraction, which are limited by the organic fraction and heterogeneity of sediment.
- Additional research is needed on EKR to optimize electrode configurations, characterize the selectivity of contaminants, define the optimal range of operating conditions, and understand the impact of EKR on sediment structure and biota.

- Emerging and novel treatments, like nanotechnologies for PAHs and ionic liquids, are promising but their high costs prevent large-scale applications. Further research is needed in these areas to develop these treatments into practical options.
- Research is needed on factors affecting treatment costs, such as energy consumption, environmental impacts, and carbon emissions, which would be used in any evaluation of economic and environmental costs.
- Optimized decision tool frameworks are needed to help determine the best options for treatments and beneficial uses while considering environmental, economic, and social benefits.
- Most of the literature reviewed for this white paper are studies focused on the testing of specific treatment technologies for *ex situ* contaminated dredged materials. Some studies also address beneficial uses (e.g., S/S) of the treated materials. However, many of the details sought for the database (Appendix A) are not reported, such as costs, project timelines, contaminant concentrations, relevant regulatory thresholds and acceptance, liability transfer, and factors related to the selection of beneficial uses. The lack of information on the full life cycle of projects involving many of the treatment technologies presented herein is a data gap for this topic.

In conclusion, we recommend exploring the opportunities to develop a platform for sharing information about treatment technologies and promote knowledge and data sharing of the salient details noted in the final bullet above including:

- Creating and maintaining a data repository or clearinghouse for data compilation on treatment technologies and beneficial use applications
- Providing broad access to the clearinghouse to allow for easy data entry by project proponents
- Establishing data quality rules to ensure consistency among data entries and to allow meaningful comparisons among projects (i.e., apples-to-apples comparisons)
- Investigating opportunities to partner with permitting agencies to capture project details
- Incentivizing knowledge and/or data sharing through partnerships with practitioners who are implementing current projects.

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Appendix A

Reference Database

Provided separately as Excel file.

Appendix B

Case Studies of Beneficial Use Applications Involving Dredged Contaminated Sediments

Appendix B
Case Studies of Beneficial Use Applications Involving Dredged Contaminated Sediments

Representative case studies were identified from gray literature including reports, documents, and conference proceedings. Targeted searches were conducted focused on this topic on websites including the Environmental Effects & Dredging and Disposal (E2-D2) database[1] and the case studies highlighted by the Central Dredging Association (CEDA).[2] In addition, conference proceedings such as the Battelle International Conference on the Remediation and Management of Contaminated Sediment from 2005 to 2023 were searched for case studies. Some case studies were provided by peer recommendations or practitioners with knowledge of existing projects. Key details including dredged volumes, treatment timelines, contaminant concentrations, and relevant costs are included when available. Case studies identified from the United States are presented first and examples outside of the United States are presented second.

Examples from the United States

PCB-Contaminated Sediment Beneficial Use at the Lower Fox River Superfund Site, Wisconsin (PIANC 2023)

Dredge material generated during the remediation of the Lower Fox River Superfund Site in Wisconsin was beneficially reused for road construction materials in local civil infrastructure projects. The Lower Fox River is located in northeast Wisconsin. Sediment from the site was contaminated with polychlorinated biphenyls (PCBs). The Wisconsin Department of Natural Resources (WI DNR), the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, and local tribal groups oversaw the remediation project, which began in 2004 and was completed in 2020 (WI DNR 2020). Dredged materials were desanded using hydrocyclones, and PCB-contaminated fines were dewatered using membrane filter presses into a filter cake transported to a landfill. More than 760,000 metric tons of dredged materials was de-sanded, generating in excess of 700,000 metric tons of sand that was tested before being beneficially used in local construction projects.

[1] https://e2d2.el.erdc.dren.mil/index.html. Accessed on August 14, 2023.

[2] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies. Accessed on August 16, 2023.

Port of Port Angeles Terminal 3, Washington State (Massingale 2022)

The Port of Port Angeles (Terminal 3) is part of a sediment cleanup site being overseen by the Washington State Department of Ecology (Ecology) through the Model Toxics Control Act (MTCA). Terminal 3 is currently in the remedial investigation and feasibility study phase to support maintenance dredge permitting and design. Dredged materials consisted of silty sand with woody debris and were contaminated with metals and organics (dioxins/furans, polycyclic aromatic hydrocarbons [PAHs], and tributyltin [TBT]). Consequently, they were not suitable for in-water disposal. Dredged material was beneficially used as fill material at the nearby K Ply site. Prior to placement, stockpiles of dredge material were tested for metals and organic contaminants. Those that met Ecology's soil acceptance criteria screening levels were consolidated and retained for beneficial use at the K Ply site. Unsuitable dredge material was amended with cement and underwent synthetic precipitation leaching procedure testing to generate leachate. Cement-amended materials with leachate that met surface water criteria for cadmium, copper, and zinc also were retained for beneficial use at the K Ply site.

Innovative Reuse and Beneficial Use Pilot Project, Cecil and Harford Counties, Maryland (Northgate Environmental Management 2022)

Approximately 1,000 cubic yards of material dredged from the Conowingo Reservoir in October 2021 was dewatered and stockpiled. Concentrations of metals in the dredged material exceeded Maryland's Innovative Reuse screening criteria (Category 1 and 2). Bench-scale testing and an economic evaluation were conducted for multiple beneficial use options, and field demonstrations are underway. The following beneficial uses were evaluated: concrete and asphalt manufacturing, cement clinker manufacturing, blended soil for highway and horticultural applications, supplemental cementitious material, and sediment stabilization with cement or binders. The economic evaluation analyzed potential markets for and revenues from products created from the dredged materials, including concrete, asphalt, cement clinker, supplemental cementitious material, blended soil, fill material for shoreline protection or restoration, and stabilized sediment for engineered fill, brick, and paver manufacturing. Gross revenue potential calculated for each product under six scenarios based on volume dredged (from 1 million to 5 million cubic yards) ranged from less than $1 million USD to more than $50 million USD.

Use of Contaminated Materials in Pavement Construction Refrigerated Container Facility, Port of San Diego, California (Stewart and Redmon 2004)

Contaminated materials excavated for a redevelopment project at the Tenth Avenue Marine Terminal in the Port of San Diego were treated using cement-based technologies. A cement treated base incorporated the contaminated materials, reclaimed asphalt/base mixture from demolition of onsite pavement, and 7 percent Portland cement. The excavated quantities ranged up to 38,000 cubic meters, more than 50 percent of which was treated and used onsite with only 11,000 cubic meters requiring offsite disposal. The savings associated with reduced disposal costs ranged from $3 million to $4.5 million.

Pilot Study on the Pneumatic Flow Tube Mixing (PFTM) Method for Stabilization and Solidification, New Jersey[3] (CEDA 2023)

Approximately 3,928 cubic meters of dredged materials form the New York/New Jersey Harbor with elevated concentrations of PAHs and metals were used in a pilot study in 2015 to test the pneumatic flow tube mixing (PFTM) method application. The PFTM technology allows for rapid conversion of dredged materials into stable mixtures to be used in construction or as fill. Following 28 days, the materials amended with 8 percent cement content was deemed acceptable in terms of strength and leachability of contaminants. Arsenic was the only contaminant detected and the majority (75–80 percent depending on percentage of cement content) was determined to be bound in the cement mix.

Pilot Test of Cement-Lock Technology, Lower Passaic River, New Jersey[4] (CEDA 2023)

A pilot test involving 500 cubic meters of dredged materials contaminated with dioxin/furans, PAHs, pesticides, and metals from the Lower Passaic River was conducted in 2005 to 2007 in a demonstration plant to create a product, Ecomelt. Treatment technologies employed with this approach include thermal treatment of dewatered sediment combined with modifiers specific to Ecomelt. The thermal treatment was reported to be successful at eliminating organic contaminants and immobilizing metals.

Examples from Outside the United States

Treatment of Dredged Materials for Incorporation into a Concrete Bicycle Path, Tournai, Belgium[5] (CEDA 2023)

A pilot-scale study, commenced in 2020, involved the treatment of approximately 16 tons of metals-contaminated sediment in Tournai (Walloon Region, Belgium) in preparation to use the materials in concrete slab for a bicycle path. The treatment entailed the deagglomeration of the dredged materials using a succession of sieving and grinding with roll crushers. A total of 13.5 tons of fine-particle material was recovered for use in the concrete formulation. Treatment costs were estimated at approximately 10.7 euros/ton.

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[3] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies/19/Use%20in%20civil%20and%20environmental%20applications
[4] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies/9/Production%20of%20grade%20cement
[5] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies/64/Preparation%20of%2013.5%20tons%20of%20sediment%20for%20incorporation%20into%20a%20concrete%20bicycle%20path

Dredge Sediments for Concrete Blocks for Jetties, Dunkirk, France[6] (CEDA 2023)

Dredged materials (approximately 440 cubic meters) from channel and dock areas in the Port of Dunkirk with elevated concentrations of organic and metal contaminants were pretreated with calcium sulfoaluminate clinker-based binders followed by fabrication into concrete blocks. The blocks were used for breakwater revetment materials in the eastern part of Dunkirk Harbor in 2014.

Phytoremediation Case Study, Livorno, Italy (PIANC 2023)

As part of the European Agriport (ECO/08/239065) project, a phytoremediation pilot study was conducted on approximately 80 cubic meters of sediment dredged from the port in Livorno, Italy. The dredged materials had a high silt clay fraction, high salinity, moderate concentrations of metals, and moderate concentrations of organic compounds. The dredged materials were mixed with sandy soil (30 percent) and topped with a layer of compost to promote plant adaptation and growth. The following plant species were selected for testing based on their drought- and salinity-tolerance: *Paspalum vaginatum* (a perennial grass), *P. vaginatum* and *Spartium junceum* (rush broom), and *P. vaginatum* and *Tamarix gallica* (French tamarisk). These plant species were planted in the dredged material-soil mixture. Monitoring conducted over 2 years involved collection of samples of the amended sediment from depths of 0–20 cm and 20–40 cm, followed by chemical and biochemical analyses. The pilot study demonstrated that the plants reduced concentrations of total petroleum hydrocarbons and metals by approximately 50 and 20 percent, respectively. The cost of the approach was less than half that of landfill disposal. The decontaminated soils generated were used in horticulture, while plants with sorbed contaminants were disposed in a landfill.

Jätkäsaari Port Redevelopment, Helsinki, Finland (PIANC 2023)

The Jätkäsaari Port Redevelopment project was initiated following the completion of the Vuosaari Harbour project in 2008. Redevelopment of the port produced contaminated dredged materials that were treated through stabilization/solidification and then beneficially used as fill material to create natural spaces and other earthen structures. The dredged materials had chemical contamination, high water content, and low strength. Therefore, the objective of the stabilization project was to bind contaminants into the clay materials and render them inert and to create a useable fill with appropriate engineering characteristics for applications within the Jätkäsaari development. The Port of Helsinki managed the project, engaged with the public, and obtained all required permits for planning, execution, and environmental monitoring of the port expansion project. Work was conducted from 2010 to 2016.

[6] https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies/30/Use%20in%20breakwater%20components

Utilization of Alternative Materials in the Harbour Constructions in Helsinki, Finland (Havukainen and Forsman 2018)

TBT-contaminated surface sediment was dredged from Vuosaari Harbour in Helsinki, Finland, from January 2003 through the end of 2008. Approximately 1 million cubic meters of soft clay and metals-contaminated dredged materials were beneficially used as structural fill material. Column and mass stabilization techniques were used to improve the bearing capacity and stability of the fill material. Samples were collected throughout the project for geotechnical planning and monitoring. Compared to alternative disposal methods, the cost of constructing an obligatory noise barrier was reduced by approximately 3 million euros.

Port of Kokkola, Finland (Bell 2023)

A pilot study was conducted on dredging and stabilization of contaminated sediments in the Silverstone (Hopeakivi) Port area in Kokkola, Finland. The pilot study was conducted in 2011 and was part of the Sustainable Management of Contaminated Sediments project. The volume of dredged materials was approximately 12,500 cubic meters and materials used for binding included 0–30 kg per cubic meter of rapid cement and 100–200 kg per cubic meter of fly ash. Drilling tests were conducted in 2012 to monitor shear strength, which exceeded the target value. Other testing of the geotechnical properties of stabilized material included strength, development of strength over time, water permeability, and environmental suitability.

Treatment of and Reuse of Dredged Material, Port of Poole, United Kingdom (Bell 2023, pers. comm.)

The construction of a sheet pile wall in a quay extension of the Port of Poole in June 2013 required removal of contaminated sediment (the specific contaminants were not reported). Approximately 2,000 cubic meters of dredged material was treated with mass stabilization methods to immobilize contaminants into an insoluble form. The process of mass stabilization was implemented onsite over a 7-day period. The stabilized materials were used onsite to reinforce the shoreline area between the sheet pile wall and the old quay.

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