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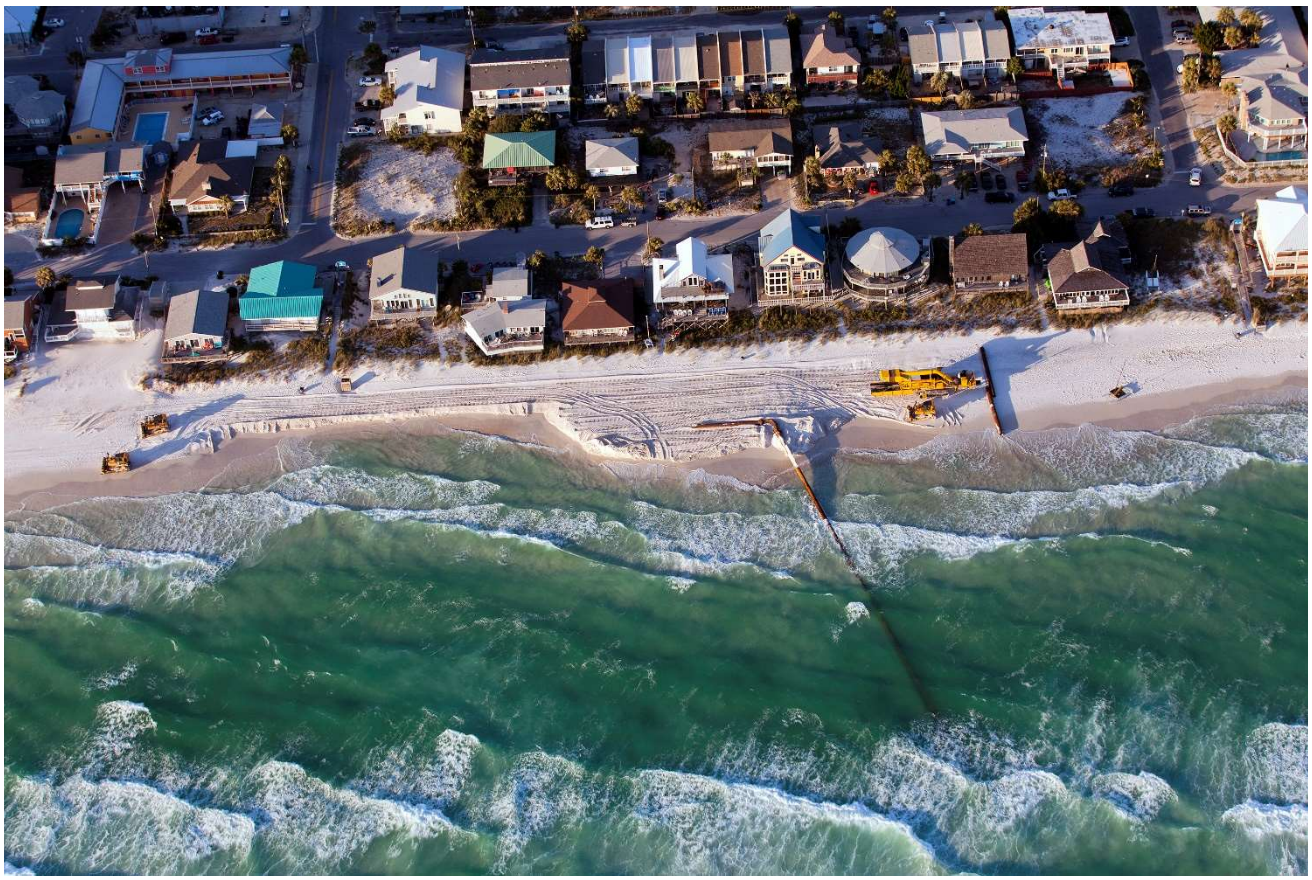

Beach nourishment at Dewey Beach, DE. Photo courtesy of Weeks Marine, Inc.

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CONTENTS

EDITOR'S NOTE

This issue of WEDA's Journal of Dredging includes two excellent manuscripts. The first manuscript comes from colleagues at Texas A&M University with a graduate student as the primary author. This manuscript synthesizes available design guidance and best practices associated with Confined Aquatic Disposal (CAD). The second manuscript is an expansion of a paper presented by Andrew McQueen at the 2023 Dredging Summit and Expo. It describes an example of using EWN best practices to manage dredged material sustainably. This specific project focused on the Ohio and Kanawha Rivers, but the lessons learned apply broadly.

I hope that you enjoy this issue as much as I have pulling it together. Many thanks to our dedicated authors for their excellent manuscripts. I hope that you will consider submitting one yourself! Please contact me if you have any questions about the submission and review process for the Journal of Dredging.

Don Hayes
Editor, WEDA Journal of Dredging
January 2024

REVIEW OF DESIGN GUIDANCE AND PAST PRACTICES OF CONFINED AQUATIC PLACEMENT WITHIN UNITED STATES HARBORS AND ESTUARIES

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ABSTRACT

Confined aquatic placement (CAP), also called confined aquatic disposal (CAD) is a method of subaqueous confinement of mildly to moderately contaminated dredged material (CDM). Since the early 2000s, CAP has become a popular method of addressing CDM as it provides a good balance between cost, logistics, regulatory acceptance, public perception, and environmental risk, compared to other placement or disposal alternatives (Fredette 2006). However, there has not been a formal review of their long-term performance or any focused and comprehensive design guidance that a practitioner can rely upon. This paper attempts to rectify that situation and provides an overview of CAP, summarizing the available guidance documents, policy, current design and construction practices, and experiences with performance. Six CAP projects within the United States were analyzed to determine variability in design, local regulatory criteria, trends by region, and monitoring protocols. Finally, recommendations are made for future guidance documents and standards to address missing data gaps in the design and monitoring of CAP cells.

Keywords: confined aquatic disposal (CAD), contaminated dredged material (CDM), engineering design, guidance, monitoring, sediments, contaminated, capping, case studies

INTRODUCTION

Every year, several hundred million cubic meters of material are dredged from United States ports, harbors, and waterways (USEPA and USACE 2004). Often, much of this sediment is determined to be “clean,” and many efforts are employed to use this sediment beneficially, such as for beach nourishment, shore protection, or wetland enhancement. However, in cases where the dredged material is found to be contaminated, it is deemed unsuitable for conventional open water placement or beneficial use and must be placed in a dedicated confined disposal facility.

There are several different containment options for the placement of contaminated dredged material (CDM), illustrated in Figure 1. Upland placement facilities such as landfills and upland confined disposal facilities (CDFs) have historically been popular options. However, these areas

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are becoming limited, with costs increasing for new site locations and existing facilities reaching capacity in many urban locations (Hales 2001). Because of this, confined placement areas and facilities located nearshore or within harbors, bays, and waterways—such as nearshore or island CDF; confined aquatic placement (CAP), also known as confined aquatic disposal (CAD); and level bottom capping (LBC)—have become popular methods of dealing with contaminated sediment. Note that LBC implies placement of CDM over existing bottom sediments and then placing a clean cap, which may then be subject to varying levels of consolidation (depending on sediment type and loading) over time.

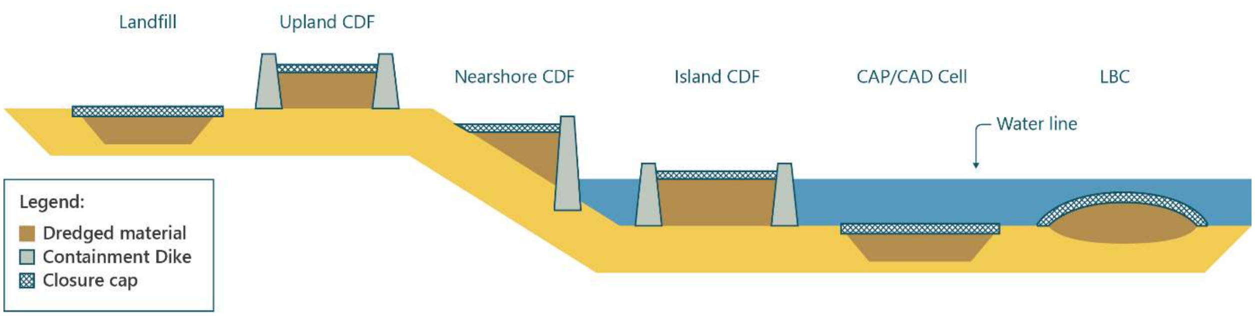

Figure 1. Containment options for managing contaminated sediments (adapted from Mohan 2021 and USACE 2015).

The four main types of sediment management facilities are as follows (Porebski and Vogt 2010):

1. **Nearshore Confined Disposal Facility:** A constructed disposal site with dikes or containment structures in the water, with the shoreline acting as another lateral containment feature. For instance, they are often used to create new land for alternative use, e.g., airports and port facilities.
2. **Island Confined Disposal Facility:** A containment facility in open water, similar to a nearshore CDF; however, it is not connected to the shoreline. Refer to Mohan et al. (2010) for more information on CDFs.
3. **Level Bottom Capping:** The placement of a mound of CDM on the sea floor capped with clean material to isolate the CDM from the surrounding aquatic environment.
4. **Confined Aquatic Placement:** A method of subaqueous confinement for mildly to moderately contaminated dredged sediment unsuitable for open-water placement or for a beneficial use project. CAP differs from LBC because cells generally end up with a final capped surface in line with or below the surrounding sea floor. CAP cells are usually sited near dredging activities or within harbors or navigation channels and are constructed from engineered pits, borrow sites from mining activities, or natural depressions (Fredette 2006). Once the contaminated sediment has been placed, the cell may then be capped with "clean" sediment to isolate contaminants from the surrounding aquatic environment. A simplified construction sequence for a CAP cell, including excavation, placement, and capping, is given in Figure 2.

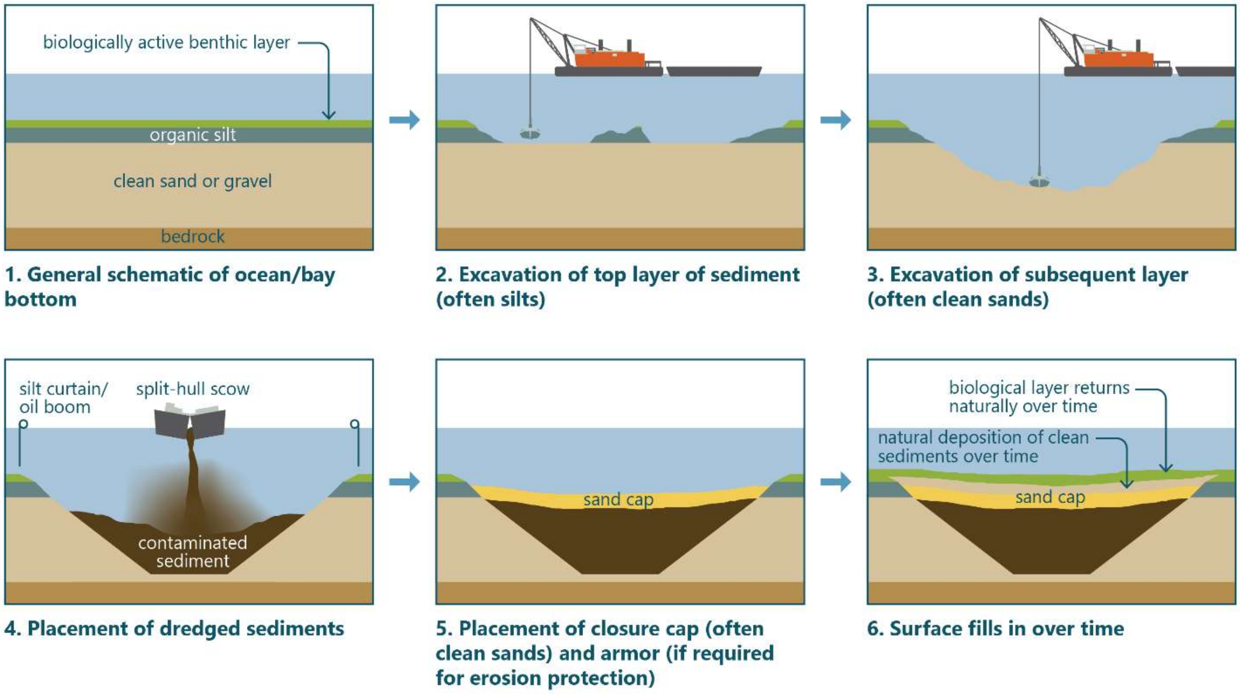

Figure 2. Construction sequence of a CAP cell, including excavation, placement, and capping (modified from USEPA 2020).

Since the early 2000s, CAP projects have become a popular method for placing contaminated sediments from dredging activities, as this method provides a good balance between cost, logistics, regulatory acceptance, public perception, and environmental risk, compared to other placement or disposal alternatives (Fredette 2006).

CAP has also been constructed within navigation channels as an economical means to place CDM (see Alfageme et al. 2002; Fredette et al. 2002). However, such sub-channel placement configurations of CAPs are mostly single-use facilities. Once the cells are filled, they are capped, and the channel is maintained at an elevation above the top of the cap. This minimum maintenance elevation above the cap often includes a factor of safety allowance so that future dredging events do not interfere with the final closure cap of the CAP cell.

CURRENT GUIDANCE AND POLICY

Most available guidance on CAP design in the United States comes from the U.S. Army Corps of Engineers (USACE) and the U.S. Environmental Protection Agency (USEPA) between the 1990s and 2000s. The USACE developed a comprehensive design guidance—*Guidance for Subaqueous Dredged Material Capping* (Palermo et al. 1998a)—based on a series of technical notes documented by the USACE that included site selection, capping design, capping placement, and monitoring (Palermo 1991a, 1991b, and 1991c; Palermo et al. 1992; Palermo and Reible 2007). Another USACE Engineer Research and Development Center (ERDC) technical note published in 2000 outlined the geotechnical design guidance for CAP cells (Rollings 2000). In addition to this, the USEPA funded the development of a report detailing the design and evaluation of in situ capping projects (Palermo et al. 1998b), which have been adopted in the report *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (USEPA 2005).

Mohan et al. (2000) presented theoretical considerations for capping design involving the use of hydraulic, chemical, and geotechnical engineering principles. This included the use of design equations to deal with a range of factors covering consolidation, chemical diffusion, current flow, and wave forces, propwash forces, ice scour, and other key design parameters.

It becomes apparent that there is no single comprehensive guidance or “go-to” manual on how to site or design CAPs. Often, reference to multiple guidance documents for various elements is required, and sometimes the guidance can be confusing or even contradictory (guidance for capping layer thickness, structure, and composition varies). This paper summarizes relevant items critical for CAP and provides cross references for further details.

Regulatory Approvals

Evaluation of CAP projects and their alternatives within the United States is broken up into federal, state, and local regulatory approvals. At a federal level, permitting for aquatic disposal of sediment will require reviews by the USACE and the USEPA and usually falls under the Clean Water Act (CWA), which regulates navigable inland waterways within the United States, including rivers, harbors, estuaries, and bays. Other federal acts that have been applicable to previous CAP cell projects include the National Environmental Policy Act (NEPA); the Marine Protection, Research, and Sanctuaries Act; the Endangered Species Act (ESA); and the National Historic Preservation Act (NHPA). Under Section 401 of the CWA, federal agencies may not issue a permit for activities that may result in any discharge into the waters of the US unless a water quality certification is issued or waived. Section 401 water quality certifications are generally issued by the State from which the discharge originates. A joint-permit processing meeting is often a good step to arrange a single meeting with all relevant regulatory agencies (federal, state, and local) so that project feedback and requirements can be efficiently gathered. Note that CAP projects usually require environmental impact statements (EIS) and sometimes environmental assessment (EA) studies to demonstrate that there are no unacceptable adverse effects on aquatic and benthic species habitats in the area.

SITING FACTORS

There are a variety of physical, hydrodynamic, chemical, biological, economic, and regulatory factors to consider when siting a new CAP cell. Some general siting conditions for CAPs are as follows (Palermo et al. 1998a, 1998b; 1998c; Fredette 2006; Mohan et al. 2010):

- **Site Geometry:** Available volumetric capacity of a potential CAP cell is largely determined by the geometry of the cell in which contaminated sediment is to be placed. Geometry is determined by the size of the pre-existing depression (constructed or natural) or by available space designated for an engineered pit and the depth to which the pit can be dredged.

- **Bottom Slope:** The bathymetry of the bed plays an important role because cells should ideally be placed on flat or mildly sloping beds. Excessive bottom slopes could adversely affect the possible storage capacity for a given surface area of the CAP cell (assuming pits would fill level). Also, larger slopes add a gravity component that can influence the lateral movement of placed sediment.
- **Water Depth:** Larger water depths generally provide more stable conditions near the placement site, as erosive forces from wave action and vessel movement are significantly reduced. However, sites that are too deep can lead to higher dispersion during placement and higher levels of water entrainment into the sediment matrix. There is also an increased expense and degree of difficulty when dredging, placing, and monitoring sites at larger water depths. Dispersion during material placement can be simulated using USACE models such as STFATE and MDFATE (USACE 2022b).
- **Hydrodynamic Conditions:** Bottom velocities due to waves and currents provide erosive shear forces that can displace material. Sites that are open to swell waves or have large fetches over which significant wind waves can form are likely to experience high wave activity and, therefore, greater energy near the bed. Other areas exposed to high tidal, or river flows may also experience elevated energy levels. These areas should be avoided where possible; otherwise, armoring of the capping layer may be required.
- **Vessel Traffic:** Substantial bottom shear can occur with both wake and propeller wash from vessel traffic. Detailed analysis of erosion potential is required for areas that experience significant vessel traffic, like ports and dedicated shipping channels, frequent bottom trawling, fishing, or other activities that may impact the seabed.
- **Distance from Dredging Area:** The CAP cell should ideally be located as close as possible to the dredging area. This includes proximity to the source location for the clean cap material. As the distance increases, so do transport costs.
- **Sediment Characteristics:** Geotechnical considerations of CAP cells will be required to estimate the potential consolidation effects that may be experienced once CAP fill and capping material have been placed. Consolidation may also increase site capacity in the long term and needs to be considered during design. Consolidation rates should be considered when determining the timing of a final capping layer over the cell or the possibility for staged placement of contaminated sediment. Refer to USACE (2000) for specific geotechnical design guidance for CAPs.
- **In-Place Contaminants:** Sites should avoid areas of already-contaminated sediment, especially where an engineered pit is to be dredged. If such sites are chosen, additional steps to manage the excavated in situ contaminated sediments will be required, or additional capacity will need to be developed in the cells (i.e., increased pit depth) to accommodate such material prior to capping with clean sediments.
- **Water Quality:** Sites should have minimal impact on dissolved oxygen, turbidity, salinity, temperature, and other water quality parameters when sites are being constructed, filled, or capped. After capping (or filling if no capping is to be conducted), sites should avoid leakage that could cause any aquatic impacts listed above.
- **Aquatic Habitat and Species:** Preferred sites minimize disturbance of aquatic habitats, fish, submerged aquatic vegetation, or otherwise sensitive resources. This often requires studies (such as EIS and EA) and close coordination with resource (regulatory) agencies.

- **Cultural Resources:** The presence of cultural resources or resources with known historic or archeological value should be investigated on a case-specific basis during siting. Documented cultural resources can be managed in a variety of ways, depending on the nature of the resource. These resources should first be mapped and surveyed to define the nature and extent of the resource area, followed by discussions with appropriate regulatory agencies and stakeholders (such as tribes or stewards) to determine if protection or retrieval of artifacts is required or if they can be buried in place to conserve them in situ.
- **Infrastructure:** Sites should allow for existing buffer areas to infrastructure, such as piers, bridges, tunnels, and pipelines.
- **Shore-Based Effects:** Potential impacts to groundwater or other shore-based impacts (such as those to aquifers, shorelines, and banks) should be considered.

Siting is often an iterative exercise requiring geographical information system (GIS)-based analysis, where graphical representations of data layers for various criteria are evaluated visually for a subset of potential sites prior to selection of the final candidate site.

DESIGN CRITERIA

Once a potential location for a CAP cell has been selected, specific evaluations are needed to design the cell and to develop construction, operation, and monitoring plans.

Figure 3 shows a flowchart specifically developed for CAP cell design. It is a modified version of similar flowcharts from previous design guidance for capping projects (Palermo et al. 1998a; Mohan et al. 2010). The figure displays a sequence of tasks to consider before the construction of a CAP cell. The tasks can be grouped into four main design steps: (1) define project objectives, (2) cell placement, (3) cell sizing, and (4) development of a monitoring program to assess project success. Note that most of these steps are applicable for other types of CDM management methods as well and will require case-by-case evaluation.

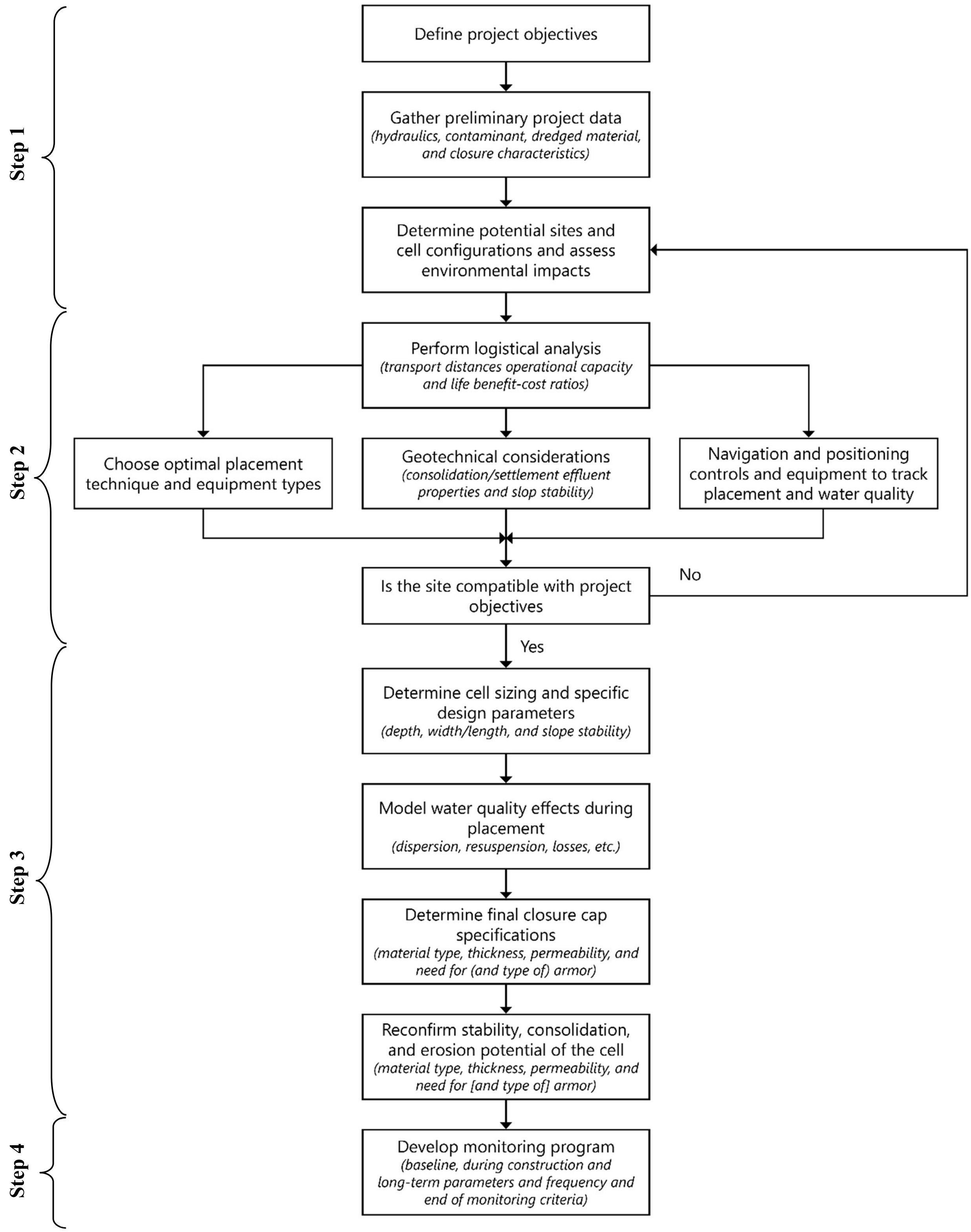

Figure 3. Considerations for CAP cell design and monitoring (modified from Mohan et al. 2010; Palermo et al. 1998a).

Alongside the design flowchart in Figure 3, the following key design considerations need to be addressed (ECCC 2021; Mohan et al. 2010; Palermo et al. 1998a, 1999). Numbers shown for each design consideration correspond to the respective step shown in the flowchart in Figure 3.

- **Design Objectives (Step 1):** The overall design objective should introduce the required features to be designed for the project and include operational aspects of the site, such as operating capacity and site life. In addition, acceptable discharge limits for contaminants need to be stated alongside any other project goals.
- **Operating Capacity (Steps 1, 2):** This refers to the total capacity available at the site to place dredged material, often expressed in cubic yards. This may or may not include a final closure cap. For clarity, the volume required for the final cap must be explicitly stated so that the net dredged material placement capacity is clear. For constructed CAP cells, additional factors should be considered such as dredging depth limitations, depth to bedrock, excavated slope stability, and geometry and orientation of the cell footprint.
- **Site Life (Step 1):** This refers to the total operating years over which CDM can be placed in the CAP site. For single-use CAP cells, the site life would normally be limited to one dredging season. For CAP cells designed for long-term use, interim caps may be required and should be considered in determining site capacity and life.
- **Hydrodynamic Analysis (Step 2):** An assessment of dynamic forcing conditions that could exist at the CAP site induced by circulation patterns and currents or waves during normal conditions as well as during storms. Analysis should involve numerical or empirical hydrodynamic modeling of the site conditions to quantify any erosive forces that may impact the CAP cell, including those induced by propeller wash, waves, and currents. In some cases, sediment transport dynamics resulting from the hydrodynamic forcing may also need to be computed to determine potential impacts of erosion and sedimentation patterns that could develop at the CAP site.
- **Geotechnical Analysis (Step 2):** Contaminated sediments are often primarily fine-grained, characterized by high in situ water contents and relatively low shear strengths. The dredging and placement process reduces the shear strength further since sediments are removed from their original location and reworked in the process. The geotechnical properties (water content, Atterberg limits, strength, and bearing capacity) of the sediments determine the maximum attainable slope of the CAP cell content, which can be a limiting factor for cell depth and capacity.
- **Placement Effects (Steps 2, 3):** CDM and final capping material should be placed in a controlled manner, regardless of placement technique and equipment used. The possible spreading of contaminants during placement (and any potential for off-site releases) should be evaluated and conform with water quality criteria. Changes in volume from in-situ channel conditions prior to dredging as compared to volume occupied during the cell filling and in the long term are also important factors in the evaluation of initial and long-term capacity. These changes in volume are dependent on the physical properties of the CDM and the method used for dredging the CDM. Once CDM has been placed, consolidation of material is likely to occur (as a function of dredged material and native sediment properties as well as lift thicknesses) and can be evaluated using tools such as the USACE PSDDF (Primary Consolidation, Secondary Compression, and Desiccation of Dredged Fill) model to determine the total capacity of the cell. Operational methods to improve sediment

consolidation and strength (such as thinner lifts of CDM placement or providing time for some settlement to occur between subsequent lifts) should be incorporated into the site operations plan to maximize cell operational capacity and site life. Placement of a capping layer over contaminated material can lead to further consolidation and mixing of the layers. This needs to be accounted for in the design as well.

- **Environmental Impact (Steps 1, 2, 3, 4):** While siting, any impacts to sensitive ocean or bay bottom environments (such as oyster beds, submerged aquatic vegetation, or essential fish habitat) must be identified, potential impacts assessed (via studies such as EA or EIS), and, if necessary, mitigation protocols developed. Further, during construction and placement, diffusion of contaminants through the water column should be mitigated and confirmed to be in line with relevant water quality criteria (often stipulated in permits). Finally, contaminant pathways within the CAP cell should be evaluated, and suitable mitigation measures should be incorporated into the design.
- **Closure Cap Design (Step 3):** Once CDM is placed, the CAP cell should receive a final closure cap to isolate the contaminants in the CDM from the surrounding environment. The design of the final protective cap is largely dependent on the site conditions, including dredged material (type, consistency, geotechnical behavior), hydrodynamics (waves, currents, circulation), and chemical dynamics (contaminant pathways, dispersion and diffusion, and other potential migration pathways). The bearing capacity of the placed CDM is a critical factor in the timing of cap placement and the ability to place the required cap material thickness(s). The cap must be designed to effectively isolate the contaminant from the surrounding aquatic environment. In some specific cases, capping of the cell may not be required if erosive forcing is low and dispersion of contaminants is determined to be negligible. Figure 4 shows a general cross-section of a closure cap design for CAP cells, including all features that may be used to provide protection against chemical diffusion, dispersion, and hydrodynamic/erosive forces. The design of the final cap configuration should consider site-specific hydrodynamic conditions, contaminant type and concentration, the volume of dredged material placed, geotechnical conditions (especially bearing capacity and slope stability), and construction feasibility. The inclusion of all these features is likely not necessary for all CAP projects, while some projects may need the inclusion of additional elements. These additional elements may include a geotextile layer if the foundation material is too soft, or soil amendments such as organoclay or activated carbon pellets if the placed CDM has high levels of polycyclic aromatic hydrocarbons (PAHs) and nonaqueous phase liquids (NAPL).

- **Monitoring (Step 4):** Various types of monitoring are required for CAP cells. First, baseline monitoring is recommended to document ambient site conditions (e.g., total suspended solids, dissolved oxygen, benthic characteristics) and allow for comparisons between pre- and post-CAP construction values. Subsequently, a monitoring program during construction is recommended. This is typically dictated by permit conditions and may include water quality indicators (e.g., total suspended solids, turbidity, dissolved phase constituents), periodic bathymetric surveys, lift thickness measurements, and volumetric tracking (to document volume of dredged material placed). Finally, a long-term monitoring program should be designed to verify that the CDM (and associated contaminants) have been effectively isolated from the surrounding environment. Long-term monitoring may include periodic bathymetric surveys, consolidation assessments, sediment coring, benthic analysis, and water quality testing. Monitoring thresholds should be predetermined along with managerial actions to be taken, if deemed necessary. These actions could include an increase in monitoring frequency, the implementation of control measures specific to the issue, or discontinued use of the site. For more than 40 years, the Disposal Areas Monitoring System (DAMOS) program has been managing and monitoring aquatic disposal sites from the Long Island Sound to Maine (USACE 2022a). Projects under DAMOS generally include well documented construction and monitoring programs, which can help determine the success of CAP projects. The Canadian Government has outlined long-term monitoring for general contaminated sediment sites under the Federal Contaminated Sites Action Plan (FCSAP) as well as in their contaminated sediment management guidance (ECCC 2021, 2022). The FCSAP states that long term monitoring should be conducted to verify that all project objectives will be met for the life of the design, with monitoring terminated once this has been verified.

  Monitoring will be site- and project-specific and should:
  - Have clear relevance to the project objectives.
  - Be transparent, repeatable, and technically sound.
  - Be integrative and comparable with similar projects regionally.
  - Be agreed upon by all stakeholders.
  - Be conducted by qualified professionals.

  Note that monitoring criteria and time frame are often site-specific and developed through collaborative discussions between the project owner, designer, regulatory agencies, and stakeholders. Generally, a minimum of 5 years of monitoring is required, with some sites requiring much longer time frames (such as 15 to 30 years) due to specific regulatory agency requirements.

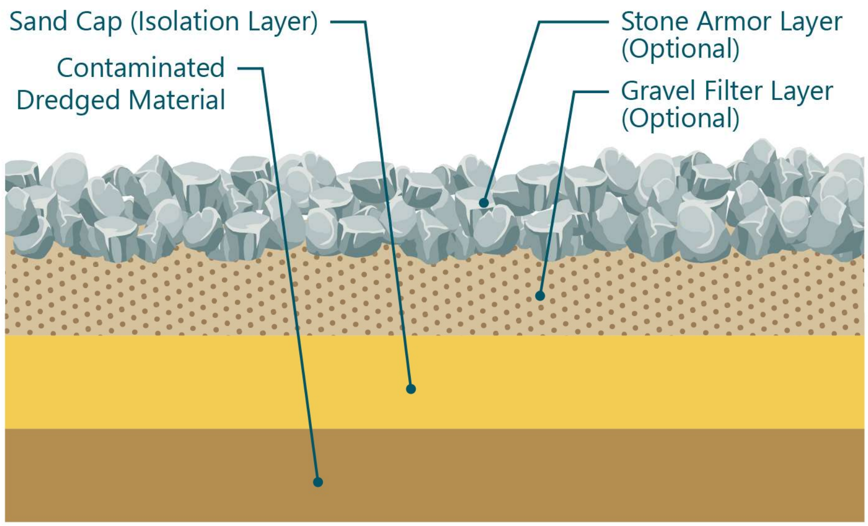

Figure 4. General schematic of closure cap for CAP cells (Mohan et al. 2000).

REVIEW OF CASE STUDIES

Six CAP projects (A through F) around the United States were reviewed from readily available literature and websites (USACE and MPA 1995; USEPA 2000; USACE 2008; Cappellino et al. 2009; U.S. Navy 2014; Beaver et al. 2017; Olsen et al. 2019; Anchor QEA 2021). These case studies are summarized in Table 1 and discussed in more detail below to highlight their features, any design guidance, modeling efforts, postconstruction monitoring, and lessons learnt for each.

Table 1. Summary of select CAP sites used for contaminated sediment management.

Name and location	Capacity	Water depth[1]	Final cap material and thickness	Monitoring
A: Port Hueneme, California	240,000 m^3	-10.7 m (MLLW)	3-m-thick sand cap with 1-m-thick rock armor layer	Sediment and porewater samples collected at 3 months, 1- and 5-years post-construction
Key features/comments: Clean sediments from CAP excavation used for nearby beach nourishment project. Conservative closure cap design due to regulatory agency preferences and to accommodate deepening of the harbor in the future.				
B: Baltimore Harbor, Maryland	47,400 m^3	N/A	N/A	Water quality and nutrient monitoring during construction. 2-year staged bathymetric survey monitoring post construction.
Key features/comments: Hydrodynamic modeling and geotechnical sampling used to inform CAP design. Unique challenges working in a high-traffic environment.				

Name and location	Capacity	Water depth[1]	Final cap material and thickness	Monitoring
C: Boston Harbor, Massachusetts	800,000 m^3	-14.8 m (MLLW)	1-m-thick sand layer	Detailed monitoring throughout project led to continual modifications of cell filling and capping operations.
Key features/comments: Multistage project with 11 individual CAP cells. Initial bearing-capacity failures observed over soft sediments, which led to modifications in closure cap and low-energy placement techniques.				
D: Providence River and Harbor, Rhode Island	900,000 m^3	-12 m (MLLW)	Uncapped (site is currently open for placement)	Bathymetric and biological monitoring of the site at 5-year intervals.
Key features/comments: Six CAP cells constructed in 2003/2004. Cells remain uncapped and are still being used as placement areas for state and private dredging. Detailed monitoring of benthic communities indicated that the biological community around the CAP cells had rebounded, leading to recommendations that capping of the cells may not be necessary.				
E: Puget Sound, Washington	300,000 m^3	-10 m (MLLW)	1.8-m-thick sand layer	Monitored at 2- to 3-year intervals including sediment and water sampling and sub-bottom profiling.
Key features/comments: One main CAP cell as part of wider marine sediment control plan. Postconstruction analysis found contaminants near CAP edges. A 30-m-wide, 0.6-m-thick "strip" of clean sediment was placed around the edges of the site to address this issue.				
F: Newport Harbor and Lower Newport Bay, California	120,000 m^3	-4 m (MLLW)	0.3-m-thick interim sand layer and 1-m-thick final sand cap	N/A[2]
Key features/comments: Two-stage construction, for both federal channel material and material from surrounding harbor.				

Notes:
1 – Water depth above finished cap level.
2 – Project not constructed at the time of writing.
m: meter; m^3: cubic meter; MLLW: mean lower low water; N/A: not applicable or no data available.

A. Port Hueneme, California

Port Hueneme is situated approximately 97 kilometers (60 miles) northwest of Los Angeles, California, and serves as the only deep-water port between Los Angeles and San Francisco. A CAP cell was constructed between December 2008 and July 2009 (Figure 5). The overall goal for the project was to remove and dispose of contaminated sediments within Port Hueneme in an environmentally safe and cost-effective manner. Contaminated sediment was deemed unsuitable for open-ocean disposal or beach nourishment. The cost and environmental effects of dredging, dewatering, transporting, and disposing of contaminated sediments in an upland landfill were found to be excessive. Therefore, the construction of a CAP facility was selected as the best alternative for an on-site sediment management option.

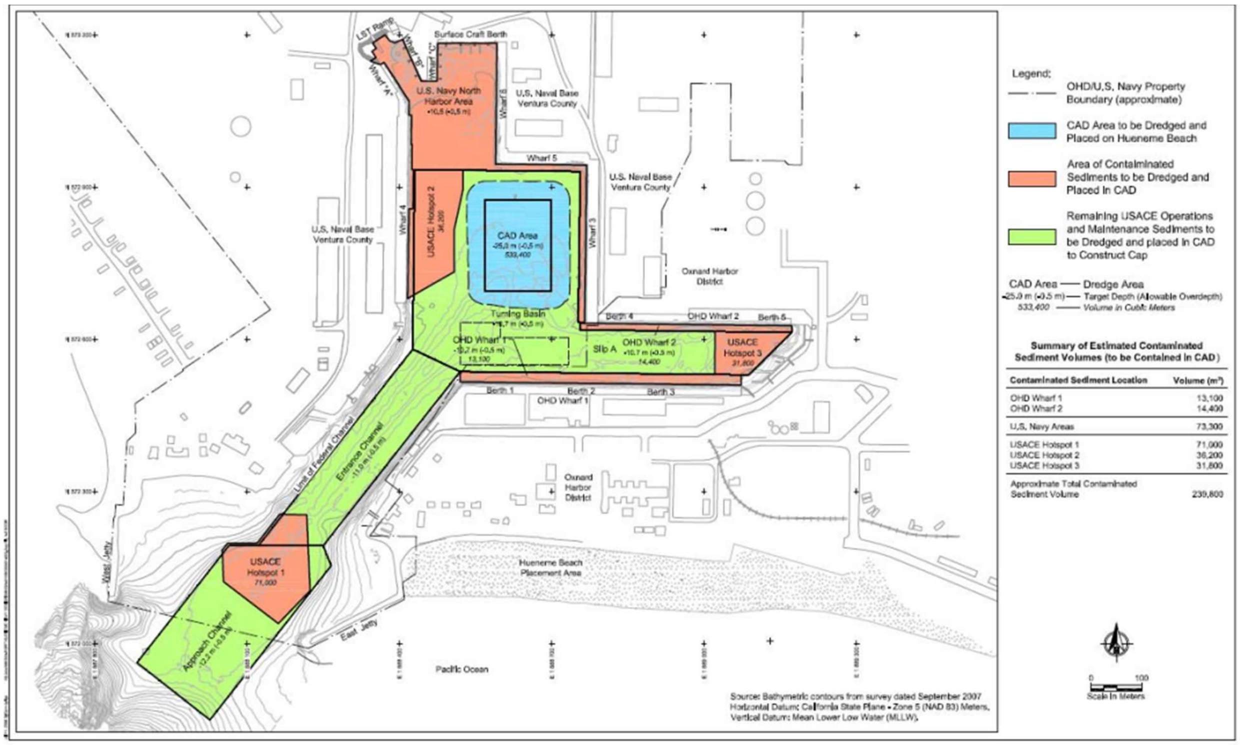

Figure 5. Project area of Port Hueneme CAP cell (blue) (Cappellino et al. 2009).

The CAP cell within Port Hueneme was constructed to a depth of -26 meters (m; -85 feet) MLLW (approximately 15 m or 49 feet below the sediment bed) with side slopes of 1:2.5. The cell was built with a clearance of 30 m (98 feet) from existing structures within the Port and did not overlap with any known areas of contaminated sediment. The total capacity of the cell was 240,000 m^3 (313,908 cubic yards [cy]), which included 5% contingency beyond expected dredging volumes. The CDM was dredged mechanically from the surrounding area with barge placement of the CDM into the CAP cell. Water quality modeling was conducted to ensure that placement would have a negligible effect on total suspended sediment concentration, except for brief periods near the cell, in the immediate proximity of the placement event.

A 3-m sand cap was placed on top of the contaminated sediment with an additional 1-m (3.3-feet) layer of rock armor. Armor rock was favored in design as scour analysis indicated that propeller wash from large Navy ships could cause significant scour at very low tides. This conservative approach to the capping design was chosen to ensure that regulatory approval was met and to provide a buffer for potential channel-deepening projects in the future. Modeling was undertaken to determine slope stability, chemical diffusion through the cap, water quality during and after placement, and cap stability considering hydrodynamic forcing.

Sediment and porewater samples were collected at 3 months, one year and 5 years post-construction to determine chemical migration through the capping layer. Results of monitoring concluded that the cap had been maintained and chemical containment had been achieved. A 2019 memorandum from the Port stated that the CAP cell was functioning as intended and was stable. Notable regulatory acts include the California Environmental Quality Act (CEQA), NEPA, ESA, and NHPA Section 106.

B. Baltimore Harbor, Maryland

Baltimore Harbor is situated along the Patapsco River within the city of Baltimore, Maryland. Due to its deep draft, location, and port infrastructure, it is one of the busiest ports on the East Coast, with heavy shipping container traffic. Annually, the Baltimore Harbor undergoes maintenance dredging of up to 1.2 million m^3 (1.57 million cy), with legislation requiring the harbor to beneficially and innovatively reuse or confine material. Due to the substantial amount of dredging required, less expensive options are exhausted and existing placement areas are becoming limited in capacity. In 2017, a CAP pilot study was conducted as part of the dredging management efforts within Baltimore Harbor to relieve pressure on existing dredged material containment facilities and to provide an additional option for dredged material management (Olsen et al. 2019).

The pilot CAP cell was constructed between berths near the Fairfield Marine Terminal, with a capacity of 47,400 m^3 (61,997 cy) to account for the volume of contaminated material dredged from nearby federal channels. A multi-phased monitoring plan was developed for the project, including nutrient and water quality monitoring during placement and regular-interval bathymetric surveying post placement to monitor consolidation and erosion of the cell material (Figure 6). Localized scour was observed in early monitoring surveys; however, the area stabilized between the 12- and 21-month surveys. The pilot study was deemed successful and was noted as being an option for future dredged material management within the Baltimore Harbor as of 2018; however, it was found that there were challenges with working in a busy, high-traffic environment, such as a harbor, that required precise coordination between all parties involved.

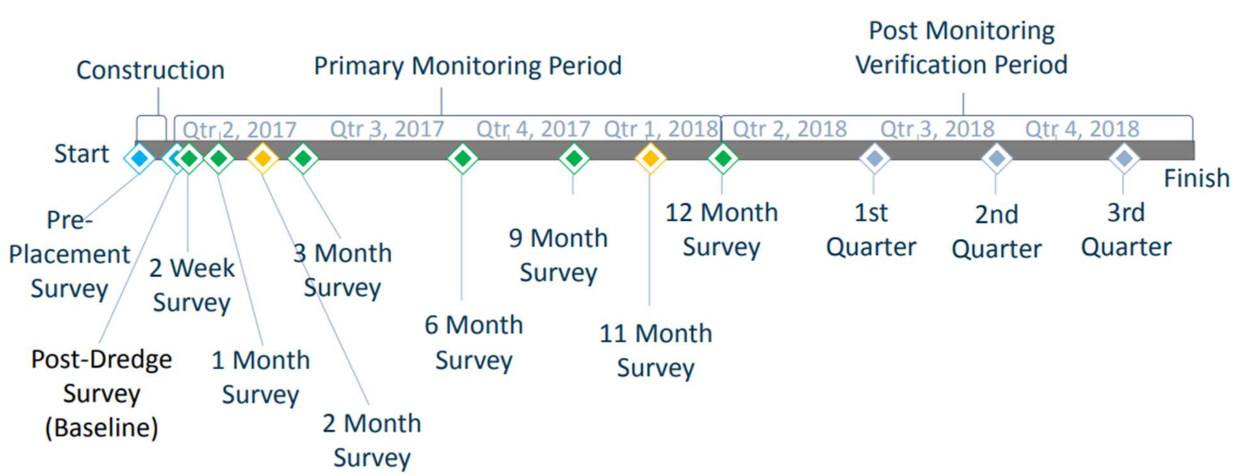

Figure 6. Monitoring schedule for the Baltimore Harbor CAP cell (Olsen et al. 2019).

C. Boston Harbor, Massachusetts

The Boston Harbor Confined Aquatic Disposal (BHCAD) site consists of 11 cells in the inner Boston Harbor. The construction of the site began in 1997 and was one of the first major uses of CAP cells in the United States (USACE and MPA 1995; Fredette et al. 2000; Fredette et al. 2002; Beaver et al. 2017). The project was conducted under the DAMOS program (USACE 2012) outlined in the Long-Term Monitoring section. It employed various means of placement, cell sizes, and capping methods over the 11 different cells (Figure 7). Monitoring of the site was broken up into multiple phases, including pre- and post- construction bathymetric surveys of individual cells, water quality assessments, SPI surveys, and sediment coring between 1997 and 2009.

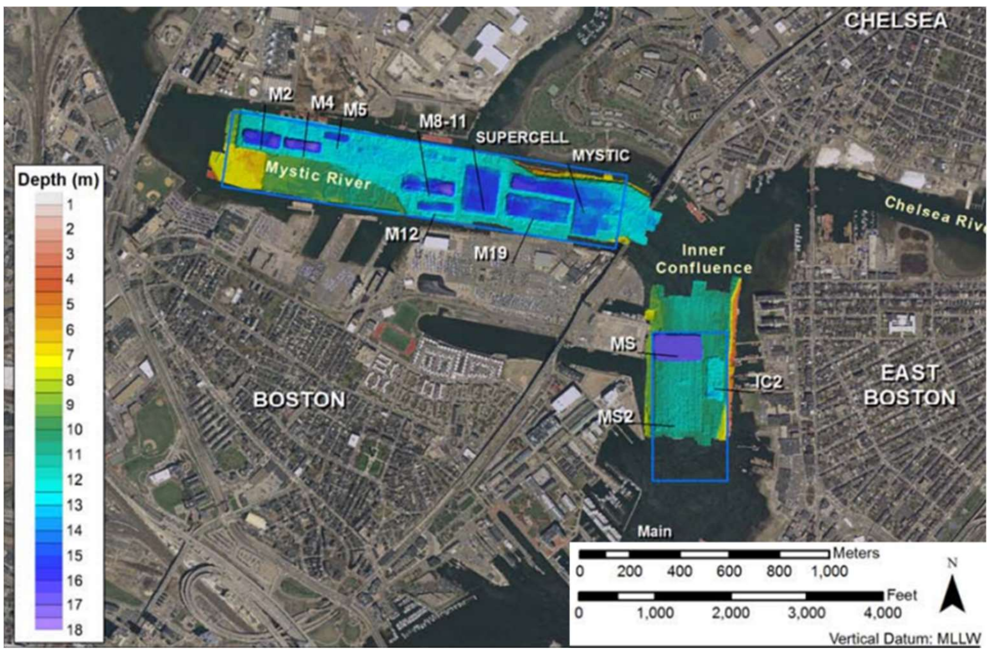

Figure 7. Overview of BHCAD site and area of bathymetric surveys conducted in 2016 (Beaver et al. 2017).

The series of CAP cells was constructed in phases to contain approximately 800,000 m^3 (1.05 million cy) of dredged material from maintenance dredging. Stiff clay underlying the channel allowed for cells with relatively steep slopes (4:1) to be constructed. A 1-m layer of clean material was used as capping for each cell. However, the time between final placement of dredged material and capping of the cell varied from cell to cell, ranging from 2 weeks to more than 12 months. Localized failures caused by exceedance of the CDM bearing capacity were observed in some cases where cells were capped too quickly prior to the underlying sediments becoming adequately consolidated. Placement of capping material was conducted using a hopper dredge, however, using a tugboat to maneuver the dredge rather than its own propulsion led to a more even distribution of material. This underscores the need to carefully evaluate the timing (schedule) and placement techniques (ideally low impact) for the final site closure cap. The last cell constructed was allowed to remain uncapped because it still had significant remaining capacity at the end of the project.

After the first year of post-construction monitoring, it was concluded that all cells were stable, with some long-term consolidation seen until 5 years post-construction. No evidence of scour or loss of material was seen at the uncapped cell, whose material had consolidated significantly. The cell surface after consolidation was located 4 to 6 m (13 to 20 feet) below the surface of the surrounding channel. This indicates that requirements for capping a CAP cell containing CDM should be evaluated on a case-by-case basis.

There were several key recommendations from this pilot study for future CAP projects, outlined by Fredette et al. (2000):

- Projects should assess whether capping a cell is necessary as benefits may be short-term due to natural sedimentation of the cell.
- Dredge fill sediments as close to in-situ density as possible to avoid excess water and maximize soil strength.
- Bathymetric surveying cannot accurately assess capping thickness due to elevation changes onset by continual consolidation of placed material.
- The combination of sediment coring and sub-bottom profiling can be an effective method of monitoring cap stability. Placing core locations along sub-bottom survey lines helps to compare these methods more successfully, rather than placement in random locations.
- Hopper or split hull barges can be used to place silty material into CAP cells successfully, with no unacceptable adverse effects on surrounding water quality.
- Gradual placement of capping material and the use of a tugboat to maneuver hopper dredges can both help to minimize mixing capping material and CDM.
- Consolidation time of material should be considered before capping a cell. If using similar material and cell dimensions as the BHCAD project, consolidation times of 5-6 months may be required. If the filling of cells occurs quickly, consolidation times of up to 1 year may be expected.

D. Providence River and Harbor, Rhode Island

A series of six cells were constructed in 2003 and 2004 within the channel of the head of the Providence Harbor (Figure 8) as part of the Providence River and Harbor Maintenance Dredging Project. This project was implemented to restore the efficiency of navigation within federal channels in Rhode Island (USACE 2001, 2008). It included maintenance dredging of 2.9 million m^3 (3.8 million cy) of material, 900,000 m^3 (1.2 million cy) of which were deemed unsuitable for open-water placement and thus placed in specifically constructed CAP cells.

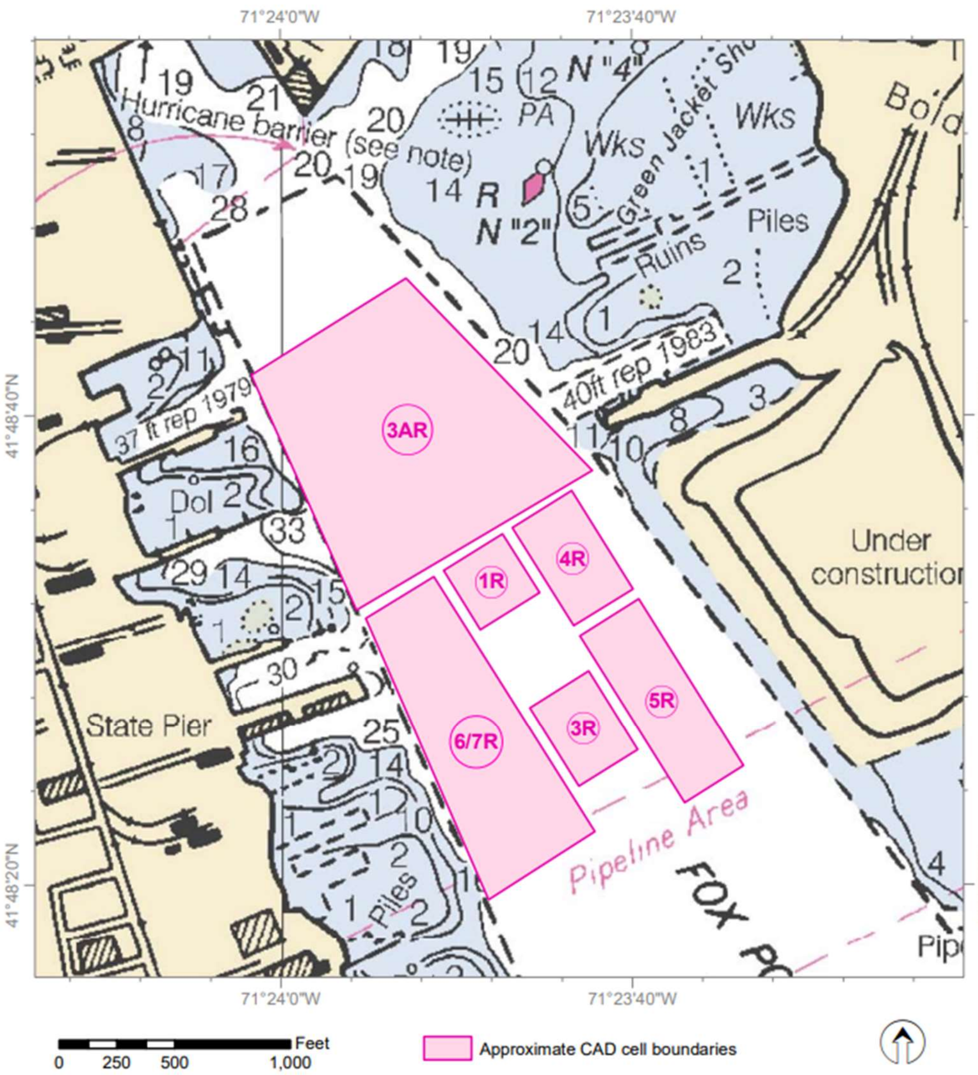

Figure 8. Approximate footprints of the six CAP cells within Providence Harbor (USACE 2008).

The six cells were constructed to depths varying between 8.5 to 17.7 m (28 to 58 feet) below the channel bed, with side slopes varying from approximately 1:2 to 1:3. Cells were not capped directly after placement to be able to receive additional material from future dredging projects, including state and private projects, with limited disposal options available as alternatives in the area.

Since construction, several bathymetric surveys have been conducted at the Providence River site, with bathymetric change measured over two time periods: 2009 to 2015 and 2015 to 2020. Results of the 2015 and 2020 surveys indicated accumulation of sediment in most cells. However, two cells experienced areas of erosion, deemed to be caused by vessel-related scouring. These areas were recommended to be avoided for future placement.

Detailed monitoring of benthic communities indicated that the biological community around the CAP cells had rebounded, leading to recommendations that capping of the cells may not be necessary.

E. Puget Sound, Washington

The Puget Sound Naval Shipyard (PSNS) is located on the Sinclair Inlet of Puget Sound, Bremerton, Washington. A CAP cell was constructed in 2001 on U.S. Navy-owned property as part of wider marine remedial actions to deal with sediments contaminated with polychlorinated biphenyls (PCBs) and mercury (USACE 2000; U.S. Navy 2016). The CAP cell was built with dimensions of 187 by 183 m (614 by 600 feet), with a depth of 9 m and side slopes of 1:3 (Figure 9). In total, approximately 308,000 m^3 (403,000 cy) of contaminated sediment were placed in the cell. The cell was left untouched for 4 months to allow for consolidation of material before capping commenced. A 0.3-m (1-foot) primary capping layer was established after this 4-month period. After an additional 2 months to allow for further consolidation, a final 1.8-m (6-foot) cap was added to the cell.

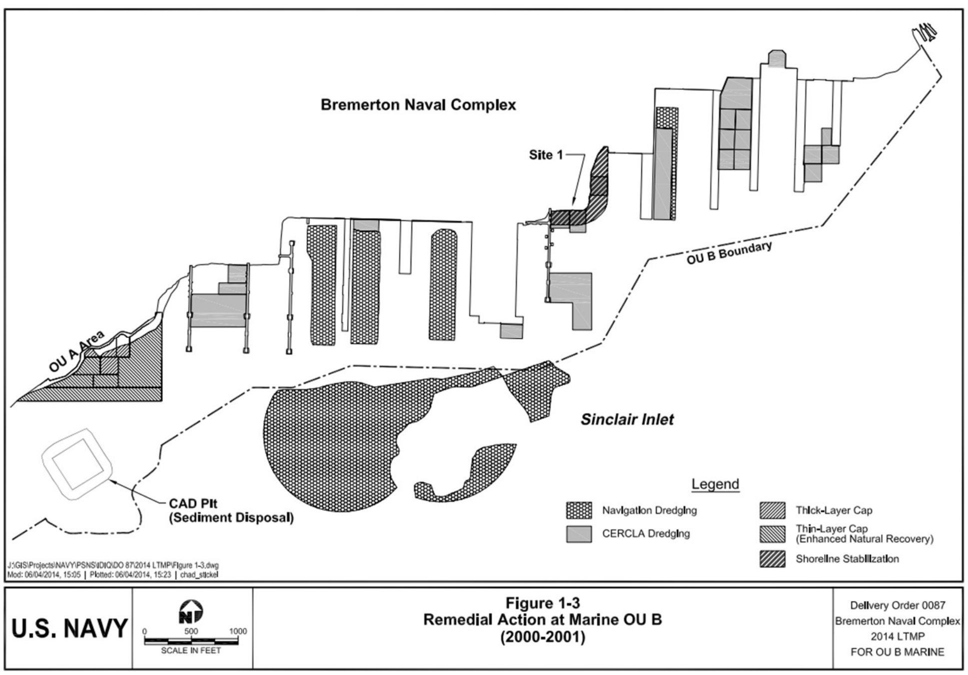

Figure 9. Location of CAP cell in relation to the Bremerton Navel Complex (U.S. Navy 2014).

Postconstruction analysis of surface sediments around the site noted high levels of contaminants near the edges of the cell, resulting from placed material leaking out during filling of the cell. To remedy this, a 30 m (98 feet) wide, 0.6 m (2 feet) thick "strip" of clean sediment was placed around the edges of the site to contain the disbursement of contaminated sediment.

Monitoring of the CAP cell was conducted at 2- to 3-year intervals from 2003 to 2014. The monitoring consisted of surface sediment sampling, sub-bottom profiling, and water quality sampling. Findings indicated that the CAP cell had stabilized, with PCB concentrations in surrounding waters meeting target levels.

F. Newport Harbor and Lower Newport Bay, California

The construction of a CAP facility in the central portion of the Lower Newport Bay has been requested by the City of Newport Beach in Orange County, California. The Newport Harbor is a small craft harbor primarily used for recreational vessels. Federal channels within the harbor require periodic dredging to remove continual sediment accumulation. Certain areas of the channel are suitable for open-ocean disposal or beach nourishment. However, portions of the dredged material are likely to exceed standards for open-ocean disposal. Therefore, a CAP facility has been proposed to place contaminated dredged sediment within Lower Newport Bay. Construction had been projected to start in late 2023 (Anchor QEA 2021).

A two-stage design of the cell is proposed to accommodate 81,730 m^3 (106,900 cy) of material dredged from federal channels, which is unsuitable for open-water placement. The plan calls for an interim 0.3-m (1-foot) sand cap plus an additional 40,000 m^3 (52,318 cy) to be placed on top of the interim cap, sourced from maintenance dredging outside of federal channels. A final 0.3-m (1-foot) cap is to be constructed once cell capacity has been met. The cell is proposed to extend 10 to 12 m (33 to 39 feet) below the seabed, with side slopes of 1:2.5. Factors to be considered in design are hydrodynamic effects (including waves, currents, scour from propeller wash, effects due to anchorage of small craft, etc.), protection against bioturbation (from benthic organisms), chemical breakthrough (due to processes like advection and diffusion), and impacts to existing groundwater resources and utilities. No monitoring schedule is readily available for this project at the time of writing.

Best Practices from Other Countries

Vogt (2009) outlined international practices and policies for disposal of CDM and noted that several countries other than the United States have successfully employed the use of CAP cells including the Netherlands, Hong Kong, Norway, the United Kingdom, and Australia. The study was conducted as guidance for Environment Canada for the management of CDM disposal or placement practices at sea. Vogt (2009) highlighted several key elements to be considered when designing and monitoring a CAP cell, including potential water column impacts, effectiveness and feasibility of capping placement, and long-term stability of the cell and capping layer. In particular, emphasis was placed on monitoring requirements and the responsibility of regulatory authorities to ensure that these requirements are owned appropriately. Requirements should be included in regulatory permits for pre, during, and post project monitoring to ensure the surrounding environment is protected, the cell and cap integrity is maintained, and liability is owned appropriately.

Oen et al. (2017) discussed the long-term monitoring of a CAP site in Oslofjord, Norway. Both chemical and biological factors were monitored, including benthic community sampling, surface sediment grab samples (to measure the quality of capping material), sediment traps (to evaluate new material deposition), infinite-sink flux chambers (to measure the flux of organic contaminants), and passive samplers (to measure dissolved concentrations in the water column). Monitoring of the site occurred four times, once before construction and then during three annual postconstruction monitoring campaigns. It was found that the combination of sampling methods was effective in capturing the short- and long-term chemical and biological recovery of the CAP cell, with the cell still functioning as designed after the 3-year monitoring period. Comparing to United States case studies above, only Providence Harbor included effective monitoring of biological factors (benthic communities). Qian et al. (2003) noted that benthic communities can take several years to recover to preconstruction levels, so monitoring of biological factors up to 3 years post construction is recommended to better understand the long-term recovery of a CAP project (Oen et al. 2017).

OBSERVATIONS AND CONCLUSIONS

There is no focused and comprehensive guidance or standard to be used in the design, construction, or monitoring of CAP cells. The specific design of CAP cells and their construction method are largely dependent on site-specific conditions and the nature of the CDM. Thus, specific design standards may not fit the needs of all users and project goals. For example, some available design guidance of subaqueous capping highlights the need for chemical isolation components and armor layers (Mohan et al. 2000; Palermo and Reible 2007), though such design is more targeted for moderately to highly contaminated sediments. Most of the case-study examples do not include any cell lining and only one includes rock armoring. Most CAP cells examined here are placed in sufficiently deep water within protected harbor environments subject to only low-energy conditions on the seabed and with the dredged material containing relatively low levels of contaminants.

The capping material for most CAP projects is generally clean and usually composed of sandy material, either dredged from a nearby navigation channel or from the surrounding area. CAP cells are typically considered for mid- to larger-sized dredging projects (e.g., harbor and channel maintenance and deepening projects), where the dredged material has low levels of contamination. Therefore, an abundant supply of clean dredged material is usually available for final cell-capping requirements from nearby dredging projects. In cases where there is not a sufficient supply of clean material, it is often still a cheaper option to dredge clean material from a nearby borrow source, or dredge clean material dug out from the cell and stockpiled to use for capping.

Long-term consolidation can lead to increased capacity at CAP sites. If conditions allow, sites may be left uncapped or have intermediary caps placed to facilitate longer-term disposal sites. This would reduce the need for construction of new CAP cells. In addition, consolidation of the material leads to lowering of the CAP cell level to below the surrounding seabed. This often leads to accretion of outside material in that seabed depression, which further isolates the CDM. In instances where a final closure cap had been placed, it was important to allow sufficient time for underlying CDM to consolidate so that bearing-capacity failures can be avoided during cap placement.

CAP projects conducted within the northeastern United States (Long Island Sound to Maine) fall under the DAMOS monitoring system. These projects generally include well-documented construction and long-term monitoring, which can be beneficial in determining the success of CAP projects. Having a site-specific, structured, and repeatable monitoring program with clear goals as outlined by the Canadian FCSAP guidance document (ECCC 2021) is a good way to ensure that the CAP project is successful in the long term. The use of multiple monitoring methods and techniques, such as bathymetric surveying, benthic surveying, sediment contaminant analysis, and water quality testing, is an ideal way to confirm the stability of the CAP cell and the health of the surrounding environment.

RECOMMENDATIONS AND FUTURE DIRECTIONS

Several key factors should be considered when designing a CAP cell. Those include details on native sediment characteristics, local hydrodynamics, cell dimensions and geometry, operating capacity and site life, placement techniques, lift thickness and placement schedule, potential water column impacts, effectiveness and feasibility of final cap placement, and long-term stability of the cell and cap layer. It is recommended that any future guidance on CAP cells should include clear instructions and directions on long-term monitoring of CAP sites post-construction.

A framework similar to the Canadian FCSAP will aid in ensuring that good long-term monitoring programs are developed and undertaken as part of US CAP cell projects. Monitoring efforts should ideally incorporate both chemical and biological factors via benthic (community) sampling, including sediment profile cameras (to assess recolonization), surface sediment (grab) sampling (to assess changes of cap material over time), sediment traps and flux chambers (to evaluate new deposition as well as to measure any new contamination), and passive samplers (to measure dissolved concentrations in the water column). Ideally, monitoring of the site should be conducted every 6 months during the first year (following cell construction or closure) and subsequently for a period of at least 3 years following cell closure. Monitoring schedules should also include monitoring the recovery of chemical and biological factors to ensure minimal impact on the surrounding environment. Additional monitoring should be considered following the occurrence of extreme events to assess any impacts to the CAP.

There is little indication of case studies designing CAP cells for large return period events, such as hurricanes, earthquakes, or tsunamis. Many of the sites lie in sheltered harbor locations but may still be exposed to forcing conditions created by extreme events under certain circumstances. Future guidance or projects should explore the impacts of large waves or earthquakes on CAP cells, including monitoring of sites after such events have occurred to determine these effects, if any.

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SUSTAINABLE DREDGING PRACTICES PRODUCE MULTIPLE BENEFITS ON THE OHIO AND KANAWHA RIVERS

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ABSTRACT

To move toward more sustainable dredging practices there is an inherent need to expand applications for beneficial use of sediments and broaden the desired social, environmental, and economic services provided. However, there are challenges to overcome to increase beneficial use of sediment in riverine environments beyond current levels. Over the past several decades, the US Army Corps of Engineers (USACE) Huntington District (the "District") has utilized beneficial use of dredged material to achieve numerous environmental, social, and ecological benefits; consistent with Engineering With Nature® (EWN) principles. Additionally, the USACE has a target of increasing beneficial use of dredged material to 70% from the current 30-40% by 2030 (i.e., "70/30" goal). Yet, to achieve these broader sustainability objectives there is a need to quantify and document current beneficial use practices within USACE to inform future progress. Therefore, the objective of this study is to present data and other information on sustainable dredging practices from three pertinent examples of dredged material management and other operational strategies that have intentionally improved or protected mussel habitat while providing other co-benefits. Among the observed or quantified benefits reported include creating side channel habitat features with placed sediments, increased native mussel populations adjacent and downstream of placed sediment, and increased efficiencies of the District's dredging program. This information can be used to communicate sustainability concepts more broadly to inform strategies that can be implemented by others to achieve multiple benefits through the application of EWN best practices using dredged sediment beneficially in riverine environments. This paper focuses on three District projects that exemplify sustainable dredge practices: Bonanza Bar and Robert C. Byrd Locks and Dam on the Ohio River and Winfield Locks and Dam on the Kanawha River.

Keywords: Beneficial use, riverine, ecosystem restoration, mussel, Engineering With Nature

INTRODUCTION

There is a growing global demand for achieving more sustainable water resources and waterborne infrastructure through innovation in dredging practices. The primary 'pillars' of sustainability include considerations of the desired social, environmental, and economic services provided (Laboyrie et al. 2018). However, there remain numerous challenges to implement sustainable dredging practices across the diversity of operating environments. Specifically, there are relatively limited quantitative and observational data in riverine environments demonstrating multiple positive outcomes through dredging. Therefore, this study focuses on successful implementation of sustainable dredging in riverine systems to inform and inspire future dredging practices (e.g., dredged material placement or management).

Achieving sustainable management of dredged material involves consideration of several factors, including 1) creating opportunities to protect or enhance ecosystems, 2) beneficially using dredge material, 3) understanding the local environment, and 4) identifying opportunities to maximize natural processes to achieve short-term and long-term goals (Laboyrie et al. 2018). These sustainability factors also align with

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the US Army Corps of Engineers (USACE) Engineering With Nature® (EWN) program which pursues an intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes (Bridges et al. 2014; Gerhardt-Smith and Banks 2014). The EWN initiative focuses on developing practical methods to provide an ecosystem approach to navigation infrastructure development and operations that is applicable across multiple USACE missions and business lines. The four key elements of EWN are: 1) science and engineering that produces operational efficiencies, 2) using natural process to maximum benefit, 3) broaden and extend the benefits provided by projects, and 4) science-based collaborative processes to organize and focus interests, stakeholders, and partners (King et al. 2020). EWN principles and practices are particularly relevant to the USACE dredging mission as evidenced by the applications of EWN research and development funding that focus on integrating sediment beneficial use into USACE navigation, ecosystem restoration, flood risk management, and water operations missions (e.g., Foran et al. 2021; Bridges et al. 2018, 2021). Additionally, the USACE has a target of increasing beneficial use of dredged material to 70% from the current 30-40% by 2030 (i.e., "70/30" goal). Yet, to achieve these broader objectives there is a need to quantify and document current beneficial use practices within USACE as a means for increasing beneficial use.

This study focuses on three riverine projects that implemented sustainable dredging practices: Bonanza Bar and R.C. Byrd Locks and Dam on the Ohio River, and Winfield Locks and Dam on the Kanawha River. Data and lessons learned from these projects can be applied elsewhere to enhance development of USACE sustainable dredging practices, inform data gaps in riverine projects aiming to use sediment beneficially, and provide inspiration for future projects.

STUDY LOCATIONS AND APPROACH

This study focused on three project locations: 1) Bonanza Bar on the Ohio River, 2) R.C. Byrd Locks and Dam on the Ohio River, and 3) Winfield Locks and Dam on the Kanawha River (Table 1; Figure 1). For each project, ecological and social benefits are herein documented through review of historical dredging quantities, costs, and bathymetric field survey data; mussel surveys (Lewis Environmental Consulting, 2001-2021), historical photographs, navigational charts, and drone and satellite imagery; water quality monitoring data, acoustic Doppler current profiler (ADCP) data, and observations from multiple site visits by District and USACE Engineer Research and Development Center (ERDC) staff. The benefits from each project are organized based on their alignment with EWN principles to: 1) leverage natural processes, 2) produce efficiencies, 3) broaden benefits, and 4) facilitate collaboration.

For mussel surveys, each mussel was identified to species. Dead shells were counted and recorded as fresh dead, weathered dead, or sub-fossil. All mussels were returned to the area from which they were collected. In addition to quantifying mussel densities in the study areas, species diversity (Shannon-Weiner Index; Equation 1) and evenness (Equation 2) were estimated.

Species Diversity (Shannon-Weiner Index): $H' = -\sum_{i=1}^{S} pi \cdot \ln(p_i)$ *Equation 1*

Where H' is the Shannon-Wiener Index, S is the number of species in the community, pi is the proportion of the *i-th* species in the sample. Results were based on the natural logarithm (ln).

Species Evenness: $= \frac{H'}{Hmax} = \frac{H'}{\ln(S)}$ *Equation 2*

Where H' is the observed Shannon-Wiener Index (Shannon Diversity Index) for the community, ln represents the natural logarithm, and S is the number of species in the community.

The Shannon-Weiner Index value increases as both the variety and abundance of different species in a particular area or ecosystem. A higher Shannon-Wiener Index value indicates higher diversity in the community, which means a community with a greater number of different species. It considers not only the number of species but also their relative abundances, making it a valuable tool for comparing and assessing the diversity of different ecological communities. Implications of higher values are often associated with more resilient ecosystems (e.g., greater functional redundancy) and improved ecological interactions. The evenness value is related, but more specifically quantifies how evenly individuals are distributed among species in a community and provides valuable information about the distribution of individuals among different species in a community. A lower evenness score would indicate a more skewed distribution with one or a few species dominating the community. Evenness allows for comparisons between different communities and changes over time can be indicative of shifts in community structure and may reflect disturbances or changes in environmental conditions. Therefore, monitoring evenness over time can provide insights into the ecological health and stability of an ecosystem.

Table 1. Selected dredging projects in the District that are demonstrating sustainable dredged material management.

Project Name	Project Goals	Location	Latitude, Longitude
Bonanza Bar	• Ephemeral island creation • Beneficial use of dredged material for channel constriction and habitat creation/restoration	Ohio River, USA	38°44'2.13"N, 82°57'11.39"W
R.C. Byrd Locks and Dam	• Using water operations to manage turbidity plume and redeposition near dredge placement for protection of sensitive habitat	Ohio River, USA	38°40'59.64"N, 82°11'9.49"W
Winfield Locks and Dam	• Beneficial use of dredged material for habitat creation/restoration	Kanawha River, USA	38°31'34.46"N, 81°54'48.42"W

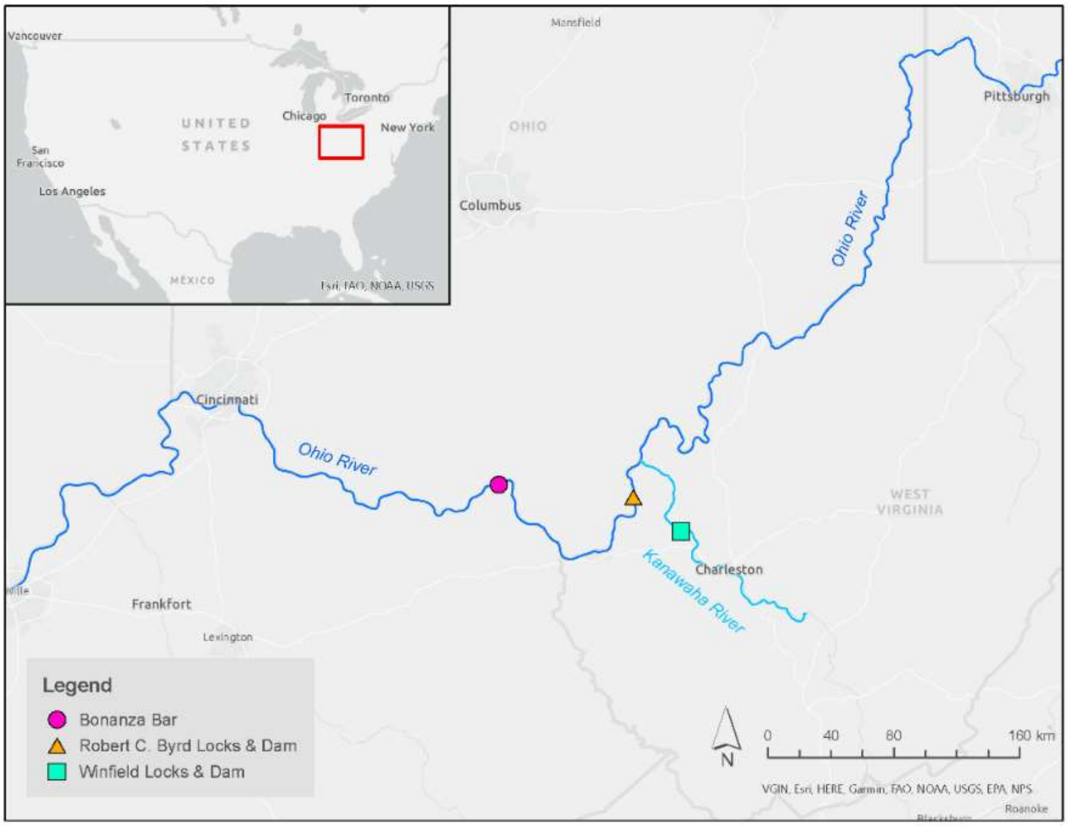

Figure 1. Locations of projects in District that are Demonstrating Sustainable Dredged Material Management.

RESULTS

Bonanza Bar, Ohio River

Bonanza Bar is an ephemeral bar created with dredged sediment that was restored to mimic its footprint in the river channel which was documented more than 50 years ago. In the early 2000s the District received approval from Kentucky Division of Water (KY DOW) to hydraulically or mechanically "stack" dredged material near the bankline with the specific intent to leave space sufficient for sustaining back-channel habitat in the slack waters created by the bar. As successful placements have occurred over the past decade, creation of Bonanza Bar has subsequently allowed for more efficient dredge material placement, reduced timing, frequency, and cost of dredging in the adjacent navigation channel, while providing valuable ecological habitat and recreational opportunities.

<u>*Leverage Natural Processes*</u>

The District is currently interested in a means of stabilizing and growing the bar to serve as additional constriction on the navigation channel, reducing or potentially eliminating the need for repetitive maintenance dredging, and stabilizing downstream and adjacent ecological resources (i.e., mussel bed habitat). Therefore, placement regions have been informed by historic bar locations and the current Bonanza Bar footprint created using dredge placement mimics the location of the natural bar formation from >50 years ago as documented in historical navigation charts. The dredge placement is unconfined, and the energy of the river is used to distribute the sediment and shape the bar (Figure 2). In 2020 immediately after placement, the island was approximately 0.6 m out of the water at its highest point. It was estimated that the bar would be submerged approximately 3 to 3.3 m during routine higher flow events like those experienced in the August 2022 site visit showing the ephemeral nature of the bar based on fluctuating water levels in the Ohio River. Due to periodic inundation, there has been no vegetative growth on the bar.

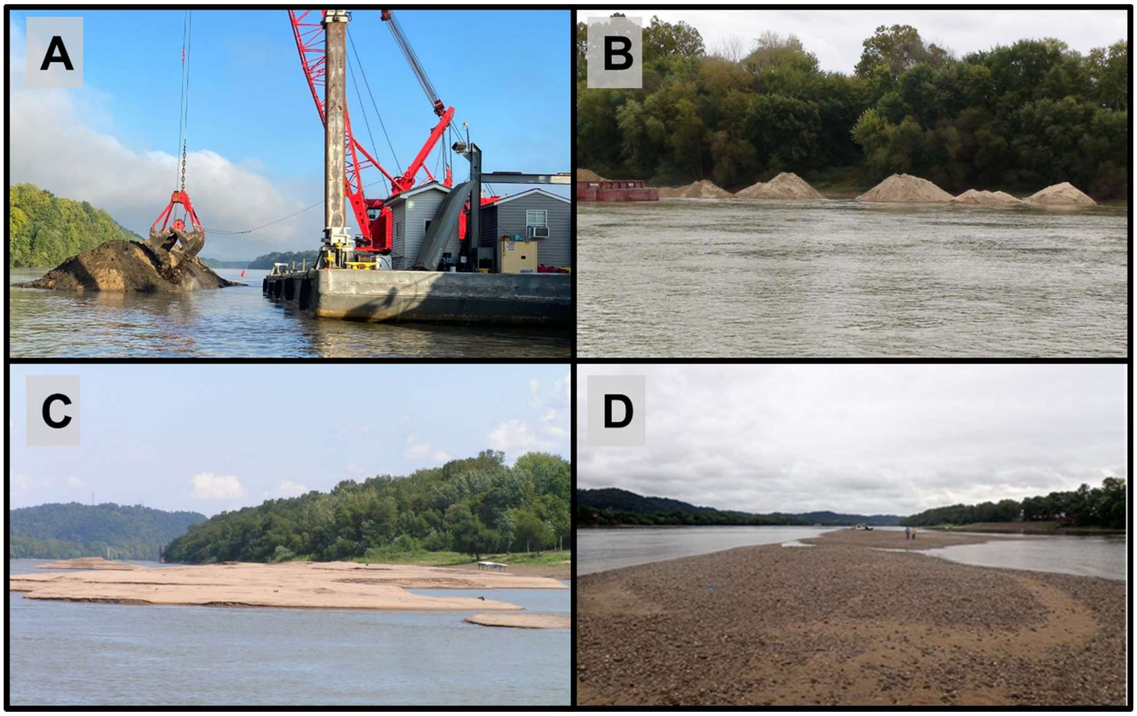

Figure 2. Bonanza Bar dredged sediment placement using clamshell dredge (A); immediately after placement (B); reduced sediment piles (C); and flattened bar (D). Photo Credits USACE Huntington District.

Produce Efficiencies

Since 2016, the quantity and frequency of dredge requirements near the Bonanza Bar have declined (Figure 3). This decrease in dredging needs has coincided with the Bonanza Bar island creation. Although it is challenging to correlate dredge quantity and cost with the influence of the island since its creation due to a myriad of variables, it is hypothesized that Bonanza Bar is concentrating the flow to maintain a more sustainable federal channel requiring less dredging. Similar results have been observed in another dredging project with the creation of riverine islands. The Horseshoe Bend project (Atchafalaya River, Louisiana) created a riverine island over time using strategic placement of dredged sediment and allowing the natural energy of the river to distribute and form the island (Suedel et al. 2014; Foran et al. 2018). Subsequently, long-term dredging requirements in the Atchafalaya River were reduced, saving significant time and costs to the federal dredging program (e.g., \$4.3 M annually; Suedel et al. 2015). For the Bonanza Bar project area, the current trend exhibits a decrease in shoaling in this reach of the Ohio River and therefore the dredging demands (and concomitant cost) have declined over the past several years (Figure 3).

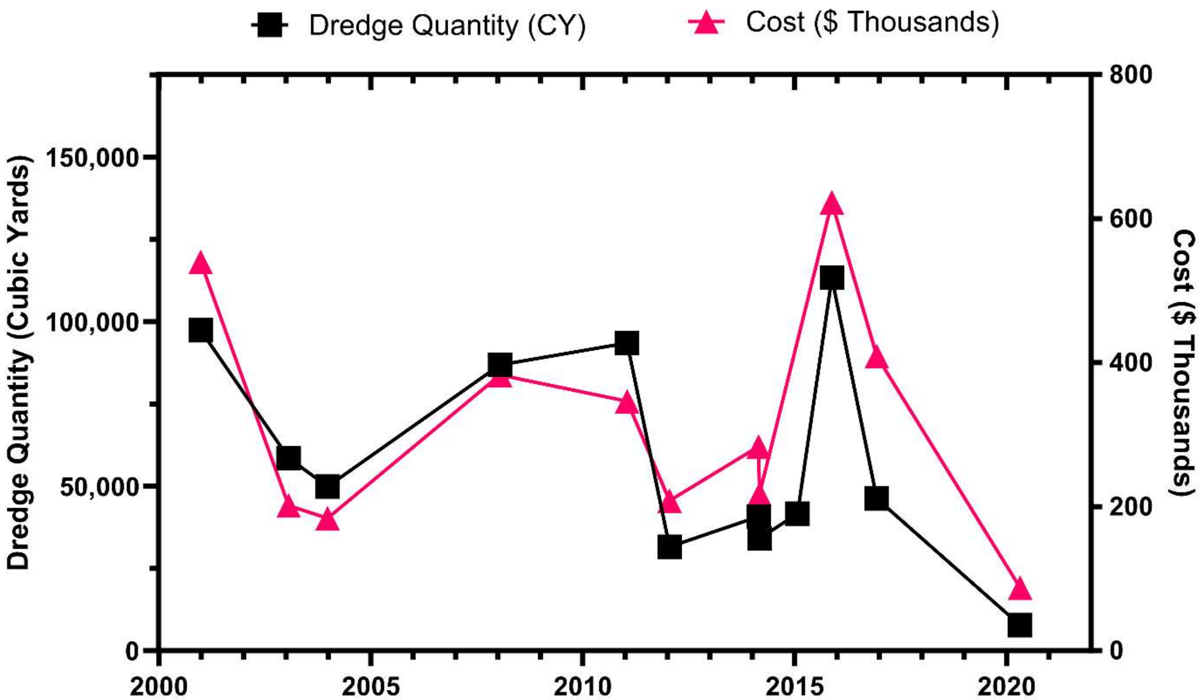

Figure 3. Bonanza Bar dredged sediment quantities (cubic yards) and costs ($ thousands) at Bonanza Bar from 2001 to 2021.

There are ongoing efforts to understand the stability and hydrodynamic consequences of the Bonanza Bar placement area. A hydraulic modeling study utilizing 2D hydraulics in the Adaptive Hydraulics (AdH) modeling software is being used to evaluate outcomes of several possible river training structures to promote bar stability. Attention is being given to the type and orientation of structure and the influence each has on velocities in the navigation channel as well as the side channel that currently supports mussel habitat. These hydrodynamic studies are investigating approaches to help stabilize and grow the bar, which include both non-structural and structural solutions. The non-structural approach would be to preferentially place larger grain size material to potentially 'armor' the bar and stabilize it. The second approach, a structural solution, would consist of building one or more river training structures to alter the hydraulics upstream and at the bar. There are multiple structure options to stabilize the bar (USACE 2012; Gailani et al. 2022). One option would be the construction of a "bullnose" chevron dike, effectively a rubble rock cap at or just upstream of the island head to take the brunt of the erosive potential of the flow. Bullnoses are commonly used to stabilize islands in the Upper Mississippi River and are considered a means of implementing EWN in riverine environments (Bridges et al. 2021). A second option would be the construction of a rootless dike, again a rubble rock structure, upstream of the bar to direct flow to the navigation channel, also reducing velocities in the shadow of the structure. A third option, based on work being done in the St. Louis District, is the construction of a wooden pile dike upstream of the bar to reduce velocities downstream and promote deposition. This third option would reduce or eliminate the rock placement required for the other structural alternatives.

Based on the existing hydrodynamics of the bar, four primary benefits to habitat are occurring: 1) adds substrates to a bar feature that can serve as habitat (e.g., mussels), 2) provides a "velocity-shed" for stabilization of mussel habitat around the bars, and 3) fish habitat benefits derived from the sheltering effects of the island against instability due to navigation and flow, and 4) habitat for island nesting birds.

Broaden Benefits

Since the ephemeral Bonanza Bar was created, numerous ecological benefits have been realized at the project location. The ecological benefits that have been observed include increased mussel populations, presence of migratory birds, and creation of riverine back-channel habitat. Mussel beds naturally occur along the left descending bank and side channels adjacent to the islands. The District has sponsored nine mussel surveys along the left descending bank at Bonanza Bar between 2001 and 2020. All mussel surveys show mussel habitat exists along the Kentucky shoreline at Bonanza Bar. Overall, increased populations of mussels were observed at this site, with the most recent survey in 2020 indicating a thriving population of mussels at the Bonanza Bar project area (Lewis Environmental Consulting, 2020; Table 2; Figures 4 and 5).

Previous surveys have identified a small mussel concentration at the upstream end of the Upper Bonanza Bar survey area, a linear mussel concentration immediately upstream of Tygarts Creek in the downstream end of the Upper Bonanza Bar survey area, and a linear mussel concentration between 500 – 900 meters downstream of Tygarts Creek in the Lower Bonanza Bar survey area (McClane Environmental Services, 2001; 2006; 2007; 2009; 2010). The 2014 survey site extended further downstream than the previous mussel surveys at Lower Bonanza Bar. The downstream extension of the survey area identified another small concentration of mussels along the Kentucky shoreline between 1,650 – 1,850 meters downstream of Tygarts Creek. The upper end of the 2014 survey area also partially overlapped the 2001 survey area and intersected a portion of the mussel concentration identified at the location in 2001. The mussel concentrations identified at the Bonanza Bar sites were all similar in characteristics and species composition (Table 2). The mussel concentrations all exist in a band of suitable substrate consisting of silt, sand, gravel, and cobble that is present in a narrow channel along the Kentucky shoreline. The band of suitable habitat extends out from the shoreline approximately 40 meters, where the river bottom comes up onto a sand bar.

No federally listed species have been found at the site and based on habitat and species composition, it is unlikely that any occur there. The most recent mussel survey at Bonanza Bar determined that continued placement on the middle or outer portions of the sand bar within the disposal area, and/or extending the outer portion of the placement further downstream is not anticipated to negatively impact mussels along the shoreline (Lewis Environmental Consulting 2020).

Starting in 2011, observational data also suggest Bonanza Bar is supporting migratory birds through stabilization of the island. Additionally, there is interest to maintain a backchannel to the bar to improve fish spawning grounds. The benefits of riverine backchannels are well documented for the benefits to fisheries. Backchannels can serve as a refuge for fish spawning grounds because the island can protect the backchannel from vessel wakes caused by navigation (Gailani et al. 2022). Thus, the backchannel can serve as habitat for rheophilic aquatic species. Additionally, most species of mussels require intermediate fish host during its life cycle, therefore promotion of fish habitat is often crucial component to sustaining and promoting mussel populations (Herman et al., 2021). Post hoc observations of Bonanza Bar over the years indicate that there is added recreational value in terms of increased use of newly created bar for fishing and swimming.

Table 2. Summary of mussel survey data for Bonanza Bar (2001 – 2020; Lewis Environmental Consulting, 2020).

	Number of Live Mussels Present								
	LBB; UBB	**UBB**	**LBB**	**UBB**	**UBB**	**LBB**	**UBB**	**LBB**	**UBB**
Scientific Name	**2001**	**2005**	**2006**	**2009**	**2010**	**2014**	**2015**	**2019**	**2020**
Amblema plicata	20	20	1	16	32	25	4	13	50
Cyclonaias nodulata					2		1		1
Cyclonaias pustulosa					26		5	18	47
Ellipsaria lineolata		1			2	1	1	1	20
Fusconaia flava	1	4		4	5	10	2	2	5
Lampsilis cardium	2	11	2	5	2	1	2		
Lampsilis ovata								WD[2]	3
Lampsilis teres					WD[2]				
Leptodea fragilis							1		
Ligumia recta	2	3		2	2	5	5	1	8
Obliquaria reflexa	1	38		24	42	30	14	21	119
Potamilus alatus	1	10		4	12	34	2	3	3
Quadrula quadrula	2	4		4	5	17	6	5	13
Reginaia ebenus								1	2
Theliderma metanevra	1	25		7	19	1	13		83
Tritogonia verrucosa									1
Truncilla donaciformis									1
Truncilla truncata									1
Total # Live[1] Mussels	**30**	**123**	**3**	**74**	**149**	**146**	**56**	**65**	**357**
Total # Live[1] Species	**8**	**10**	**2**	**9**	**11**	**10**	**12**	**9**	**15**
Species Diversity[3]	**1.63**	**2.28**	**2.08**	**1.91**	**1.87**	**1.97**	**2.11**	**1.68**	**1.84**
Evenness[4]	**0.78**	**0.84**	**0.73**	**0.87**	**0.62**	**0.68**	**0.85**	**0.76**	**0.68**

LBB = Lower Bonanza Bar; UBB = Upper Bonanza Bar

[1]Live: encountered alive

[2]Weathered dead: encountered as a weathered dead (WD) shell only; not included in live counts

[3]Species diversity (Shannon-Weiner Index); See Equation 1

[4]Evenness: See Equation 2

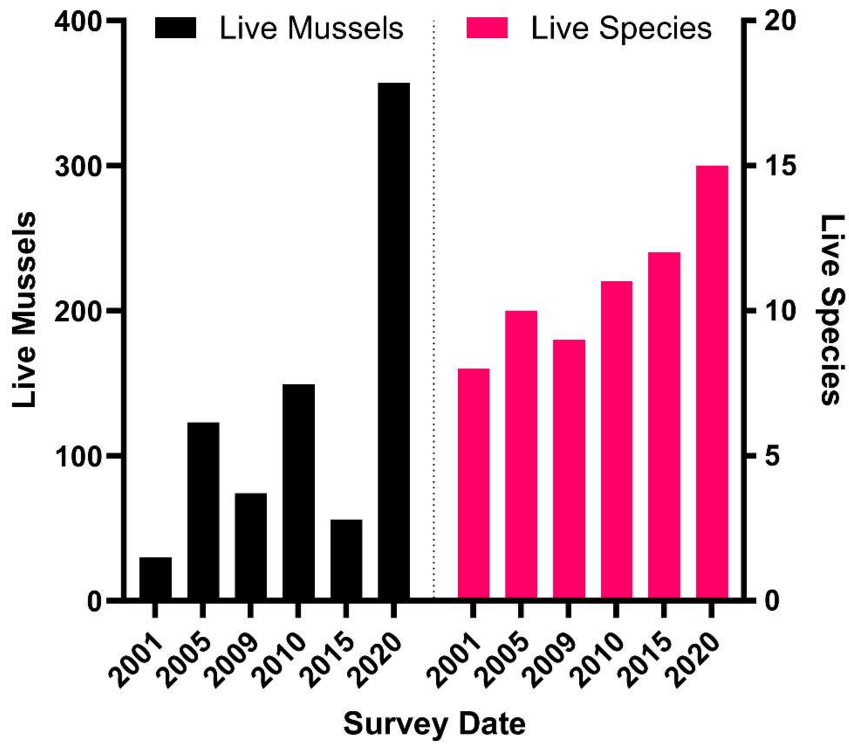

Figure 4. Trends in the number of live mussels and mussel species observed in upper Bonanza Bar 2001 – 2020 (data source: Lewis Environmental Consulting, 2020).

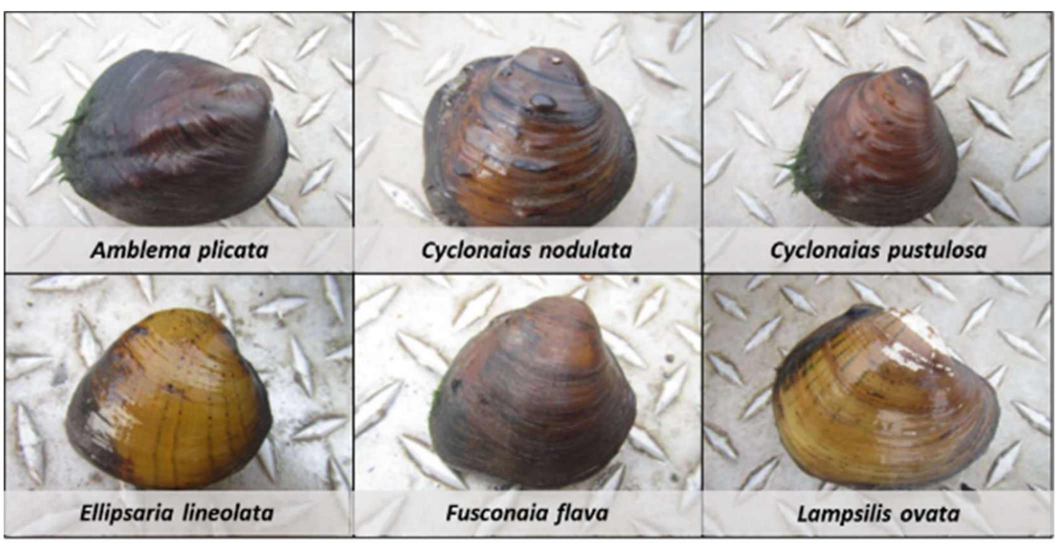

Figure 5. Photographs of select native mussel species observed at Bonanza Bar since 2001 (from Lewis Environmental Consulting 2020).

<u>Collaboration</u>

A stakeholder driven approach is being used to guide the District's navigation program. State and federal partners (e.g., US Fish and Wildlife Service, KY Department of Natural Resources; KY DOW) encouraged the District to redirect the placement of dredged material away from the bank to incorporate side channel habitats; the District willingly complied as it was immediately apparent the benefits from this approach. The District worked closely with KY DOW to obtain the water quality certification (WQC) permit allowing for the placements to occur at Bonanza Bar. Stakeholder meetings occur once per year and the District's proactive approach transformed a contentious atmosphere to one of collaboration. Stakeholder meetings have transformed over time for several reasons: 1) mussel beds began to form and increase in size and diversity of species, 2) the District proactively decided against using the lower Bonanza Bar as a placement area due to the proximity to mussel beds. The overall "tipping point" in collaboration was a change in philosophy by the District to adapt to a more sustainable approach to dredged material management.

R.C. Byrd Locks and Dam, Ohio River

At the R.C. Byrd Locks and Dam project, innovations in managing water operations during dredge placement activities allowed the dredging program to meet goals of supporting safe and reliable waterborne transport while protecting sensitive mussel bed habitat from plumes and redeposition of sediments during active dredging operations. Additionally, the use of advanced environmental monitoring tools at the R.C. Byrd dredge sediment placement area allows for real-time monitoring of turbidity and sedimentation and improves risk communication and management of nearby sensitive mussel beds. These innovations in environmental monitoring have improved protective measures to be implemented during placement operations while concomitantly improving stakeholder relationships.

R.C. Byrd often requires dredging two to three times per year due to the persistent sedimentation issues below the downstream lock approach. With an average of nearly 90,000 cubic yards (69,000 cubic meters) of dredge material annually, channel maintenance needs far exceed average Ohio River navigation projects (Figure 6). Due to significant sedimentation below the project, presence of endangered mussels, and the importance of the navigation mission, dredging operations at R.C. Byrd require continued cross-agency collaboration to best meet the diverse objectives. The combination of using the natural flow of the Ohio River with strategic placement of the dredged material and operation of the R.C. Byrd roller gates to reduce dredging impacts to downstream mussel habitat, makes this project a unique application of EWN principles.

<u>Produce Efficiencies</u>

The District's Water Quality Team has employed real-time environmental monitoring stations to test and report parameters at a mussel bed near the dredge disposal area. Additionally, the District has incorporated an innovative approach to minimizing impacts of dredging operations by using targeted flows at the dam (i.e., steering currents) to direct flows of the river and use the river's energy to steer dredge plumes away from the sensitive habitats along the shoreline (Figure 7a). To successfully inform this approach and coordinate with the Water Operations staff on the gate operations and use of steering currents, improved near-real time monitoring stations have been used. The District has developed platforms and tools which can monitor sedimentation, and any increases in turbidity and decreases in dissolved oxygen during active dredging and placement activities in addition to the use of ADCP to inform current velocity vectors (Figure 7b). These innovations in monitoring during dredging and placement activities at R.C. Byrd have been critical to ensure that minimization and avoidance goals are achieved through steering current operations.

As an example, in 2015, these advanced water quality monitoring techniques helped avoid environmental impacts to downstream mussel beds which include Federally protected species when dredging and placement triggered increased turbidity concentrations and sediment deposition due to low-flow conditions. As a result, the District ceased dredge operations at the site until the following season when favorable conditions returned. The decision to shut down dredging operations because of these impacts has allowed the District to meet the minimum requirements of dredging operations while remaining compliant with the Endangered Species Act and the Clean Water Act. This was the first time the District was forced to shut down dredge operations due to low flow river conditions and showed the District's commitment to protecting the local mussel resources. Such infrequent shutdowns do not impinge on the District's navigation mission and as such these dredged material management practices are considered sustainable.

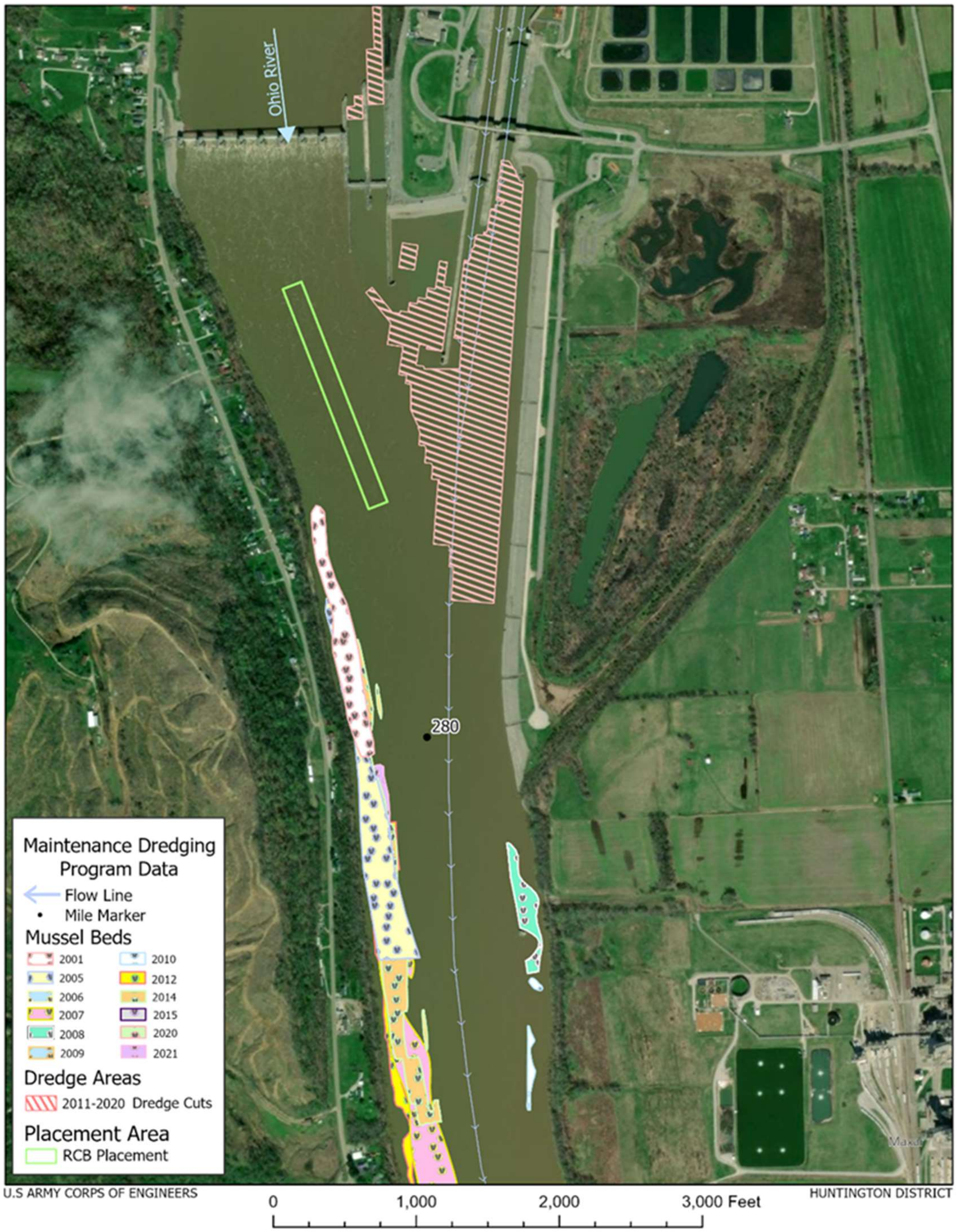

Figure 6. R.C. Byrd Locks and Dam project location including the dredge area, dredged material placement area, and mussel beds observed over time (2001-2021).

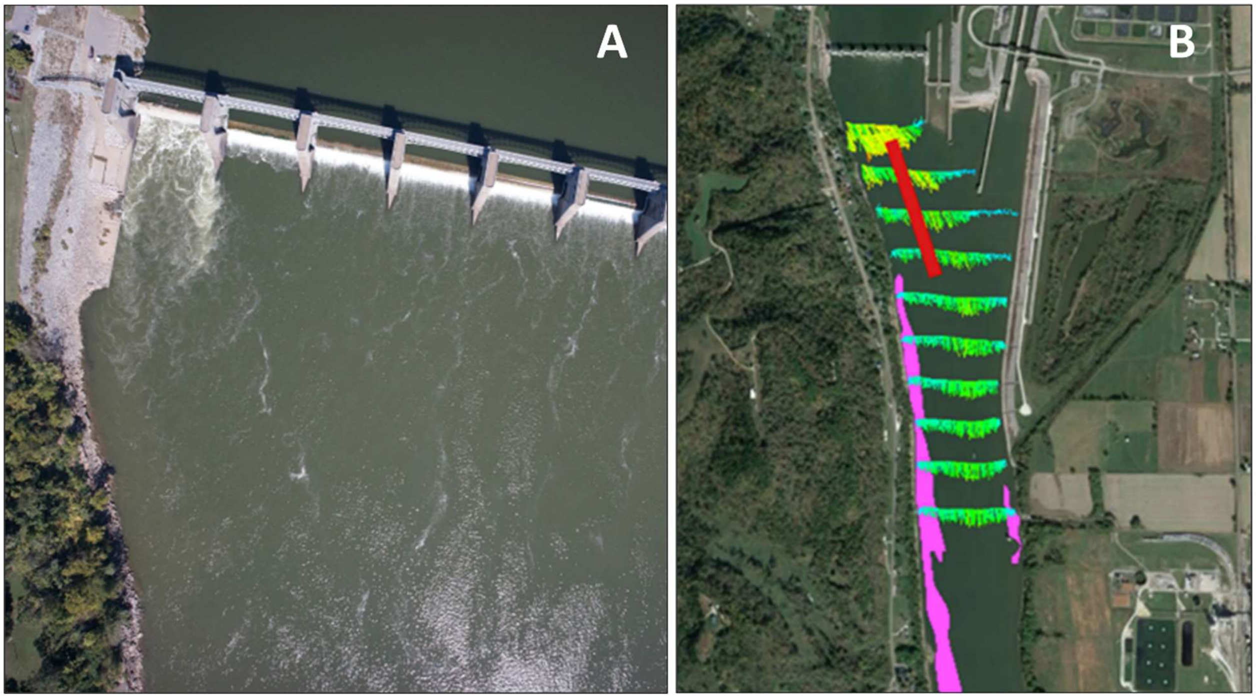

Figure 7. R.C. Byrd Locks and Dam satellite image showing (A) gate operations to produce a 'steering current' and (B) the acoustic Doppler monitoring during dredging operations. Note: The dredge placement area is shown as a red polygon. The mussel beds are shown as light purple polygons along both banklines. Velocity vectors are shown as thin arrows ranging in color from blue (slow) to green to yellow to red (fast) depending on intensity of flow. (Source: Google Earth. DigitalGlobe 2021. http://www.earth.google.com).

Broaden Benefits

The presence of diverse, high quality mussel beds on the right descending bank at R.C. Byrd requires careful planning and consideration when the project requires maintenance dredging. The historic disposal area was on the right descending bank, just below the dam. On suggestion of partnering agencies, it was relocated to a mid-channel area. This has proven to be a wise environmental choice, as mussel density and diversity have improved over time downstream of this location.

Nine mussel surveys have been conducted along the right descending bank downstream of RCB between 2001 – 2023 (McClane Environmental Services, 2012; McClane Environmental Services and Lewis Environmental Consulting, 2012; 2014; 2016; 2017; 2021; 2023; Table 3; Figure 8). American Municipal Power (AMP) Ohio also sponsored one mussel survey at this location during future planning for a possible hydroelectric facility at RCB (EA Engineering, 2009). All mussel surveys confirmed that a diverse mussel community exists along the right descending bank. These surveys have identified 27 live species in this reach of the Ohio River (Table 3). Of note is the presence of the federally endangered *Plethobasus cyphyus* mussel (Figure 9), which was encountered alive in 2009, 2011, 2016, 2017, and 2021 as well as a weathered dead relic shell in 2014 (Lewis Environmental Consulting 2021). In 2023, for the first time *Obovaria subrotunda* (round hickorynut) was present at the site which is a Federally threatened mussel species (Figure 9). Based on the results of these sampling efforts, the mussel community has shown improvement over time, with 2021 data indicating that the number of species collected, species diversity, and species evenness were improved compared to other years' surveys (Table 3; Figure 8).

Table 3. Summary of mussel survey data for R.C. Byrd Locks and Dam (2011, 2016, 2021, 2023; Lewis Environmental Consulting 2021, 2023).

	Number of Mussel Present			
Scientific Name	**2011**	**2016**	**2021**	**2023**
Actinonaias ligamentina		2	2	
Amblema plicata	35	36	32	41
Cyclonaias pustulosa	97	147	216	270
Ellipsaria lineolata	47	82	97	165
Ellipitio crassidens	7	15	19	28
Fusconaia flava				4
Lampsilis cardium	4	6	3	1
Lampsilis ovata		3	1	25
Lampsilis siliquoidea		2		4
Lampsilis teres	1			
Lasmigona camplanata	2		1	1
Leptodea fragilis	5		5	4
Ligumia recta	27	26	14	105
Magalonaias nervosa	2	2	5	6
Obliquaria reflexa	153	220	349	548
Obovaria subrotunda**				1
Plethobasus cyphyus*	1	1	1	
Pleurobema cordatum	7	9	11	18
Pleurobema sintoxia			1	
Potamilus alatus	30	32	21	75
Quadrula quadrula	1	2	8	10
Reginaia ebenus	1		3	2
Theliderma metanevra	8	15	15	16
Tritogonia verrucosa				1
Truncilla donaciformis		1		
Truncilla truncata	7	1	8	2
Total # Live[1] Mussels	**435**	**602**	**812**	**1327**
Total # Live[1] Species	**18**	**18**	**20**	**21**
Species Diversity[2]	**1.97**	**1.86**	**1.72**	**1.84**
Evenness[3]	**0.68**	**0.64**	**0.57**	**0.6**

[1]Live: encountered alive

[2]Species diversity (Shannon-Weiner Index); See Equation 1

[3]Evenness: See Equation 2

*Federally Endangered

**Federally Threatened

Of these surveys, data from 2011, 2016, 2021, and 2023 (Lewis Environmental Consulting 2021) had comparable methodology and spatial coverage to make meaningful comparisons of trends in mussel abundance. Overall, there is a positive increase in the number of live mussels present at the R.C. Byrd site since 2011, indicating that the sustainable dredging practices are providing positive ecological benefits. There were statistically greater number of live mussels at R.C. Byrd between the 2011 and 2016 survey dates (p=0.008; α = 0.05), and a statistically greater number of live mussels between 2016 and 2021 (p=0.01; α = 0.05), and 2021 and 2023 (p=0.01; α = 0.05). These data indicate that the innovations and efforts by the District's dredging program have minimize the dredging impacts which has allowed the mussel bed to grow in size, density, and diversity.

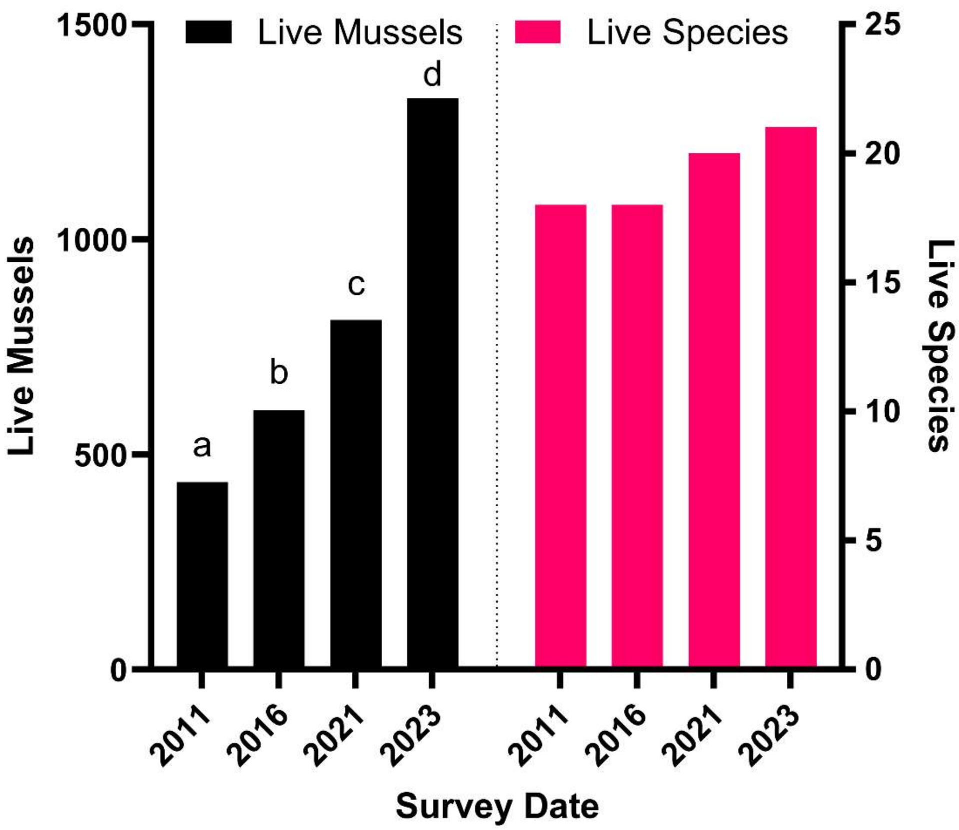

Figure 8. Summary of mussel survey data for R.C. Byrd Lock and Dam dredging monitoring (2011, 2016, 2021; 2023 data from Lewis Environmental Consulting 2021, 2023). Bars for live mussels with nonmatching letters are statistically different (*p*<0.05; α = 0.05).

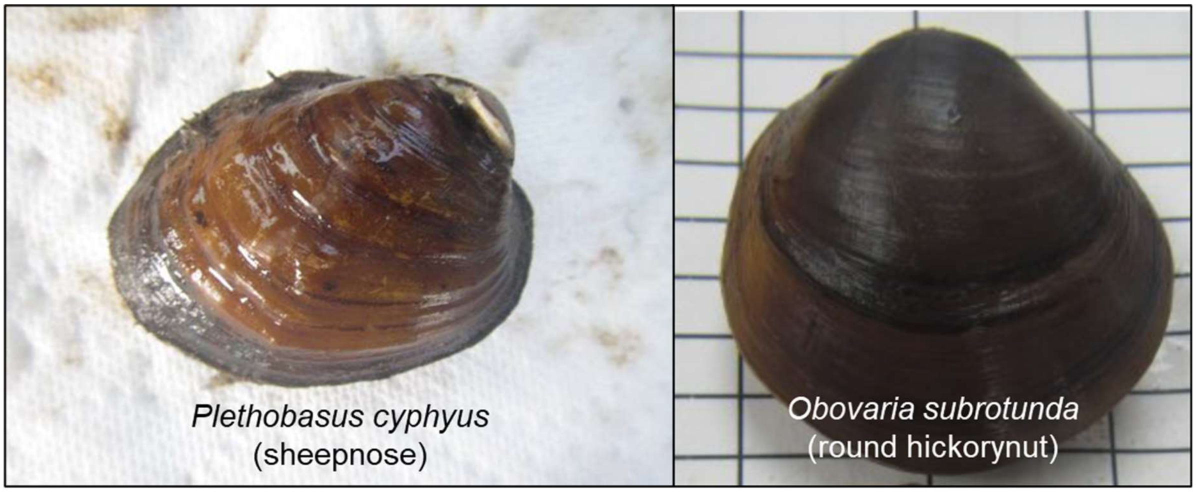

Figure 9. Photographs of Federally endangered mussel species *Plethobasus cyphyus* (sheepnose) (left) and Federally Threatened mussel species *Obovaria subrotunda* (round hickorynut) (right) observed downstream of R.C. Byrd Dam (from Lewis Environmental Consulting 2021, 2023).

Winfield Lock and Dam, Kanawha River

Beneficial use of dredged sediments at Winfield Lock and Dam have improved habitat and subsequently increased populations of mussels at the site (Table 4). Consequently, dredge material placement as a method for improving sediment characteristics conducive for mussel beds is a preferred in-river placement strategy recognized by state and federal wildlife agencies at this location. The Winfield site on the Kanawha River, a tributary to the Ohio River and a commercially navigable river managed by the District, is another example of efficient and sustainable use of dredge material. The material is placed against the bank, creating a velocity shelter which accumulates and maintains preferred substrates for mussels and fish. Since placement, increases in mussel density and diversity have been observed both upstream and downstream of the disposal location. Similar to the Bonanza Bar project, the in-river placement of dredged material at the Winfield site is considered a sustainable management practice consistent with EWN principles.

<u>Produce Efficiencies</u>

Notable efficiencies are being realized at the Winfield project location. This is especially true due to the development and maintenance of a velocity shed at the site using dredged material from the adjacent navigation channel. Because the disposal site location was on an outside bend just downstream of the navigation dam, much of the substrate had been scoured to bedrock. The multiple placement efforts over time have shielded downstream velocities and have not allowed the site to return to the previous hard bottom strata that prevented mussel bed establishment. In addition, relocating dredge materials have continued to seed the area with gravels, sands, and silts that promoted establishment and subsequent sustainment of the mussel beds.

Although data are incomplete at this project site, there are a few putative benefits that are being observed anecdotally. By decreasing the channel bank width through creation of the island bar, there is a potential for increased velocity and consequent decrease of material shoaled in the navigation channel. A notable example of this sustainable dredged material management practice is the Horseshoe Bend project in Louisiana on the lower Atchafalaya River (Foran et al., 2018). Reducing the distance for placement of dredged material reduces the cost of dredged material transport; for this reason, placement at the Winfield disposal site is the least cost placement alternative.

Overall, the efficiencies that are being realized at the Winfield disposal site are being derived by placement of the dredge material just beyond the curvature of the meander bend. This enables creation of an island bar which hydrodynamically confines flows on either side of the bar, contributing to a natural clean out of the navigation channel. This likewise offers a potential reduction of future dredging needs at this location.

Broaden Benefits

The use of this area for dredged material placement has improved the mussel habitat over the downstream area that previously consisted of boulders and bedrock, substrates that provide poor mussel habitat. The finer silts, sands, and gravels placed at the site are being relocated downstream by the river's energy and settling around the boulders and covering the bedrock, thus improving bottom habitat value for mussels (Huehner et al. 1987; Figure 10).

Mussel habitat exists downstream of the Winfield Lock and Dam (Figure 11). The District has sponsored five mussel surveys downstream of Winfield Locks and Dam between 2002 and 2023 (Table 4; Figure 12). All five of the mussel surveys generally covered the same area; however, they varied in coverage from year to year. Starting in 2014, surveys detected multiple areas where mussels were dense enough to be classified as a mussel concentration and as mussel beds. Results compared between the 2014 and 2023 surveys indicated a relatively similar number of mussels located around this placement area (Lewis Environmental Consulting 2018, 2023; Figure 12). In the most recent survey conducted in 2023, mussels were observed scattered throughout much of the survey site but were patchy in distribution and density.

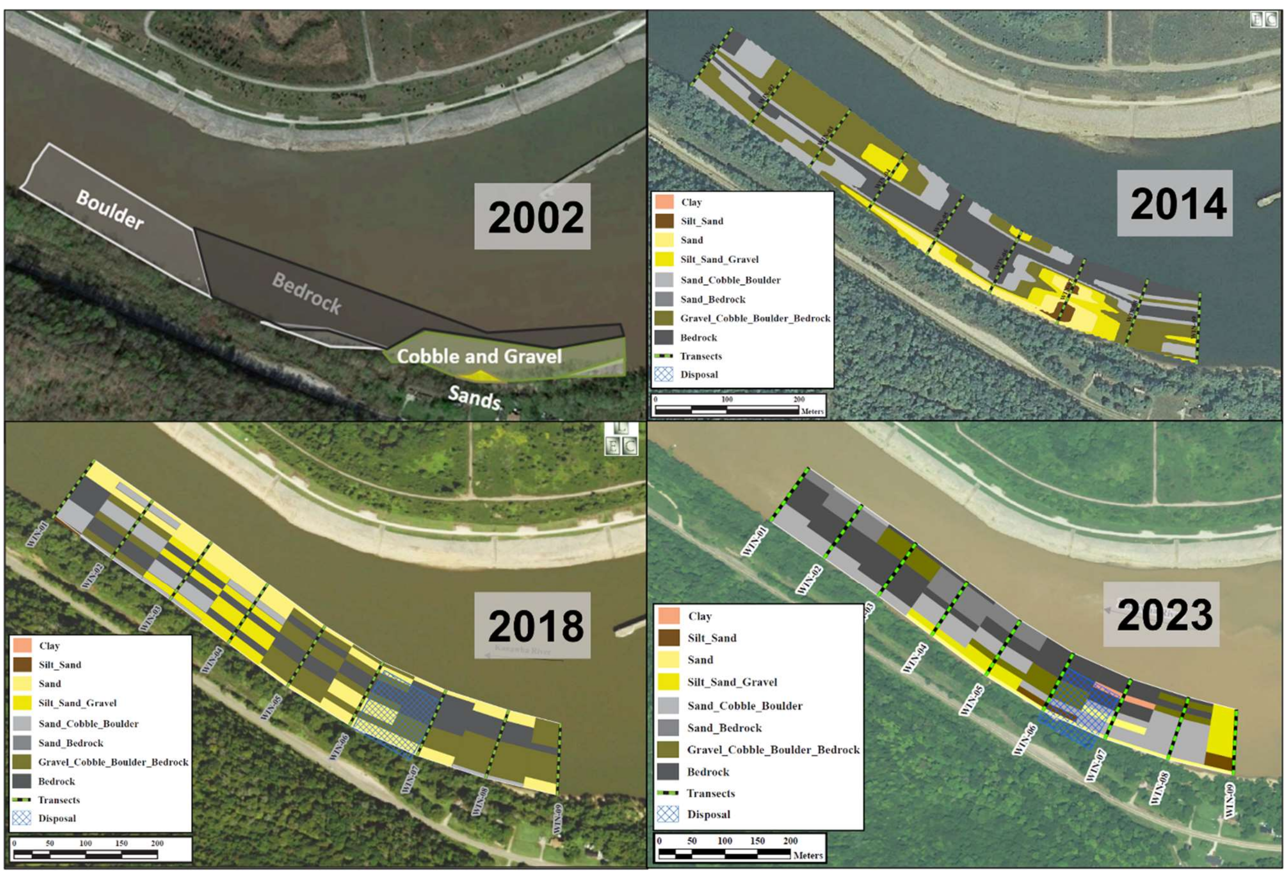

Figure 10. Delineation of habitat substrate types near the dredging placement area at the Winfield project site in 2002, 201, 2018, and 2023 (from Lewis Environmental Consulting 2018, 2023).

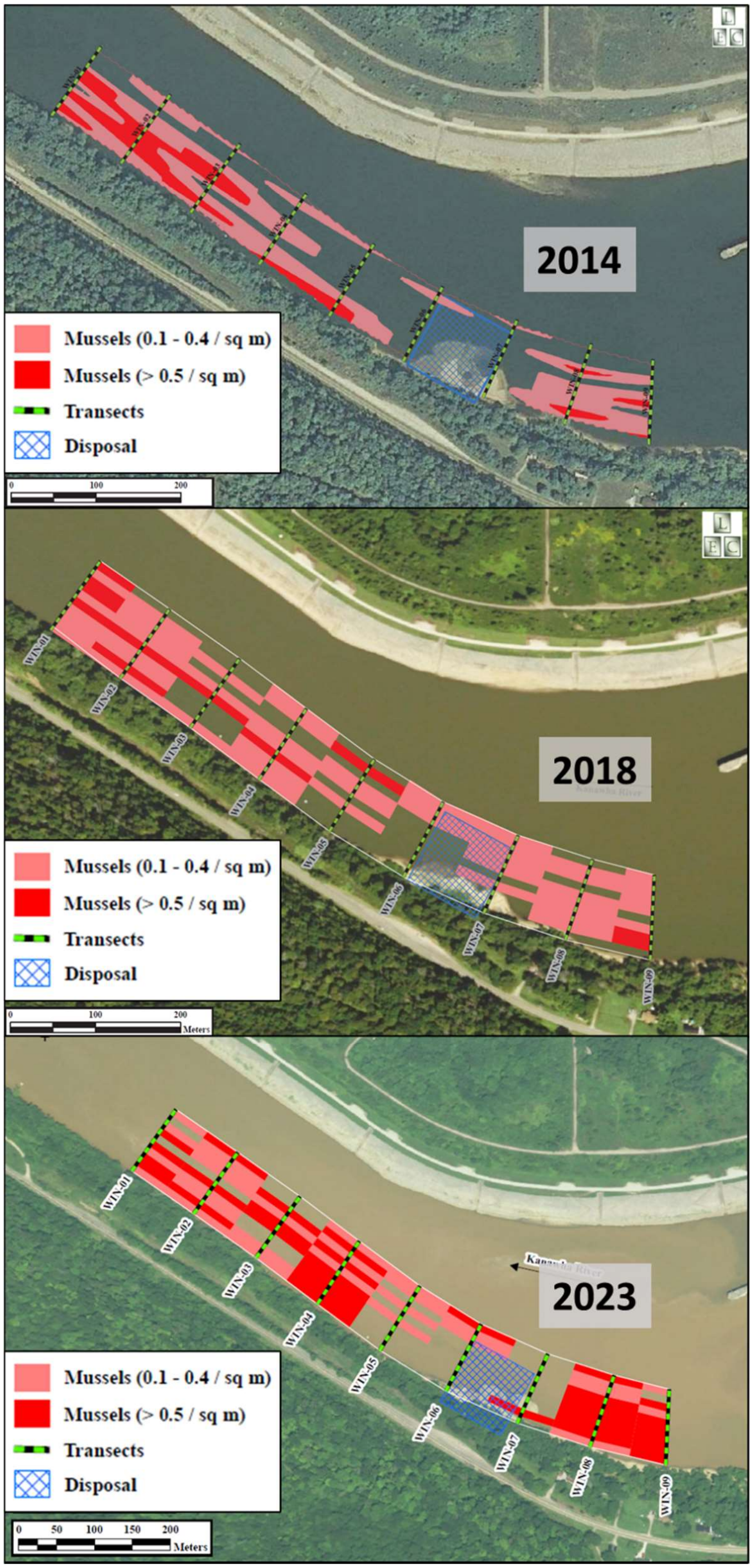

Figure 11. Mussel densities near the dredging placement area at the Winfield project site in 2014, 2018, and 2023 (from Lewis Environmental Consulting 2018).

Table 4. Summary of mussel survey data for Winfield Locks and Dam (2002, 2007, 2014, 2018; 2023; Lewis Environmental Consulting 2018, 2023).

	Number of Mussel Present				
Scientific Name	**2002**	**2007**	**2014**	**2018**	**2023**
Actinonaias ligamentina					3
Amblema plicata	3	1	22	8	67
Cyclonaias pustulosa			1	2	9
Cyclonaias tuberculata					1
Ellipsaria lineolata					1
Fusconaia flava			1		
Lampsilis cardium	1		3	3	4
Lampsilis ovata					13
Lampsilis siliquoidea					7
Lampsilis teres					3
Lasmigona camplanata	8		8	4	5
Lasmigona costata	1				
Leptodea fragilis	WD[2]		1	WD[2]	WD[2]
Ligumia recta			3	11	12
Megalonaias nervosa				1	
Obliquaria reflexa	2	1	24	51	80
Potamilus alatus	24	7	90	59	124
Ptychobranchus fasciolaris					1
Quadrula quadrula	5	5	43	37	82
Tritogonia verrucosa					1
Truncilla truncata			1		WD[2]
Total # Live[1] Mussels	**44**	**14**	**197**	**176**	**413**
Total # Live[1] Species	**7**	**4**	**11**	**9**	**16**
Species Diversity[3]	**1.38**	**1.09**	**1.73**	**1.60**	**1.89**
Evenness[4]	**0.71**	**0.78**	**0.89**	**0.72**	**0.68**

[1]Live: encountered alive

[2]Weathered dead: encountered as a weathered dead (WD) shell only; not included in live counts

[3]Species diversity (Shannon-Weiner Index); See Equation 1

[4]Evenness: See Equation 2

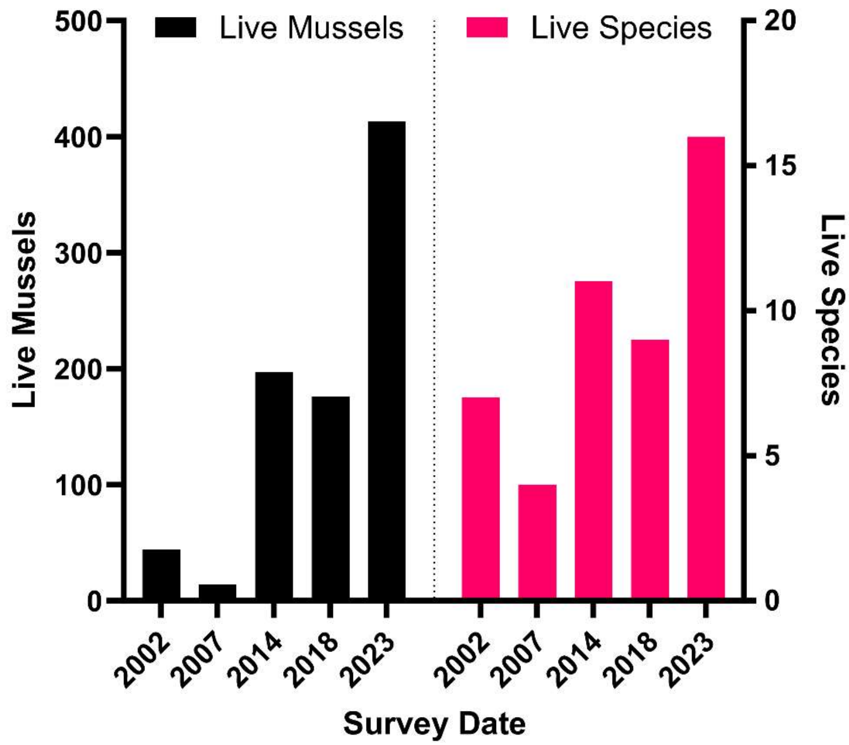

Figure 12. Summary of mussel survey data for Winfield Locks and Dam (2002, 2007, 2014, 2018; 2023; data from Lewis Environmental Consulting 2018, 2023).

CONCLUSIONS

The District's sustainable dredge material management practices on the Ohio and Kanawha Rivers have successfully applied innovations to achieve multiple benefits while executing the USACE's navigation, water operations, and ecosystem restoration missions. The three projects presented in this paper demonstrate practices in riverine environments that apply principles of sustainable dredging and EWN by leveraging natural processes, producing efficiencies, broadening benefits, and intentionally and meaningfully engaging meaningful science-based collaboration to achieve shared goals. Data and lessons learned from these projects can be applied elsewhere to enhance development of USACE sustainable dredging practices, inform data gaps in riverine projects with the goal of achieving increased sediment beneficial use, and provide inspiration for future projects. Some of the key benefits achieved include:

- Restoring the historic Bonanza Bar island footprint and side channel habitat has allowed for more efficient dredge placement, reduced timing, frequency, and cost of dredging in the adjacent navigation channel, while providing valuable ecological habitat and recreational opportunities.

- Innovations in managing water operations at R.C. Byrd Locks and Dam during dredge placement activities allowed the District dredging program to meet goals of supporting safe and reliable waterborne transport while protecting sensitive mussel bed habitat from dredge plumes and redeposition of sediments.

- Advanced environmental monitoring tools at R.C. Byrd dredge sediment placement allows for real-time monitoring of turbidity and sedimentation and improves risk communication and management of nearby sensitive mussel beds. These monitoring advancements have improved protective measures to be implemented during placement operations while concomitantly improving stakeholder relationships.

- Beneficial use of dredged sediments at Winfield Locks and Dam have improved habitat and subsequently increased downstream populations of mussels. Consequently, dredge material placement in-river as a method for improving sediment characteristics conducive for mussel beds is a preferred placement strategy recognized by state and federal wildlife agencies at this location.

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DATA AVAILABILITY

All data provided in this report are available from the corresponding author by request. Andrew McQueen; andrew.d.mcqueen@usace.army.mil

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