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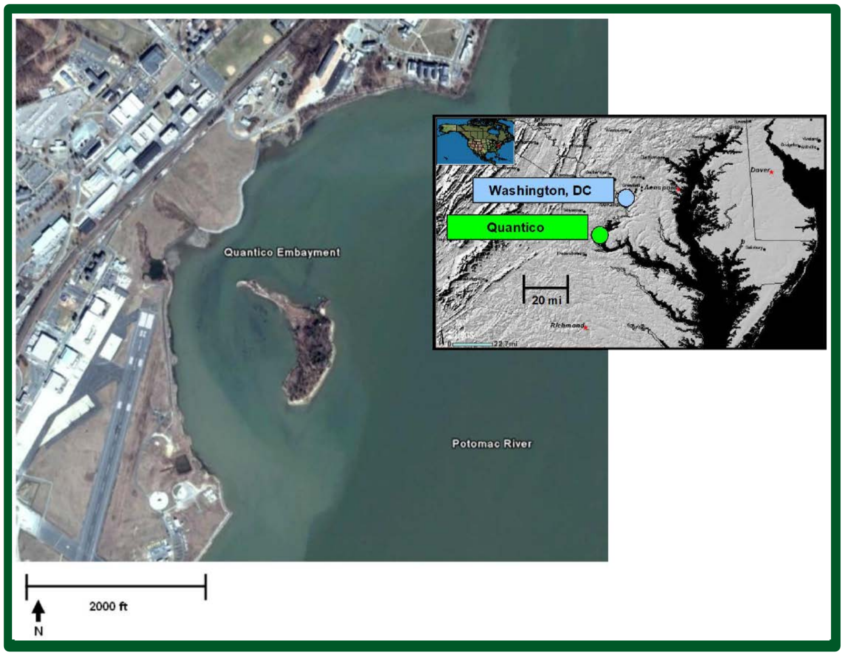

Demonstration and Validation of Enhanced Monitored Natural Recovery at DoD Sites

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14. ABSTRACT The objective of this project is to foster broader understanding and acceptance of the EMNR remedy through demonstration and validation of performance and cost-effectiveness at DoD contaminated sediment sites. Broader use of EMNR has several potential benefits to DoD and the broader scientific community, including reduced material costs compared to conventional isolation capping and/or dredging, accelerated recovery and reduced long-term monitoring costs compared to MNR, elimination of removal and disposal costs associated with dredging, and elimination/reduction of impacts to benthic communities compared to conventional isolation capping and dredging remedies. Because most of the contaminated sediment at Navy/USMC and DoD sites often falls into the "moderately" contaminated classification, EMNR has the potential to find widespread application, particularly as an adjunct to other more active remedies that might be applied in areas of higher contamination at the site. With cleanup costs estimated to exceed $1B, the broader application of EMNR could save DoD tens to hundreds of million dollars. EMNR also could facilitate more rapid acceptance and site closure for DoD sites where MNR is the most appropriate remedy but agency resistance or concerns make MNR acceptance difficult.

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Enhanced Monitored Natural Recovery, sediments, Chemicals of concern, GPS, Habitat Enhancement Cap, Investigation-Derived Waste, National Pollutant Discharge Elimination System, Remedial Design, Thin layer capping, Total organic carbon

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ACRONYMS AND ABBREVIATIONS

%	Percent
µg/kg	Microgram per kilogram
µm	Micrometer
B-IBI	Benthic Index of Biotic Integrity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm	Centimeter
CoC	Chemicals of concern
CTD	Conductivity, temperature, and density sonde
CY	Cubic yard
DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DDX	The sum of DDD, DDE, and DDT
DoD	Department of Defense
DoN	Department of the Navy
DQOs	Data quality objectives
D50	Median particle size
ENMR	Enhanced monitored natural recovery
ENVIRON	ENVIRON International Corporation
ER-N	Environmental Restoration – Navy
ESTCP	Environmental Security Technology Certification Program
FS	Feasibility study
ft	Foot or feet
GPS	Global positioning system
HEC	Habitat enhancement cap
IDW	Investigation-derived waste
in	Inch(es)
IRA	Interim remedial action
LTMP	Long-term monitoring plan
m	Meter(s)
m^2	Square meter(s)
MCB	Marine Corps Base
MHHW	Mean higher high water

MLLW	Mean lower low water
mm	Millimeter(s)
MNR	Monitored natural recovery
MQO	Measurement quality objective
MSL	Mean sea level
NCP	National Contingency Plan
NOV	Notice of violation
NPDES	National Pollutant Discharge Elimination System
OBS	Optical back scatter
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PO	Performance objective
ppb	Parts per billion
ppt	Parts per thousand
PRG	Preliminary Remediation Goal
PSD	Particle size distribution
psu	Practical salinity units
QAPP	Quality Assurance Project Plan
QWS	Quantico Watershed Study
RD	Remedial design
SARA	Superfund Amendments and Reauthorization Act
SEAP	Sediment Ecosystem Assessment Protocol
SED-FSP	Sediment friction sound probe
SPI	Sediment profile imagery
SPME	Solid-phase microextraction
SSC	SPAWAR Systems Center
SWI	Sediment-water interface
t	Time
TLC	Thin-layer capping or thin-layer cap
TOC	Total organic carbon
USMC	United States Marine Corps
VADEQ	Virginia Department of Environmental Quality
y	Year

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The objective of this project was to foster broader understanding and acceptance of the enhanced monitored natural recovery (EMNR) remedy through demonstration and validation of performance and cost effectiveness at contaminated Department of Defense (DoD) sediment sites. Our approach to demonstration and validation of the EMNR process focused on the following key technical performance issues:

- Utility of available monitoring tools to address EMNR performance
- Short-term implementation success
- Ability to project the potential for long-term remedy success
- Determination of the mechanisms and processes that regulate EMNR effectiveness

These demonstration and validation criteria formed the basis of the Performance Objectives (POs). Data was collected in support of these POs and provided multiple lines of evidence for assessing the effectiveness of EMNR as a remedy at contaminated sediment sites.

TECHNOLOGY DESCRIPTION

EMNR involves the placement of a thin layer (commonly, < 30 cm) of clean sand or clean sediment over contaminated sediment, coupled with ongoing natural recovery processes and a monitoring program, to achieve ecological recovery and risk reduction at contaminated sediment sites. In general, this thin-layer capping (TLC) is not designed to provide complete chemical isolation, but to provide a reasonable degree of physical isolation and reduction towards lower chemical concentrations targeting site-specific remedial action objectives and remedial goals; EMNR also reduces potential resuspension or transport of contaminated sediment particles (Palermo et al., 1998).

The project site for implementation of this study was Site 99, the Quantico Embayment site, Quantico, Virginia. Grain sizes of the TLC were selected in the final design to be stable during both normal river flows and during periods of flood flows and storm-generated waves. Ideally, sediment sizes would be chosen to match surrounding grain sizes within the freshwater tidal systems of the Potomac River. While clean sand was used at the Quantico Site, TLC material can include a broader range of clean material, including clean dredged sediment that meets the chemical criteria for reuse. In some cases, dredged sediment may be preferable to quarried sand because it has natural organic matter to support benthic life and to help sequester and retard dissolved contaminant transport from underlying sediment.

DEMONSTRATION RESULTS AND POTENTIAL IMPLEMENTATION ISSUES

Although conventional isolation caps have demonstrated effectiveness in the management and remediation of chemically impacted sediment, rigorous demonstration and validation of the effectiveness of EMNR remains limited (USEPA 2005). Ongoing questions regarding the application, performance, and ecological impacts of EMNR have limited its widespread implementation.

To address these implementation issues, the following relevant questions were posed. Evaluation of these questions based on the literature compiled and the demonstrations conducted as part of this project are presented below.

Is artificially increased sediment deposition via TLC placement an effective strategy for enhancing MNR and accelerating natural system recovery rates?

The effectiveness of the TLC strategy for accelerating MNR appears to be a viable remediation approach depending on site conditions. From a process perspective, key aspects of the success of the TLC and the overall EMNR approach are that: (1) the TLC remain relatively stable above the sediment to be isolated; (2) any new deposition is relatively clean compared to surface sediment goals, even if the rate of deposition is low; (3) bottom-up mixing of the TLC is limited to the extent that the elevated levels of contamination in the underlying sediment do not unduly influence the exposure in the surface sediments following placement of the TLC; (4) advection rates through the cap are not so significant that they lead to a high level of porewater movement from below the TLC into the TLC; and (5) the remedy should demonstrate direct reduction in bioavailability over the short term and long term. For the Quantico embayment site, all of these conditions were documented to be satisfied. Multiple measures of cap thickness and elevation indicated that the cap material was maintaining relative stability within design guidelines. New deposition, as characterized by sediment traps and surface sediment interval samples, was generally low in DDX (the sum of dichlorodiphenyldichloroethane (DDD), dichlorodiphenyldichloroethylene (DDE), and dichlorodiphenyltrichloroethane (DDT)). Bottom-up mixing was documented to be limited. While advection rates were not directly measured, porewater measurements at critical intervals within the cap showed that advection was not significant enough to unduly influence the concentrations within the cap. Finally, direct measurements of bioavailability including uptake in organisms and porewater concentrations generally indicated significant reductions over both short and long time periods out to two years.

How sensitive is EMNR performance to the accuracy of TLC placement?

Sensitivity of the EMNR performance to the accuracy of TLC placement appears to be relatively high because the layer being applied is generally thin and on the same order of magnitude in thickness as the bioactive zone of the sediments. To be effective, the TLC must also accommodate a certain degree of bottom-up mixing that is likely to occur either during the installation or due to physical or biological disturbance over time. Thus, key aspects of the sensitivity to placement include the relative thickness of the TLC compared to the bioactive zone, the degree of bottom-up mixing that is expected based on construction methods, and site-specific likelihood of physical and biological disturbance following placement. For the demonstration at Quantico Embayment, the bioactive zone was relatively shallow because of the freshwater, riverine nature of the site. Also, it was observed that the installation of the TLC generally achieved target thickness throughout the site so that there were few areas where biological activity was likely to interact with the underlying sediments.

What are the short-term construction (risk-of-remedy) effects associated with EMNR and to what extent does TLC application influence benthic community survival?

The primary risks related to the construction of the TLC appear to be potential short- to mid-term effects on the benthic community, along with some amount of disturbance of the native sediment associated with the depositing of the TLC material. The effects on the benthic community are expected to be a function of both the initial covering of the native sediments, which can result in smothering of the existing infaunal community, as well as the potential that the community could be degraded over the mid-term as a result of the differing grain size and total organic carbon (TOC) characteristics of the TLC material. From our laboratory treatability studies, we observed significant smothering effects from placement of thin layers of sand over infaunal organisms. However, at the demonstration site at Quantico Embayment, we observed relatively rapid recovery of the benthic community following construction of the TLC. While the sand material may not have provided optimal habitat initially, it was observed that over time, top-down mixing of relatively clean sediment deposits into the surface layer tended to improve the habitat characteristics, and a general improvement in benthic community health was observed.

Under what range of physical, biological, and chemical conditions will EMNR be effective?

The range of effectiveness of EMNR was not completely explored in this project. However, general considerations for the selection of EMNR are becoming well established. From a physical perspective, the remedy should generally be applied at sites that are relatively quiescent and not subject to significant physical disturbance that would disrupt or penetrate the cap to a degree that the underlying sediments would be re-exposed or significantly mixed into the TLC. The native materials must also have the physical strength to support the TLC so that gravitational mixing does not lead to failure of the TLC. From a biological perspective, the TLC thickness should consider the nature and scale of bioactivity in the surface sediments and the expected route of exposure for the risk endpoints under consideration. From a chemical perspective, EMNR is generally viewed as being most effective at sites where MNR would be effective, but deposition rates are potentially too low to reach the desired clean-up goals in a reasonable amount of time. Most sites where EMNR has been applied have exposure levels that are near risk thresholds, as opposed to higher concentration hot spots. For the Quantico Embayment site, our results reflect these physical, biological, and chemical conditions.

With respect to grain size, TOC content, and other biogeochemical parameters that influence habitat quality, how can EMNR design be optimized?

This remains a key question that was not thoroughly addressed in this project. Follow-on studies have been proposed to address this optimization question. In general, EMNR has been carried out using TLCs constructed with sand, which is optimal from a stability and construction perspective, but not necessarily optimal from a habitat or environmental protection perspective. The sand materials are often not consistent with the grain size characteristics of the native sediments, and thus create a habitat that is also inconsistent with the site conditions. In addition, the sand material contains essentially no TOC, which may create a less optimal habitat while also providing little to no binding capacity for contaminants. While the traditional sand TLC was shown to be effective over two years at the Quantico Embayment site, future development of a more comprehensive approach and guidance for the selection and optimization of EMNR that addresses this question would be highly beneficial to the broader implementation of the remedy.

How effective is EMNR in reducing chemical mobility and biological exposure potential in surface sediment?

Overall, review of the historical literature, coupled with our experience with the Quantico Embayment site, indicated that EMNR can be highly effective in reducing exposure in surface sediments. EMNR remedy effectiveness seems to be a function of three primary considerations: site condition for the selection of EMNR, proper design of the EMNR remedy to meet site-specific conditions, and adequate monitoring to assure remedy success and address any potential defects in the TLC. For the Quantico Embayment site, the EMNR remedy was shown to be effective in reducing exposure in surface sediments as measured by bulk sediment total DDX concentrations, porewater DDX concentrations, and direct measurement of bioaccumulation in two site-exposed benthic organisms.

1.0 INTRODUCTION

This project evaluated the performance of enhanced monitored natural recovery (EMNR) as an innovative and cost-effective remedy for legacy sediment contaminants. This evaluation was conducted under field conditions at the Quantico Marine Corps Base (MCB), Quantico, Virginia. The remedy involved the placement of a thin-layer cap (TLC) of clean sand to enhance natural recovery and reduce contaminant bioavailability to benthic organisms and subsequent potential threats to higher trophic levels.

1.1 BACKGROUND

Contaminated sediment clean-up costs at Navy and United States Marine Corps (USMC) sites are estimated to exceed $1 billion. For these sites, ecological recovery and reduced exposure risks are achieved primarily by reducing chemical bioavailability and exposure in surface sediment, thereby controlling or eliminating chemical exposure pathways. However, moderately impacted Navy/USMC sites lack cost-effective remedies for sediment management. Currently, the primary remedial options implemented by the Navy/USMC are dredging, isolation capping, and monitored natural recovery (MNR, USEPA 2005). Dredging is expensive, difficult to implement without generation of residuals, and may result in negative impacts to aquatic habitat, the benthic community, and surface water quality. Conventional isolation capping, although less expensive than dredging, may also negatively impact benthic community structure and composition and, by altering site bathymetry, may negatively influence the quality of aquatic and near-shore habitats. MNR is cost effective, but its utility as a remedial strategy is highly site-specific and may require years or decades to demonstrate adequate risk reduction.

EMNR refers to the combination of MNR with TLC, and it has the potential to accelerate and improve the effectiveness of MNR as a remedial strategy. A hypothetical demonstration of the benefit of TLC addition to MNR is presented in Figure 1. The MNR scenario in Figure 1 represents an environment in which capping is not considered as a component of system recovery. Both the MNR and EMNR surface sediment concentrations approach regional background levels with time. The EMNR scenario accelerates sediment concentration reductions, but results in some level of rebound due to the natural deposition of sediments with background chemical concentrations over the clean cap material. The rebound also may be due to biological mixing of the clean sediment material with underlying native sediment or porewater migration through the TLC. Notably, background chemical concentrations establish asymptotic clean-up levels for all technologies, including capping and dredging.

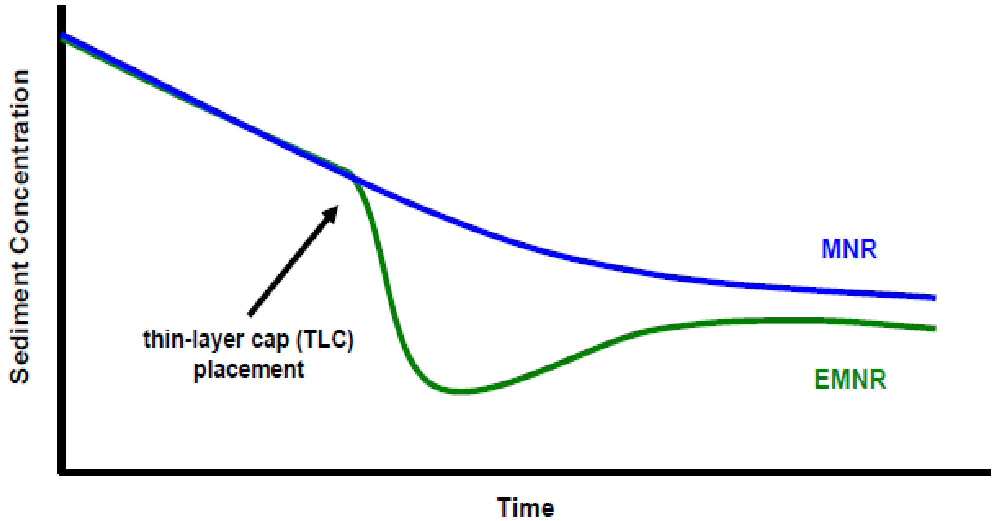

Figure 1. Hypothetical Relationship between Chemical Concentrations in Surface Sediment and Temporal Evolution of System Recovery under MNR and EMNR.

1.2 OBJECTIVE OF THE DEMONSTRATION

This project aims to broaden understanding and acceptance of the EMNR remedy through demonstration and validation of performance and cost effectiveness at contaminated DoD sediment sites. Our approach to demonstration and validation of the EMNR process will focus on the following key technical performance issues:

- Utility of available monitoring tools to address EMNR performance
- Short-term implementation success
- Ability to project the potential for long-term remedy success
- Determination of the mechanisms and processes that regulate EMNR effectiveness

These demonstration and validation criteria form the basis of the Performance Objectives (POs). Data was collected in support of these POs and provided multiple lines of evidence for assessing the effectiveness of EMNR as a remedy at contaminated sediment sites. Results of this demonstration will provide DoD site managers and regulatory agencies with well-documented cost, performance, and risk-of-remedy data with which to evaluate EMNR during the remedy selection phase and to gauge remedy effectiveness during the monitoring phase.

1.3 REGULATORY DRIVERS

The remedy at the Quantico Embayment is being conducted in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA). Implementation of the CERCLA remediation process is outlined in Title 40 of the Code of Federal Regulations (40 CFR) Part 300, National Oil and Hazardous Substance Contingency Plan (NCP).

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

EMNR couples TLC—the placement of a thin layer (commonly less than 30 cm) of clean sand or clean sediment over contaminated sediment—with ongoing natural recovery processes and a monitoring program to achieve ecological recovery and risk reduction at contaminated sediment sites. In general, the TLC is not designed to provide complete chemical isolation, but to provide a reasonable degree of physical isolation and to rapidly achieve low chemical concentrations targeting site-specific remedial action objectives and remedial goals; EMNR also reduces potential resuspension or transport of contaminated sediment particles (Palermo et al., 1998).

The design thickness for a TLC is typically driven by the bioturbation depth for organisms that are expected to colonize the cap surface, underlying sediment chemical concentrations, and the expected contribution of natural deposition processes to further isolate sediment contaminants. Accurate placement with respect to cap thickness presents a significant challenge to TLC. The industry has developed a variety of cap placement methods to improve placement accuracy and to assure uniform distribution of cap materials. The thinness of the cap generally produces minimal impact on bathymetry, permitting application in areas where thicker caps would not be feasible without dredging. Material selection is critical in assuring a reasonable degree of stability in the response to currents, waves, and other potential physical disturbances.

EMNR has emerged over the last 5–10 years as a viable hybrid of traditional capping and MNR. The development and application of the technology thus draws heavily from the lessons learned in the development of these component remedies. EMNR can be viewed in two phases: the active phase when the TLC is implemented and the performance/recovery phase during which the effectiveness of the TLC and ongoing natural processes are gauged through monitoring. The active phase of EMNR diverges from traditional capping in its reliance on a relatively thin cap layer; to assure effectiveness, cap thickness generally must be more carefully regulated for EMNR than for a thicker isolation cap. The performance phase integrates monitoring strategies consistent with both capping and MNR. At most sites, effectiveness is based on the combination of the TLC and ongoing deposition processes that combine to reduce surface sediment chemical concentrations and isolate deeper sediment contaminant deposits.

As documented in the *Review of Thin-Layer Placement Applications to Enhance Natural Recovery of Contaminated Sediment* (Merritt et al. 2010), EMNR has been implemented successfully at the Wyckoff/Eagle Harbor Superfund Site in Bainbridge Island (Washington), the Ketchikan Pulp Company Site in Ketchikan (Alaska), and the Bremerton Naval Complex in Bremerton (Washington). Chemicals of concern (CoC) addressed using EMNR include mercury and other metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and diffusive toxicants including sulfide, ammonia, and 4-methylphenol. For these sites, EMNR was selected for those portions of the remedial area in which stated goals were to reduce the concentration of chemicals in the biologically active zone of sediment in a manner that would enhance the potential for ecologically balanced re-colonization, while not causing widespread disturbance to existing habitat.

2.2 CHARACTERISTICS OF THE TLC AT THE QUANTICO MARINE CORPS BASE, QUANTICO, VIRGINIA

The project site for implementation of this study was Site 99, the Quantico Embayment site, Quantico, Virginia (Figure 2). Conceptual design drawings of the Quantico TLC are presented in the Draft-Final Remedial Design (Battelle 2009) and include plan view, cross-sectional representations of the cap, and highlights shore-side topography and placement area bathymetry. At the Quantico Embayment site, the EMNR cap was designed to address sediments that are moderately contaminated with the chlorinated pesticide dichlorodiphenyltrichloroethane (DDT) and its derivatives dichlorodiphenyldichloroethane (DDD) and dichlorodiphenyldichloroethylene (DDE). For this document, when not specified individually, DDT, DDD, and DDE are defined collectively as DDX.

The contaminated sediment within the Quantico Embayment remedial footprint (10.9 acres) was covered with a thin-layer Habitat Enhancement Cap (HEC) (Figure 3). The HEC (also referred to in this document as a thin-layer cap) involved placement of capping material (sand) under water. It was designed to provide physical isolation of the contaminated sediment from the benthic environment while preventing resuspension or transport of contaminated sediment, providing viable wetland habitat for several species. With the exception of the Sewage Treatment Plant drainage channel, no dredging or excavation was conducted.

The HEC was constructed in the summer of 2014 and the grain sizes of the cap material were selected in the final design to be stable during not only normal river flows, but also periods of flood flows and storm-generated waves. Ideally, sediment sizes would be chosen to match surrounding grain sizes within the freshwater tidal systems of the Potomac River. The HEC material consisted of common sand fill material, poorly to well sorted with less than five percent fines passing a 200-micron sieve and with a grain size distribution characteristically between fine and coarse grain. The material had a minimum median particle size (D50) of 0.5 mm or greater (NAVFAC WA 2011).

For the Quantico Embayment, the HEC was placed by spreading a sand slurry over the remedial footprint. Sand was delivered to the site by truck and barge and transferred into a mixing tank, where water was added to form a slurry. The slurry was pumped to a shallow-draft spreader barge that discharged it at a carefully controlled rate to spread the cap material evenly over the sediment. Because it was not possible to place a perfectly uniform cap layer underwater, and to place a cap with a minimum thickness of six inches, construction specifications called for the placement of an average of 9–12 inches of material over the remedial footprint to ensure a minimum of six inches throughout (NAVFAC WA 2011).

Additional details regarding cap placement were defined in the Final Remedial Action Work Plan dated February 2012 (AGVIQ-CH2M HILL 2012) and are not discussed further in this document.

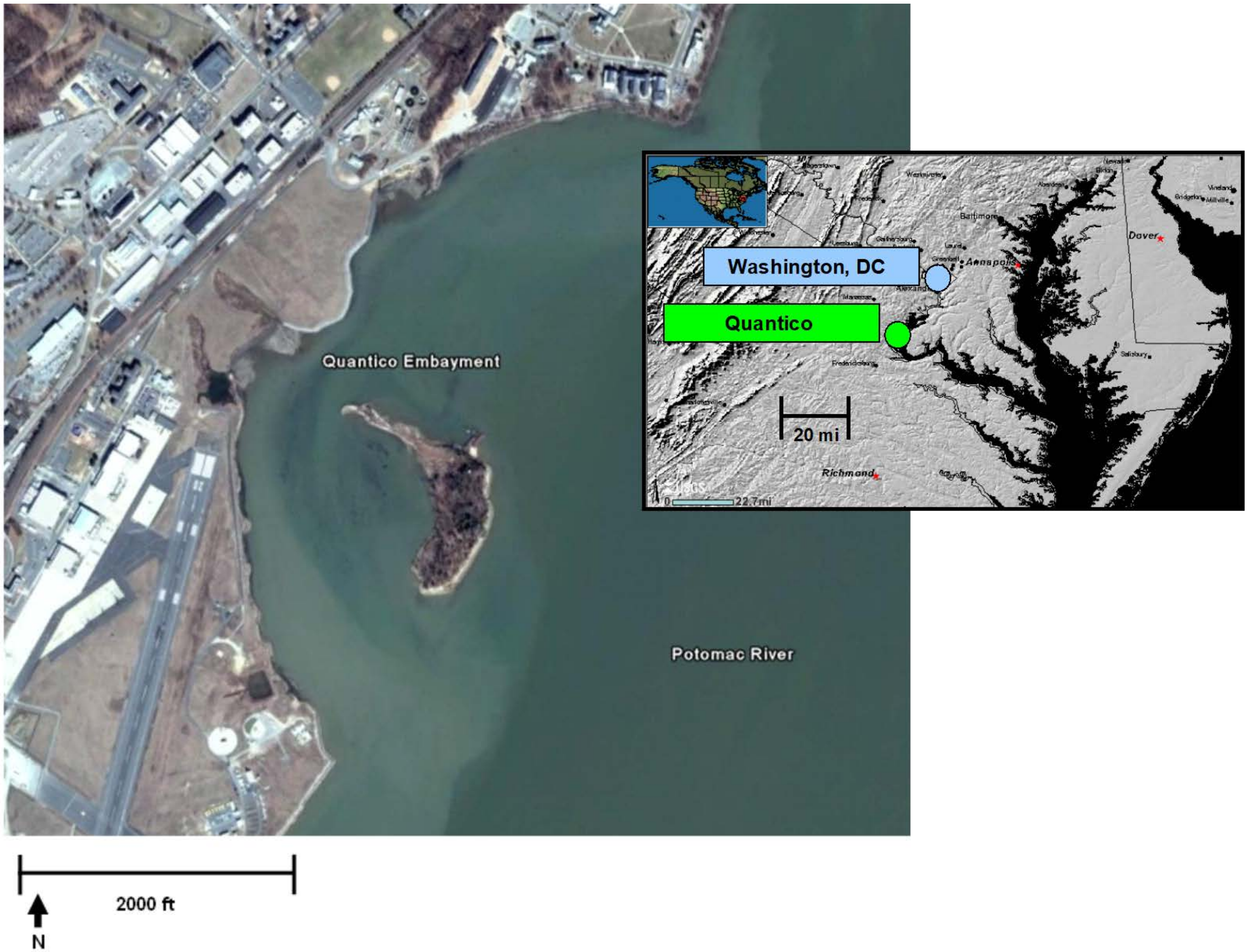

Figure 2. **Quantico Embayment, Quantico Marine Corps Base, Quantico, Virginia.**

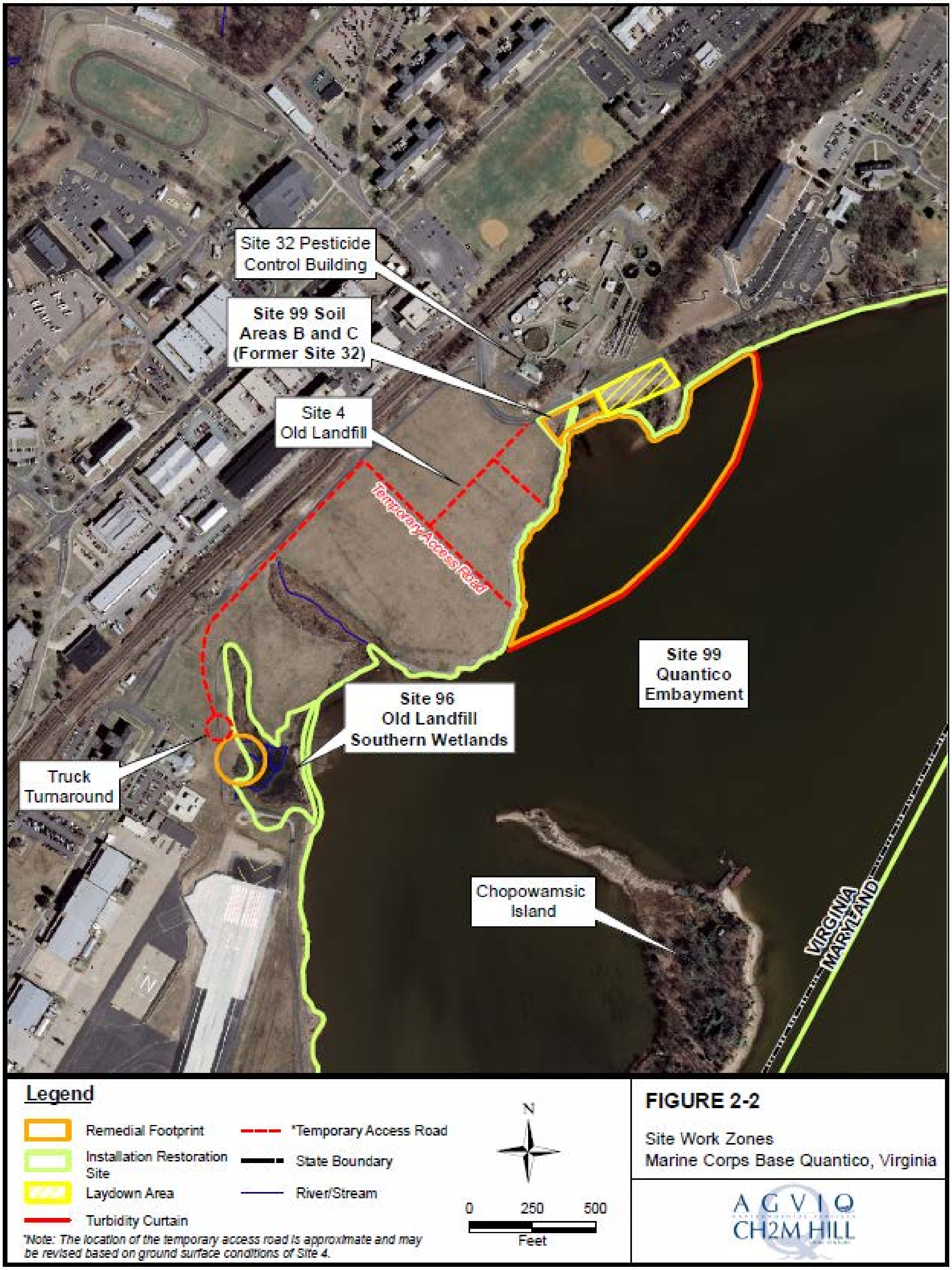

Figure 3. **Site 99 Work Areas (referenced from AGVIQ-CH2M HILL 2012).**

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Successful implementation of EMNR is contingent on both the effectiveness of the capping technology and the degree to which background site conditions are understood. If both aspects of implementation are realized, EMNR is expected to result in a stable, *in situ* sediment remedy that is accomplished with minimal short-term disturbance to the benthic ecosystem. As with all *in situ* remedies, limitations to success include the fact that the remedy leaves chemical contaminants in place and that changes to site hydrodynamic conditions (such as those resulting from long-term variation in near-shore land use, flow magnitude, or tidal range) could impact the long-term physical stability of the cap. Such limitations can be overcome, however, with careful design considerations and an accurate, site-specific understanding of the role that hydrodynamics plays in chemical fate and transport, and by institutional controls that limit anthropogenic disturbances of the remedy.

As a primary advantage, EMNR provides a low-cost alternative that leverages ongoing natural recovery processes and accelerates them to cost-effectively reduce ecological and human health risks. EMNR also minimizes ecological impacts that may be realized by more aggressive technologies like dredging and capping. By minimizing negative ecological impacts, EMNR may be more ecologically suited to existing habitats and may be employed to accelerate post-remediation habitat recovery.

EMNR presents as primary disadvantages a higher cost than a pure MNR remedy, a minimal barrier provided by the thin cap over the contaminated sediments, and a limited binding capacity of sand materials generally used, which may not always protect against porewater migration or other processes that may introduce contamination to the cap.

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3.0 PERFORMANCE OBJECTIVES

This demonstration project was designed to evaluate the performance and effectiveness of the Quantico EMNR remedy and the utility of available monitoring tools to address EMNR performance, short-term implementation success, the ability to project long-term remedy success, and the understanding of the mechanisms and processes that regulate EMNR effectiveness.

The demonstration project was designed to provide baseline (pre-cap construction) monitoring and post-construction long-term monitoring at 2, 14, and 25 months after installation of the EMNR cap. Performance was analyzed using a combination of quantitative and qualitative tests to achieve the objectives of the project, provided in Table 1. The extent to which expected performance metrics were achieved was evaluated from data collected during the pre-construction baseline monitoring and post-construction monitoring.

Although the duration of this project may not be sufficient for a full evaluation of long-term remedy effectiveness, results of this project do provide insight into the overall effectiveness of the EMNR remedy over the two-year monitoring period. This demonstration project also evaluated the utility of various innovative tools and approaches to monitor remedy effectiveness; the efficacy of those tools also is evaluated herein. To the extent possible, the post-remedy two-year monitoring results were used to project certain facets of long-term remedy effectiveness using empirical data, conceptual models, statistical analyses, or other approaches. A fully definitive evaluation of remedy performance may require longer-term monitoring, the need for which is discussed in Section 8 and is also captured within the long-term monitoring plan for the site (Battelle and Neptune, 2010).

Table 1. Performance Objectives for EMNR at Quantico Embayment.

Performance Objective	Data Requirements	Success Criteria	Success Criteria Met
Evaluate cap placement and determine physical stability of TLC	Sediment core profiling (visual classification)	Average cap thickness should not be less than six inches or a minimum cap thickness of two inches in the areas targeted for a six-inch cap.	Yes
	Bathymetry	Bathymetric changes in elevation should be qualitatively consistent with cap thickness measurements made by coring. Average elevation change measured by bathymetry with cap thickness specifications at coring stations should be on the order of six inches and the majority of the cap area should show positive elevation change from 2014 baseline.	Yes
	Sediment Profile Imagery (SPI)	SPI camera should distinguish TLC from native sediment and resolve cap thicknesses less than or equal to the camera penetration depth. SPI measured cap thickness should be qualitatively consistent with cap thickness measurements made by coring.	Yes
	Sediment Friction Sound Probe (SED-FSP)	SED-FSP measurements should be able to distinguish TLC from native sediment with an accuracy in identifying mixing depth within 50% of estimates indicated by grain size analysis of sediment cores.	Yes
Determine the extent of sediment and contaminant mixing	Sediment core profiling (visual classification)	Mixing and deposition layers are clearly visible and can be distinguished from cap material. Mixing and deposition layer thicknesses can be quantified to support interpretation of contaminant profiles.	Yes
	SPI camera	SPI camera should distinguish mixing and depositional layers associated with the TLC and provide qualitative estimates of the degree of mixing to support interpretation of contaminant profiles.	Yes
	SED-FSP	SED-FSP should distinguish mixing and depositional layers associated with the TLC and provide qualitative estimates of the extent of mixing and deposition to support interpretation of contaminant profiles.	Yes
	Surface sediment total organic carbon (TOC) content and grain size	Changes in TOC and grainsize from baseline, post-cap placement, and long-term monitoring results can be used to quantify vertical mixing and deposition to support interpretation of contaminant profiles.	Yes
	Sediment Traps	Sediment trap mass provides quantitative estimate of new deposition. Sediment trap chemistry provides estimate of depositional flux to support interpretation of contaminant profiles.	Yes
	Surface sediment chemistry	Vertical mixing and deposition do not alter contaminant profiles sufficiently to cause failure of the EMNR remedy.	Yes
Evaluate surface sediment chemical concentration reductions	DDX analyses from core samples	Significant reduction in DDX compared to baseline and/or levels should not increase beyond sediment preliminary remediation goals (PRGs); 650 ppb total DDX. Reduction in exposure compared to baseline is sustained over 2 years.	Yes

Performance Objective	Data Requirements	Success Criteria	Success Criteria Met
Evaluate reductions in chemical bioavailability and bioaccumulation	*In situ* bioaccumulation tests	Significant reduction in bioaccumulation and surface sediment porewater concentrations of DDX compared to baseline. Reduction in bioaccumulation and porewater concentrations compared to baseline levels are sustained over 2 years.	Yes
	DDX concentrations in sediment porewater with passive samplers (SPME)		Yes
Determine the rate of benthic recovery	Pre- and post-cap placement benthic taxonomic surveys	Comparable or improved benthic community conditions relative to baseline by the end of the two-year monitoring period.	Yes
	SPI camera images within and around perimeter of TLC footprint	Use SPI results to identify infaunal successional stages, RPD depth, and verify bioturbation depth.	No due to method limitations

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4.0 SITE DESCRIPTION

4.1 SITE LOCATION

The site selected for the EMNR demonstration is an embayment of the Potomac River referred to as the Quantico Embayment (Figure 2 and Figure 3). The Quantico Embayment is located at the Quantico Marine Corps Base (MCB), approximately 35 miles south of Washington, D.C., and 75 miles north of Richmond, Virginia. The site offered a unique opportunity to evaluate a full-scale implementation of EMNR at a DoD site. The costs associated with conducting this demonstration (estimated >$4 M for cap installation alone) would be prohibitive without the opportunity to leverage the effort with the ER-N remedial effort. The Quantico Embayment presented as a highly desirable site for demonstration and validation of the EMNR process because of the unique leveraging opportunity at a DoD site, the presence of a baseline ecological risk analysis (Battelle and Neptune and Co., 2004; TtNUS 2006; Battelle and Neptune and Co., 2005), the presence of existing data to characterize the nature and distribution of CoCs, including DDX, and the low energy conditions in the embayment. The location of the TLC in Quantico Embayment is presented in Figure 4.

Figure 4. Approximate extent of TLC in the Quantico Embayment. The cap area encompasses sediment with surface sediment DDX concentrations greater than or equal to 200 µg/kg (Adapted from Battelle 2008).

4.2 SITE GEOLOGY/HYDROGEOLOGY

The demonstration site at Quantico is a shallow embayment with an average water depth of 1.5 m. The embayment is approximately 190 acres. This location is defined predominantly as a freshwater system, with minimal tidal influence (between 0.3 m to 0.7 m tidal range). Surface water salinity at this site ranges from between 0.5 practical salinity units (psu) to 3 psu, with the higher salinity occurring during lower river flow conditions in the late summer and early fall. Sediment is typically fine grained, with greater than 55% silt and clay (Battelle and Neptune 2004). More coarse-grained sediment is located along the shoreline and adjacent to outfalls, and finer-grained sediment (with >80% silt and clay) is located in outer areas of the embayment (Battelle et al., 2007). Based on the grain size distribution and evidence of low flow velocities within the embayment, it is assumed that this site is depositional in nature. Additional information is discussed in existing reports (Battelle 2005, 2008, 2009; Battelle et al., 2004, 2005, 2007) and therefore is not presented here.

4.3 CONTAMINANT DISTRIBUTION

The Quantico Embayment and adjacent habitats, including the Southern Wetlands, have historically received numerous potential contaminants from several sources such as the Site 4 Old Landfill, the Former Pesticide Control Building, the Mainside Sewage Treatment Plant, and the active Marine Corps Air Facility (MCAF) Quantico, including a number of historical and current storm water outfalls that had or have discharge points.

Although CoCs at this site included PAHs, metals, chlorinated pesticides, and PCBs in both surface (0–10 cm) and subsurface (>10 cm) sediment, the presence and concentration of DDX compounds drive the requirement for site remedy. DDX compounds, consisting of DDT and its degradation products DDD and DDE, have generally been measured at the highest concentration levels in the northern portion of the inner portion of the Quantico Embayment adjacent to the northern edge of the Site 4 Old Landfill and the potential runoff stream from the Former Pesticide Control Building (Figure 3). Sediment sampling suggests that DDX concentrations both increase with depth in the sediment and are generally highest in the near-shore area (Battelle, 2007).

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

This project examined changes in physical, chemical, and biological parameters of the site prior to and following placement of a TLC in support of EMNR demonstration.

Physical parameters assessed in this project included the following:

- The distribution, coverage, uniformity, and minimum and maximum thicknesses of the TLC after placement
- The stability of the TLC to hydrodynamic forces
- Changes in TLC stability over time resulting from natural sedimentation, benthic mixing, and hydrodynamic forces

Chemical parameters included:

- Surface sediment chemical concentrations following cap placement
- Monitoring of the extent to which the new sediment (cap) surface may be recontaminated from either the water column (top-down) or via mixing with underlying sediment (bottom-up)
- Movement of contaminants via porewater migration

Biological parameters included:

- Assessment of community recovery following cap placement and characterization of the extent to which cap placement and the creation of a new sediment surface may affect the health and composition of the benthic community
- Assessment of ecological risk reduction via monitoring of DDX bioaccumulation in invertebrates

5.2 BASELINE CHARACTERIZATION

Pre-placement monitoring represents baseline characterization of physical, chemical, and biological conditions. Baseline characterization was initially conducted in spring (April–May) and fall (August–September) of 2009 to target different environmental and ecological conditions at the site (SSC Pacific, Environ and Army Corps of Engineers 2009). However, due to delays in the TLC installation, all follow-on work was postponed until such time that the regulatory work at Site 99 (TLC installation) would resume. In conjunction with plans to proceed with post-cap monitoring, a related Environmental Security and Technology Certification Program (ESTCP) Project (ER-201130, Gunther Rosen, Principal Investigator) was able to proceed and use Site 99 as part of their demonstration of the SEAP Protocol. Because the SEAP project is an integral component of this demonstration project, every effort was made to ensure that project objectives could be aligned to maximize the benefit to each project. Sampling related to ESTCP Project ER-201130 to establish additional baseline conditions was conducted in October 2012. Data collected in each baseline characterizations included the following parameters as summarized in Table 2.

Table 2. Summary of Baseline Characterization Activities.

Parameter	Baseline 1 Spring 2009	Baseline 2 Fall 2009	Baseline 3 Fall 2012
Bathymetry	X	--	--
Hydrodynamic monitoring (current meter)	X	X	--
Deposition rates and concentrations of DDX in deposited sediment (sediment trap)	--	X	--
Physical and chemical analysis of sediment cores	--	X	X [1]
Concentrations of DDX in tissue from *in situ* bioaccumulation testing	--	X	X
Concentrations of DDX in tissue from native pelagic invertebrate	--	X	--
Concentrations of DDX in porewater (*ex situ* passive sampling)	--	X	--
Concentrations of DDX in porewater (*in situ* passive sampling)	--	--	X[2]
SPI	--	X	--
Benthic community census	X	--	X

[1] Grab samples only

[2] Samples provided to D. Reible but results not used in this demonstration

5.3 TREATABILITY OR LABORATORY STUDY RESULTS

Prior to field sampling, laboratory sediment was used to examine the uptake of DDX by a representative benthic invertebrate and to assess survival and growth of representative benthic species following placement of the TLC, as well as fate and transport mechanisms of DDX (initial mixing of TLC material with native sediment, bioaccumulation and biotransport of DDX in benthic organisms, etc.). The data allowed several fundamental uncertainties regarding capping and DDX fate and transport to be addressed under controlled laboratory conditions, as well as provided information to optimize the experimental design for post-capping chemical and biological measurements. For physical burial effects and bioaccumulation, a series of three laboratory experiments were conducted in in July 2009 by Dr. Guilherme Lotufo at ERDC facilities in Vicksburg, Mississippi. Detailed methods and results of the experiments are provided in Appendix B of the final technical report.

5.4 FIELD TESTING

The post-cap placement monitoring was performed in the short-term (two months post-cap placement), and long-term (one and two years post-cap placement). Long-term monitoring was conducted in the fall each year to coincide seasonally with baseline characterization (Baseline 2 and Baseline 3). Table 3 summarizes post-cap placement monitoring activities, including tools or parameters to evaluate each physical, chemical, and biological characterization.

Table 3. Summary of Post-placement Activities.

Parameter	0 months post-placement	2 months post-placement	14 months post-placement	25 months post placement
Bathymetry	X	X	X	X
Friction sound probe	--	X	X	X
Deposition rates and concentrations of DDX in deposited sediment (sediment trap)	--	X	--	X
Physical and chemical analysis of sediment cores	X [1]	X	X	X
Concentrations of DDX in tissue from *in situ* bioaccumulation testing	--	X	X	X
Concentrations of DDX in porewater (*ex situ* passive sampling)	--	X	X	X
Concentrations of DDX in porewater (*in Situ* passive sampling)	--	X[2]	X[2]	X[2]
SPI	--	X	X	X
Benthic community census	--	X	X	X

[1] Confirmation sediment core profiling only

[2] Samples provided to D. Reible but results not used in this demonstration

Table 5 provides the schedule for the baseline characterization, remedy placement, and post-placement monitoring events.

Table 4. Baseline Characterization and Post-placement Monitoring Event Schedule.

Event	Dates
Baseline 1	April to May 2009
Baseline 2	August to September 2009
Baseline 3	October 2012
Remedy Placement 0 Months Post-Placement	June 2014
Short Term Post-Placement Monitoring: 2 Months Post-Remedial Monitoring Event	September 2014
Long Term Post-Placement Monitoring: 14 Months Post- Remedial Monitoring Event	September 2015
Long Term Post-Placement Monitoring: 25 Months Post- Remedial Monitoring Event	August 2016

5.5 SAMPLING METHODS

A description of sampling conducted including collection methods, analytical methods, and approach to data treatment and evaluation is described below.

5.5.1 Bathymetry

The objective of the bathymetric surveys was to document the water depths in the capping area prior to and following the placement of the cap. Changes in water depths before and after the cap placement provide a general indication of the spatial distribution and uniformity of the placement. Changes in water depths over time following the cap placement provide a general indication of the stability of the cap and a basis for interpretation of finer-scale coring measurements at the multi-metric stations. Bathymetry data over the cap footprint were collected just prior to cap placement and during three post-cap survey events on 31 March 2015, 23–24 August 2015, and 23 August 2016. The first data set, collected by Waterway Surveys and Engineering Ltd. just prior to the cap installation, was provided by the Remedial Program Manager to include in our evaluation. Data collection for the 2015 and 2016 post-capping surveys was conducted using a Teledyne Oceanscience Z-Boat 1800 remote control hydrographic survey boat with a Ceepulse 100™ 20 kHz echosounder integrated with a Hemisphere A101 Global Positioning Satellite (GPS) receiver.

5.5.2 Hydrodynamic monitoring (Current Meter Measurements)

InterOcean S4 current meters were deployed at two on-cap locations (Q1-S4 and Q2-S4) prior to the installation of the cap and carried out two rounds of measurements. The first round was in the spring of 2009, during the period 9 April 2009 to 2 May 2009. The second round was during the fall of 2009, during the period 1 September 2009 to 27 September 2009. Critical velocities were estimated using equations by Soulsby (1997).

5.5.3 Friction sound probe

The Sediment Friction Sound Probe (SED-FSP) uses friction-sound as a method for *in situ*, screening-level measurement of grain size. On a theoretical basis, friction-sound is believed to be generated when phonons are produced by the breaking or excitation of atomic or molecular bonds as a contact surface moves over or through a particle matrix. Friction-sound intensity has been shown to be a linear function of the radius of particles in contact with the surface and the velocity of the probing surface. The SED-FSP unit developed and used by SPAWARSYSCEN PACIFIC employs this correlation to infer grain size. The effectiveness of the SED-FSP system was demonstrated in a variety of contaminated sediment management scenarios including measurement of thickness of a contaminated sediment cap site located on the Anacostia River in Washington, D.C. during ESTCP Project No. ER-0919.

SED-FSP surveys were conducted as part of the post-capping surveys of 2014 and 2016. Equipment problems during the 2014 SED-FSP survey precluded the collection and use of valid data, so only the 2016 data were used. During the 2016 survey, SED-FSP measurements were collected at 21 on-cap and 6 off cap locations. Cap thickness data were acquired from sources in addition to SED-FSP, including a post-capping coring survey conducted by the construction contractor in 2014, coring surveys conducted at the multi-metric cap stations during the post-capping surveys of 2014, 2015, and 2016, and SPI camera surveys during the post-capping surveys of 2014, 2015, and 2016.

5.5.4 Sediment Traps

Sediment traps were deployed during three events, including the fall baseline event in 2009, the post-cap survey in September 2014, and the post-cap survey in August 2016. Procedures generally followed the methods described in Blake et al. (2007). During each event, traps were placed at three locations including the north, middle, and south areas of the cap. Traps were deployed for periods ranging from about 14–23 days with the shortest deployment during 2016 and the longest deployment during 2009. Details are provided in Section 5.6.4 of the final report. Sediments collected in each trap grouping were combined, homogenized, placed into laboratory containers, and shipped for further chemical analysis. Trap sediments from each deployment were analyzed for TOC, grain size, percent moisture, and DDT compounds.

5.5.5 Bulk Sediment

Undisturbed, intact, continuous sediment cores were collected in general accordance with ASTM 1391 (ASTM 2008), utilizing a TLC integrity coring device developed by SSC PACIFIC in collaboration with the University of California San Diego (UCSD). Five replicate cores were collected at each multi-metric station to achieve sufficient sample mass. An additional five replicate cores were collected at multi-metric station 5 and were treated as a field duplicate. At the onshore processing area, the cores were split lengthwise, sediment core profiling was conducted (visual sediment texture classification as described below), and photographs were taken of each core. The interface of the bottom of the TLC and native sediment was visually identified. Each core was sectioned into intervals as follows:

- Within the thin layer cap:
  - 0–2 cm below the water-cap interface
  - 2–5 cm below the water-cap interface
  - 5–7 cm below the water-cap interface
- Across the mixing boundary between the cap and the underlying native sediment:
  - 0–2 cm above the cap-native sediment interface
- Within the underlying native sediment:
  - 0–2 cm below the cap-native sediment interface
  - 2–5 cm below the cap-native sediment interface
  - 5–7 cm below the cap-native sediment interface

Additionally, a petite Ponar grab sampler was used to collect surface (0–10 cm) sediment samples at the two off-cap reference areas and the benthic community census samples.

Sediment was processed and analyzed for the following parameters. **Sediment core profiling** (visual classification) and logging for sediment texture was performed in general accordance with ASTM D2488 (ASTM International 2009). The depth of the cap-native sediment interface was also noted for each core and was averaged for the five replicate cores to determine a single depth measurement at each station. Also, a determination of the extent of mixing was made based on qualitative visual observations of each core. The **total organic carbon** (TOC) content of sediment samples were analyzed by 9060A in baseline and 2- and 25-month events and Walkley Black in 14-month event (heated during digestion). The **grain size** distribution of sediment samples was analyzed by ASTM Method D422. Sediment samples were analyzed for **DDX congeners** following EPA method 8081A.

5.5.6 *In Situ* Bioaccumulation

Evaluation of the reduction of DDX uptake utilized *in situ* bioaccumulation experiments (Rosen et al 2012, Greenberg et al., 2002). Two species of laboratory-reared organisms, *Lumbriculus variegatus* (oligochaete worms) and *Corbicula fluminea* (freshwater clams), were deployed by SPAWAR the technical team and US EPA ERT divers using Sediment Ecotoxicity Ring (SEA Ring) for 14 days at multi-metric stations on- and off-cap in pre-(baseline 2 and baseline 3) and post-placement events (2-, 14-, and 25-month post-placement). The SEA Ring is a patented (U.S. Patent No. 8,011,239), autonomous multi-chamber sampler used primarily for toxicity and bioaccumulation testing (Burton et al., 2013) and has successfully completed USEPA's Environmental Technology Verification (ETV) Program (McKernan et al., 2014). Following overnight purging, organisms were weighed, composited, and frozen for analysis for DDX congeners following EPA 8081B and lipids.

5.5.7 Porewater (*Ex Situ* Passive Sampling)

DDX in sediment porewater was assessed through application of ex situ Solid Phase Micro-Extraction (SPME). Diffusion of DDX in sediment porewater was used to estimate bioavailability of DDX within the cap layer and native sediment. Procedures followed methods outlined in You, et al. (2007) and Yang, et al. (2008). SPME fibers were exposed to sediment for two weeks, retrieved and extracted with hexane, which was then analyzed following EPA 8081A. To estimate a concentration of DDX in sediment porewater, the concentration of DDX in the fiber coating must be at equilibrium. Experiments by You, et al. (2007) have confirmed the sufficiency of the agitation method we have used to reach approximate equilibrium (approximately 90% of steady state or more) for DDX in the fiber coating. Steady-state concentrations of DDX in the fiber coating were assumed.

5.5.8 Sediment Profile Imagery

Sediment profile imaging (SPI) is a benthic sampling technique in which a specialized camera is used to obtain vertical cross-section photographs of the upper 15–20 cm of the sediment column. This reconnaissance survey technique rapidly collects, interprets, and maps data on physical and biological sediment characteristics. Measurements obtained from SPI are used to characterize surface sediment types and layering, evaluate benthic habitat quality, and follow ecosystem recovery after emplacement of a cap remedy or abatement of natural or manmade disturbances. A total of 51, 32, and 21 stations were surveyed during the baseline, 2-month, and 14-month events, respectively.

5.5.9 Benthic Community Census

During each sampling event, a petite Ponar grab sampler collected triplicate grab samples at each of the stations, and the content of each grab sample was sieved through a 500 micrometer (μm) mesh opening sieve and preserved (USEPA 2007). Invertebrates were identified to the lowest possible taxonomic level and enumerated. Four biological indices commonly used to assess benthic community health were used to evaluate the data: total abundance, taxa richness, species diversity, and species evenness. Additionally, the methodology used by Llansó (2002) to derive the Chesapeake Bay benthic index of biotic integrity (B-IBI), assessing benthic community health and environmental quality in the Chesapeake Bay, was followed for determination of the health of the benthic community at Quantico Embayment during the various phases of this demonstration.

5.6 SAMPLING RESULTS

5.6.1 Bathymetry

The site contractor collected cores at a total of 83 stations during the post-construction verification survey conducted from 28 May 2014 to 9 June 2014. Figure 5 summarizes the thickness at these stations.

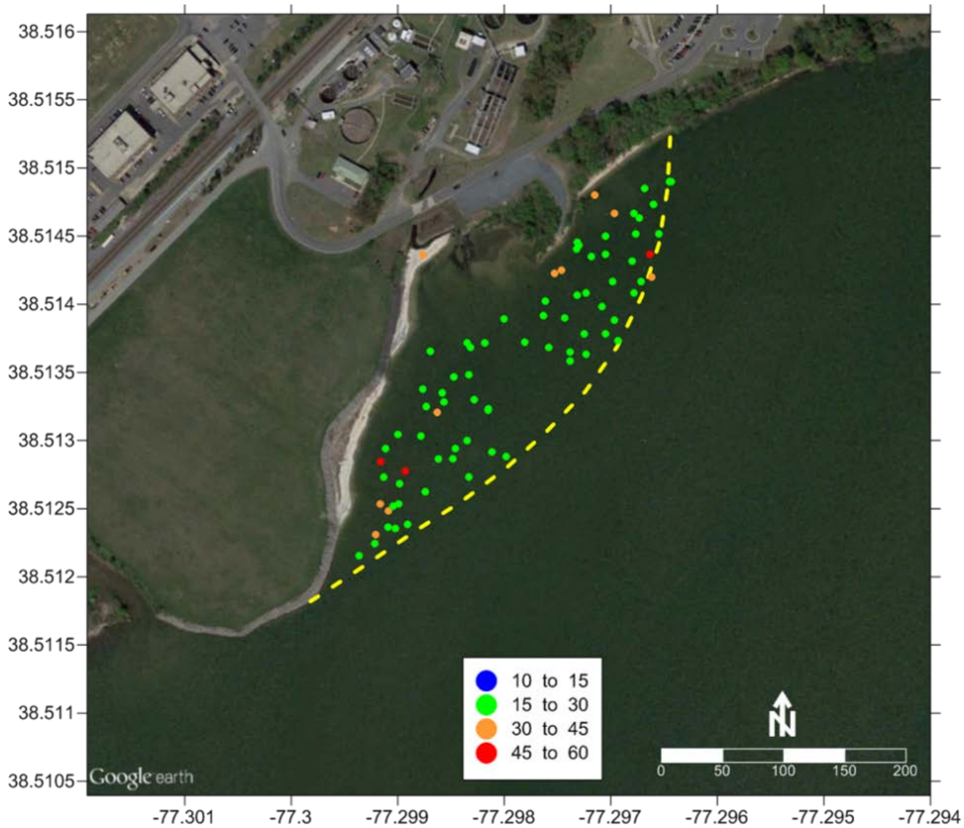

Figure 5. Results for Cap Thickness Measurements Collected by the Site Contractor Immediately Following Construction of the Cap in 2014 (units are in cm).

Difference maps were developed from the bathymetric grids to evaluate changes between the pre- and post-cap condition as well as to evaluate stability of the cap following the cap placement. Figure 6 shows the difference maps for subtraction of the 2014 elevation from the 2015 elevation and the 2014 elevation from the 2016 elevation. Positive changes in elevation throughout the majority (>82%) of the target cap area were observed up to about 37 cm. The mean difference in the target cap area was 14 cm, which is still comparable to the minimum target thickness of 15 cm (6 inches).

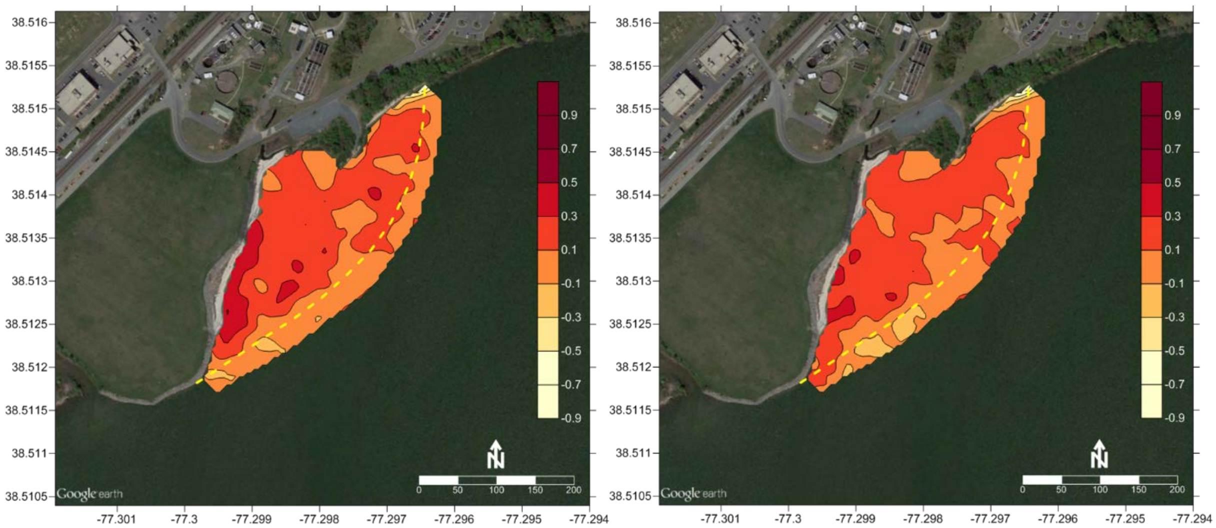

Figure 6. Difference Map for the 2014 Pre-cap Baseline Compared to the 2015 Post-Cap Survey (left) and Difference Map for the 2014 Pre-cap Baseline Compared to the 2016 Post-cap Survey (right). The yellow dashed line indicates the offshore boundary of the area targeted for the thin-layer cap. Positive differences indicate 2015 elevations that are higher than 2014 elevations. Units are meters.

Table 6 shows the comparison of elevations changes from the 2015 and 2016 SSC Pacific bathymetric surveys to the estimated cap thickness from the on-cap coring stations. The results are qualitatively comparable except for station QT-3, where the bathymetry consistently showed a smaller change in elevation than was reflected in the cores. Annual surveys for the two years following the cap placement showed only very small changes in elevation, indicating that the cap appears to be relatively stable in elevation.

Table 5. Comparison of Cap Thickness Based on Coring with Change in Elevation Based on Bathymetry Difference from the Pre-construction 2014 Baseline (inches) at the Five On-cap Stations.

Station	2015		2016	
	Coring	Bathy	Coring	Bathy
QT-1	5.9	4.1	5.9	5.6
QT-2	6.7	12.6	6.7	7.3
QT-3	9.1	3.3	9.8	1.6
QT-4	15.4	10.0	9.4	10.4
QT-5	16.3	12.6	17.5	12.2
Average	10.7	8.5	9.9	7.4

5.6.2 Hydrodynamic Monitoring (Current Meter Measurements)

To evaluate stability of the cap, measured currents from the 2009 surveys were compared to critical threshold velocities for particle motion and suspension as described in the methods section above. These thresholds differ for the two stations primarily due to the differences in water depth, with the southern station (Q1-S4) being shallower and thus having slightly lower velocity thresholds. The full version of the Final Report shows comparisons for each station under the spring and fall flow conditions. These results indicate that currents at the site are generally low relative to critical threshold velocities at both sites and under both flow conditions. Thus, it is unexpected that the cap would be disturbed by normal spring and summer currents; however, the cap could be disturbed under storm conditions, especially storm-associated waves due to the shallow nature of the site.

5.6.3 Sediment Friction Sound Probe

Cap thickness was re-surveyed on 9 August 2016, using the SED-FSP system at 24 on-cap and 6 off-cap locations. The SED-FSP differs from the coring in that it provides a full profile of estimated mean grain size (D50) to a depth of about 60 cm below the sediment-water interface (SWI). Figure 7 shows the SED-FSP results for the five multi-metric on-cap stations where sediment cores were also collected. In general, the SED-FSP and cores at these stations show reasonable agreement, both with respect to the cap thickness and with respect to the magnitude of the mean particle size in the cap. Overall, the SED-FSP provided a rapid means of assessing the spatial distribution of mixing and new deposition and its potential influence on the TLC.

The SED-FSP results indicated an average thickness for cap material of about 17.1 cm, and an average combined thickness of cap and mixed material of about 32.6 cm at the on-cap stations. The cap material thickness at the on-cap stations ranged from 0.0–44.5 cm, with a standard deviation of 12.8 cm. For the combined cap and mixed material, the thickness at the on-cap stations ranged from 16.5–59.1 cm with a standard deviation of 13.5 cm. These average values and ranges are generally consistent with the values observed during the 2014 post-construction survey taking into consideration that the cap material had been mixing with both underlying native sediment and new sediment deposits over time. These ranges are also quite consistent with the values measured directly (by observation) from the cores collected at the multi-metric stations (Table 7).

Results from the 25-month event showed that depositional layers and mixing were clearly evident in the SED-FSP mean grain size profiles. All of the 24 on-cap stations (100%) evaluated in the survey had at least a trace layer of new deposition. Twenty-three stations (96%) showed evidence of top-down mixing, 22 (92%) showed evidence of bottom-up mixing, and 7 (29%) showed evidence of interleaved layering. Consistent with the other measures of mixing, SED-FSP results showed top-down mixing to be generally more significant, with an average extent over the on-cap stations of 8.3 cm compared to an average of 4.5 cm for bottom-up mixing. The average depth of the new deposition layer at the on-cap stations was 3.7 cm.

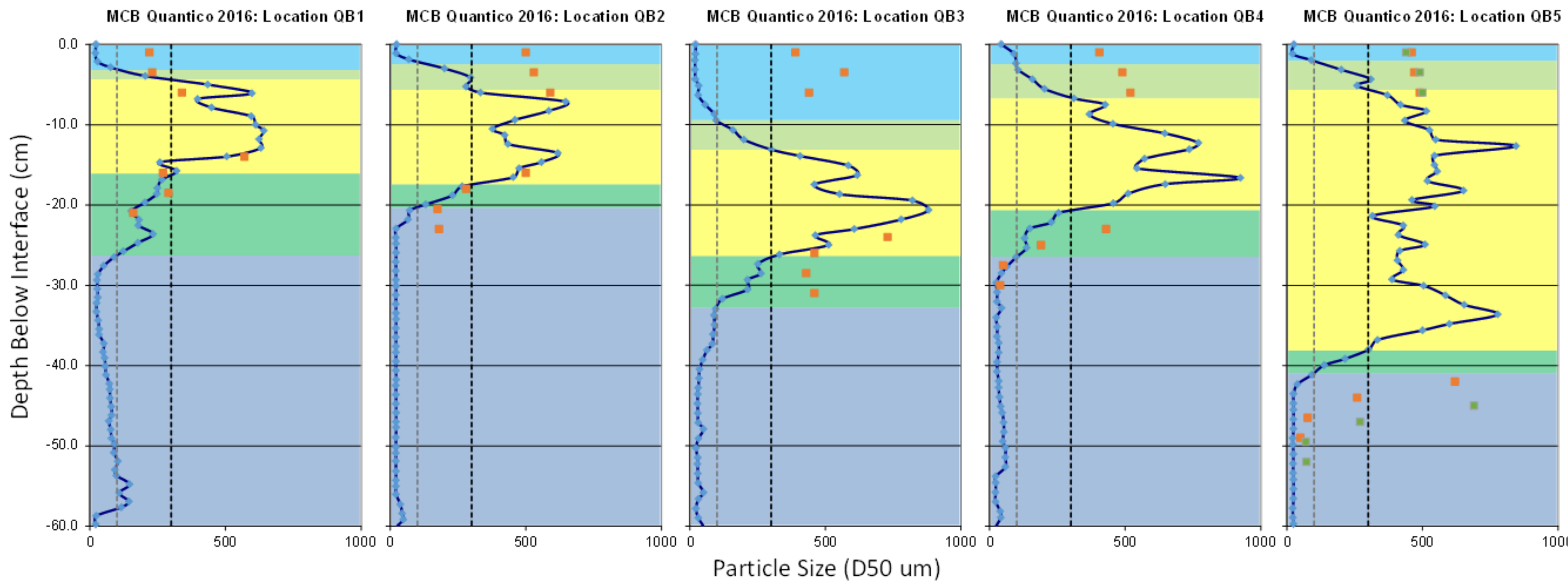

Figure 7. Examples of SED-FSP Profiles for the Multi-metric Stations QE1–QE5 (left to right) during the 2016 Post-cap Survey. Blue lines and diamonds represent the SED-FSP data, while orange square symbols (and green for QE5 station duplicate) show measured D50s from the cores collected at these stations. Blue colors indicate native material, green tones indicate mixed zones, and yellow color indicates predominant sand.

Table 6. Comparison of the Cap Thickness Estimated from Coring and SED-FSP, and the Change in Elevation from the Bathymetry Measurements (inches).

Station	2016		
	Coring	Bathy	FSP
QT-1	5.9	5.6	10.5
QT-2	6.7	7.3	6.8
QT-3	9.8	1.6	8.4
QT-4	9.4	10.4	8.9
QT-5	17.5	12.2	14.5
Average	9.9	7.4	9.8

5.6.4 Sediment Traps

Samples from the sediment traps were analyzed to determine deposition rates, particle physical characteristics, chemical concentrations, and chemical mass flux to the cap area. Deposition rates ranged from 5.6–14 g/cm^2/year (y) across the stations and the events. Assuming a sediment density of 2.66 g/cm^3, these rates translate to deposition thicknesses in the range of 4.3–9.0 cm/y. These relatively high rates likely represent a combination of both new deposition and local resuspension.

Particle size and TOC characteristics for the sediment trap samples indicate that deposited sediments were dominated by fines (silts and clays) with sand fractions generally in the range of 10%, with the exception of the post-capping events at the North station where the sand fraction was in the range of 50% (Table 8). The results suggest that the physical characteristics of the sediments depositing in the cap area did not change substantially between the baseline and post-capping events, except at the North station, where the increase in sand content in the sediment traps during the post-capping events indicates that there may be more physical disturbance in this area with sufficient energy to either transport or resuspend sand-sized particles. Because the elevated sand content was not present in the baseline traps, it is more likely that the sand is associated with local resuspension of cap material.

Table 7. Grain Size Distribution and TOC for Sediment Trap Samples.

Sampling Event	Station	%gravel	%sand	%silt	%clay	%fines	%TOC
Baseline Sept 2009	South	0.0	11.8	48.6	39.6	88.2	4.6
	Mid	0.0	15.8	53.0	31.2	84.2	5.7
	North	0.0	4.6	54.2	41.2	95.4	4.7
Post-Cap Sept 2014	South	0.0	7.4	75.9	16.7	92.6	4.5
	Mid	0.0	10.4	72.4	17.2	89.6	3.9
	North	0.0	56.2	33.8	10.0	43.8	2.2
Post-Cap Aug 2016	South	0.0	11.7	59.1	29.2	88.3	1.2
	Mid	0.0	11.9	58.4	29.7	88.1	1.2
	North	0.0	45.5	34.6	19.9	54.5	0.8

Table 9 summarizes chemical concentrations of DDX compounds found in the traps' sediments. The results show a clear trend with reduced concentrations of total DDX following the cap placement as reflected in the low concentrations in trap materials from the 2014 and 2016 events. Reductions in trap sediment concentrations across the cap stations for the 2014 and 2016 events averaged about 70% and 65%, respectively. The total DDX and TOC concentrations observed in the post-capping trap samples were consistent with levels found in the off-cap reference stations to the east of the cap, suggesting that deposition onto the cap is likely coming from off-cap sediments rather than from disturbance of the cap sediments themselves (with the possible exception of the North station area as discussed previously).

Table 8. Chemistry Results for the Sediment Trap Samples. Grey shaded cells indicate non-detects listed at ½ the reporting limit. Units are µg/kg dry weight.

Sampling Event	Station	2,4'-DDE	4,4'-DDE	2,4'-DDD	4,4'-DDD	2,4'-DDT	4,4'-DDT	Sum DDx
Baseline Sept 2009	South	0.04	32.43	10.71	45.15	2.38	15.12	105.83
	Mid	0.04	24.19	10.86	68.22	1.91	33.32	138.54
	North	0.04	35.59	20.85	72.20	2.12	32.93	163.73
Post-Cap Sept 2014	South	0.20	8.69	3.29	15.20	0.20	4.38	31.95
	Mid	0.23	7.30	3.92	8.43	0.23	4.24	24.35
	North	0.26	10.70	6.56	34.20	1.32	13.60	66.64
Post-Cap Aug 2016	South	0.19	14.00	5.60	27.30	0.19	2.39	49.67
	Mid	0.21	12.80	5.17	29.40	0.21	1.85	49.64
	North	0.20	9.74	5.22	24.10	0.20	5.55	45.01

The depositional flux to the sediment bed is a function of the deposition rate and the chemical concentrations associated with the depositing particles, as shown in Table 10. As with the trap concentrations, the depositional fluxes showed a marked decrease following the installation of the cap. The reduction was consistent across both sampling events with reductions in mass flux of total DDX of about 63% for 2014 and 72% for 2016. Reductions in mass flux for the post capping events were driven primarily by changes in DDX concentrations, as the deposition rates were relatively constant across the baseline and post-capping events. The North station was an exception, especially during the 2014 event, when both the deposition rate and higher concentrations led to a relatively high deposition flux compared to other stations.

Table 9. Mass Flux Results for the Sediment Trap Stations. Grey shaded cells indicate flux rates based on non-detects listed at ½ the reporting limit. Units are ng/cm^2/y.

Sampling Event	Station	2,4'-DDE	4,4'-DDE	2,4'-DDD	4,4'-DDD	2,4'-DDT	4,4'-DDT	Sum DDx
Baseline Sept 2009	South	0.33	268	88.5	373	19.7	125	875
	Mid	0.26	155	69.4	436	12.2	213	885
	North	0.48	425	249	863	25.3	394	1957
Post-Cap Sept 2014	South	1.43	63.9	24.2	112	1.43	32.2	235
	Mid	1.94	61.6	33.1	71.2	1.94	35.8	206
	North	3.66	150	92.3	481	18.6	191	937
Post-Cap Aug 2016	South	1.25	92.2	36.9	180	1.25	15.7	327
	Mid	1.17	71.4	28.8	164	1.17	10.3	277
	North	1.95	94.9	50.9	235	1.95	54.1	439

Overall, the sediment trap results indicate relatively high deposition rates, with rates consistent between pre- and post-capping conditions. While deposition rates remained relatively constant, the DDX concentrations in the depositing sediments was substantially lower in both post-capping sampling events. This was reflected in reductions of 65–70% in the depositional mass flux of DDX to the capping area.

5.6.5 Bulk Sediment

Cap Thickness

Table 11 summarizes the results of the cap thickness based on visual observations from sediment core profiling. There appears to have been a slight shifting of the cap material from the northern end to the southern end; however, overall, the average thickness observed two months post-placement (30 cm) decreased slightly in the first annual event (25 cm) and then remained constant in the second annual event (25 cm).

Table 10. Comparison of depth (cm) to cap-native sediment interface, represented as mean ± standard deviation (minimum to maximum), for 2-, 14-, and 25-month monitoring events.

Station	2-Month	14-Month	Change from 2-Month (cm)	25-Month	Change from 2-Month (cm)
1	18 ± 1 (16–18)	15 ± 1.2 (13–16)	-3	15 ± 8.6 (4–26)	-3
2	40 ± 5 (35.5–47.5)	17 ± 1.8 (15–19)	-23	17 ± 1.3 (15–18)	-23
3	28 ± 4 (22–32)	23 ± 1.3 (21–24)	-5	25 ± 8.2 (21–40)	-3
4	32 ± 1 (31.5–34)	39 ± 0.9 (38–40)	7	24 ± 3.9 (18–28)	-8
5	33 ± 2 (31–35.5)	41 ± 2.3 (39–45)	8	43 ± 1.5 (42–46)	10
5DUP	33 ± 1 (30.5–34)	42 ± 1.3 (41–44)	9	46 ± 1.5 (44–48)	13

Grain Size

The grain size distribution at Quantico Embayment was characterized prior to cap placement and was, on average, 59% sand in the cap footprint (Table 12). Following cap placement, the fraction of sand in the surface sediment remained similar, at around 93%, throughout the three post-cap monitoring events. This consistency indicates that the cap was successfully placed and indicates the overall stability of the material over two years post-capping.

Table 11. Mean Percent Sand in Sample Intervals On- and Off-cap Collected during Each Event.

Interval (cm)	Location	Baseline 2	2-Month	14-Month	25-Month
0–2	On Cap	62%	95%	97%	89%
2–5	On Cap	58%	93%	93%	92%
5–7	On Cap	57%	87%	96%	92%
0–2 AI	On Cap	--[a]	95%	97%	97%
0–2 BI	On Cap	62%	73%	73%	77%
2–5 BI	On Cap	58%	64%	69%	68%
5–7 BI	On Cap	57%	60%	75%	54%
0–10	Off Cap	37%	48%	44%	22%

a. 0–2 AI interval did not exist prior to cap placement

Bulk Sediment Chemistry

In all post-placement events, concentrations of total DDX in surface sediments (0–2 cm, 2–5 cm, and 5–7 cm below the SWI) were below the most stringent preliminary remedial goal of 650 µg/kg, dw for Site 99 Quantico Embayment (NAVFAC 2011), with the exception of one sample in the two-month event (Station 1, 0–2 cm below SWI, northern end of TLC). Concentrations of total DDX in these surface sediments were an average of 973 µg/kg, dw in the baseline 2 event, decreased in the short-term monitoring (210 µg/kg, dw) and continued to decrease in the first and second annual long-term post-placement events (104 µg/kg, dw in the 14-month event and 51 µg/kg, dw in the 25-month).

Significant reductions in concentrations of total DDX in surface sediment between the baseline and 2-month ($p = 0.02$, 77% decrease), 14-month ($p = 0.002$, 48% decrease), and 25-month ($p < 0.0001$, 91% decrease) events were observed (Figure 8(a)). The 14-month event shows wide variation in average on-cap percent reductions, driven by monitoring station 2's increase in DDX concentrations from 170 to 510 µg/kg. Excluding this value results in a reduction of 79 ± 39% (Figure 8(b)). On average, greater reductions in surface sediment DDX were observed at on-cap stations than at off-cap stations for each event. In the short term, off-cap reductions in the 2-month event were 52% compared to 77% decrease observed at the on-cap stations. Over the long term, reductions of 39% and 41% were found at the off-cap stations, while decreases of 48% (79% with outlier removed) and 91% were observed at the on-cap stations for 14- and 25-month events, respectively.

Overall, these results indicate the thin-layer cap effectively reduced concentrations of total DDX in surface sediment after placement, and these significant reductions were sustained and were greatest in the second annual monitoring event as natural deposition continued to sequester contaminated sediments.

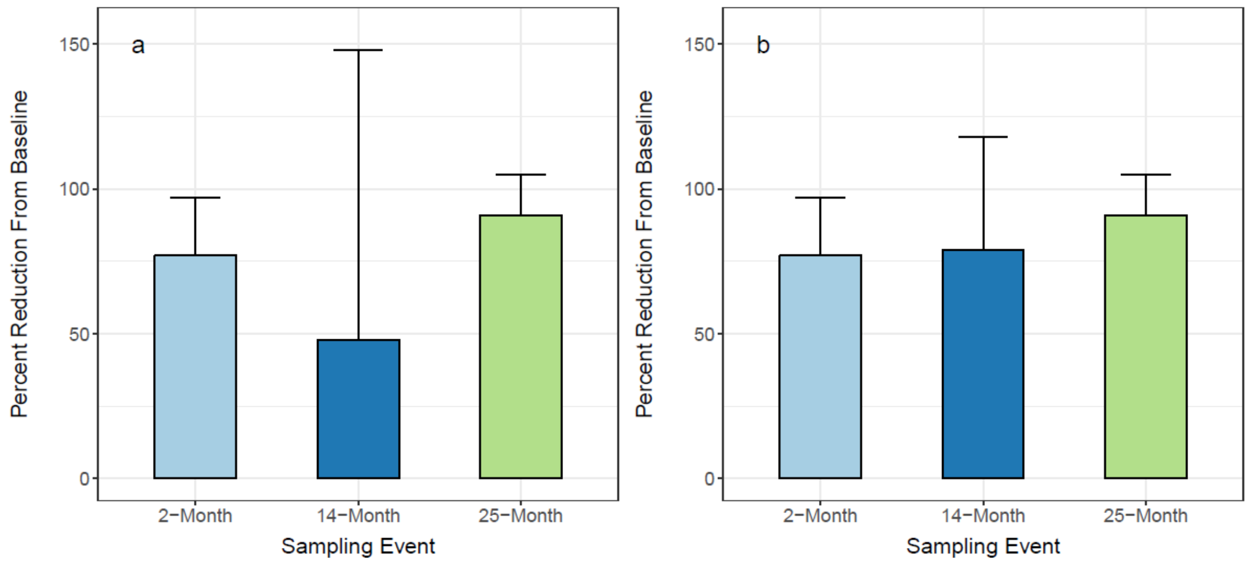

Figure 8. Reduction (%) in Surface Sediment (0-7 cm) Total DDX Concentrations Compared to Baseline: (a) Including All Data, and (b) Excluding Increase of DDX Concentrations at One Station during the 14-month Event.

5.6.6 *In situ* Bioaccumulation

Uptake of total DDX in *Lumbriculus variegatus* (*L. variegatus*) tissue was reduced in the 2-, 14- and 25-month post-remedy events at the on-cap stations by an average of 72%, 67%, and 86%, respectively, compared to baseline 3 (lipid weight basis, Figure 9). Concentrations in the short- and long-term post-placement events were significantly lower ($p < 0.05$) than baseline 3 (Figure 9). There was no difference among on cap stations during the three post-cap monitoring events ($p > 0.05$). Uptake was also reduced for the off-cap station: 32%, 41%, and 71% reductions for the 2-, 14-, and 25-month post-placement events compared to baseline 3, respectively. It should be noted that the baseline bioaccumulation levels were already quite low, so while the percent reductions in the off-cap stations are substantial, the levels themselves generally just remained in an already low range of values.

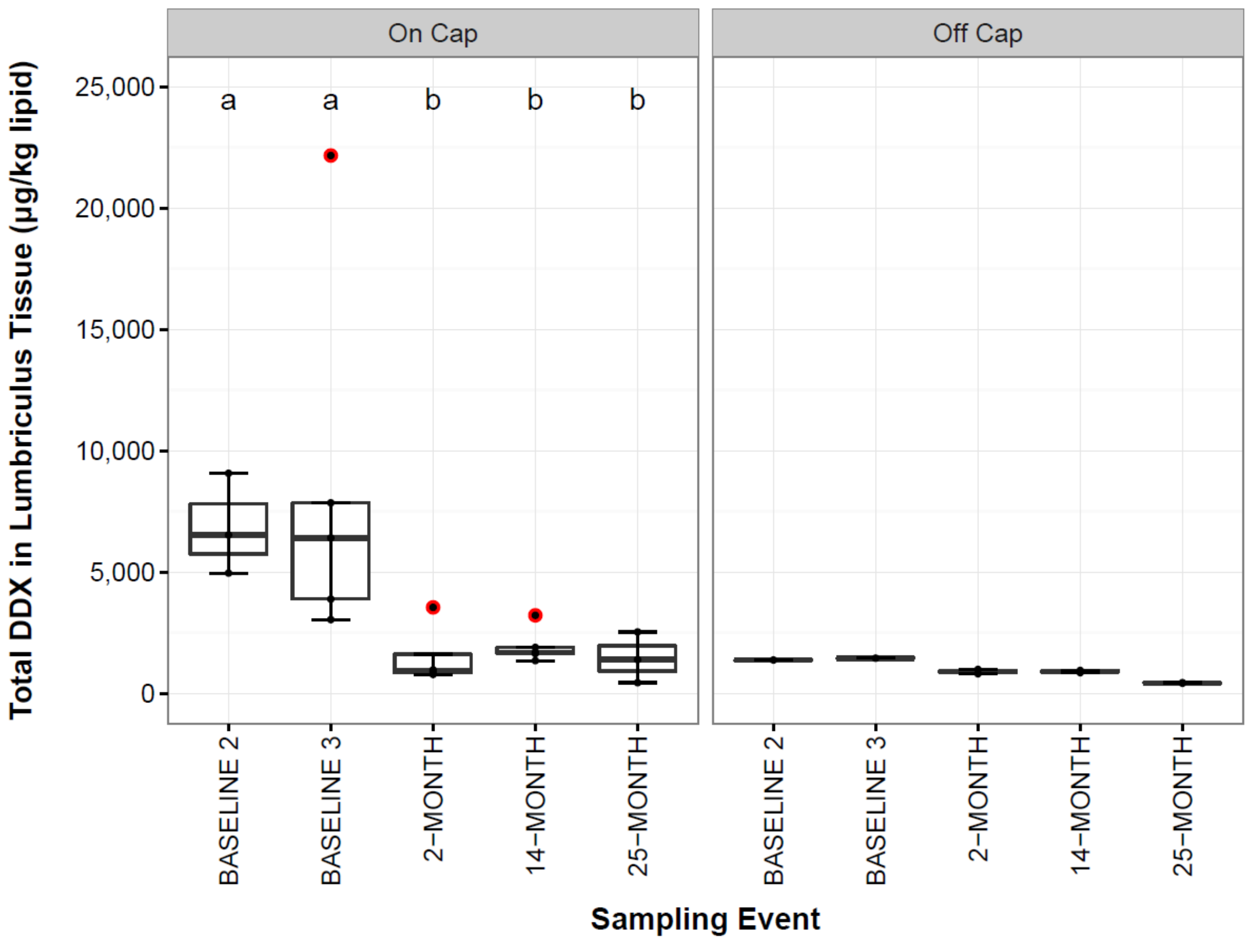

Figure 9. Concentration of Total DDX in *L. variegatus* Tissue (µg/kg lipid) for All Available On- and Off Cap Stations. Significant differences ($p < 0.05$) represented as different letters above boxes. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

Uptake of total DDX in *Corbicula fluminea* (*C. fluminea*) tissue was reduced in the 2-, 14-, and 25-month post remedy events at the on-cap stations by an average of 55%, 25% and 33%, respectively, compared to baseline 3 (lipid weight basis, Figure 10). At station 3, a short-term reduction in uptake of 25% was observed in the 2-month event; however, uptake increased in the 14- and 25-month events (74% and 57%, respectively) compared to the baseline 3 event. At the off-cap station, the greatest reductions were observed in the short-term (83%), followed by increase in uptake in the 14-month event, then a reduction of 58% in the 25-month event. Concentrations in the 2-month event were significantly less than the baseline 3 ($p < 0.05$), but there were no differences between the baseline, 14-, and 25-month events ($p > 0.05$, Figure 11). Results from the off-cap stations show variable total DDX tissue concentrations over time, with the lowest concentrations observed in the 2- and 25-month events.

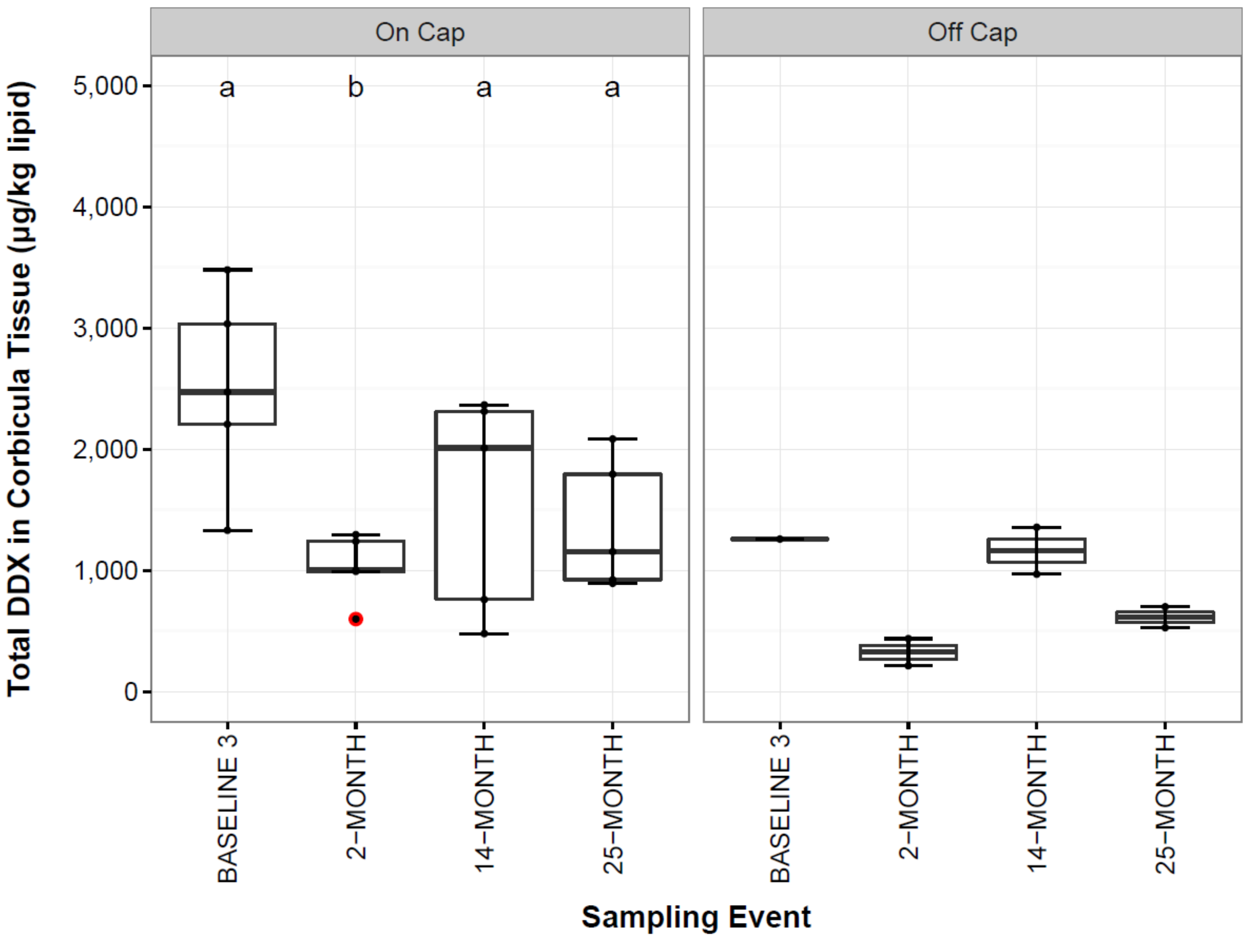

Figure 10. Concentrations of Total DDX in *C. fluminea* Tissue (µg/kg lipid) for All Available On- and Off Cap Stations. Significant differences ($p < 0.05$) represented as different letters above boxes. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

5.6.7 Porewater (*Ex Situ* Passive Sampling)

Concentrations of total DDX in surface porewater for on-cap sediments averaged 7.1 ng/L in the baseline 2 event, decreased in the short-term monitoring (2.9 ng/L) event, and remained below baseline concentrations in the first and second annual long-term post-placement events (3.7 ng/L in the 14-month event and 3.0 ng/L in the 25-month event; average top 7 cm below SWI).

Significant reduction in total DDX concentrations in the upper 7 cm were observed between the baseline event, the 2-month event ($p < 0.001$, 61% reduction), and the 25-month event ($p < 0.01$, 48% reduction) (Figure 11). The 14-month porewater DDX concentration was reduced compared to baseline, but the difference was only marginally significant ($p=0.1$, 30% reduction, Figure 11). Results of this analysis indicate that cap placement resulted in slight but significant reductions in porewater total DDX concentrations in surface sediments (0–7 cm), and that reductions were sustained through 25-months.

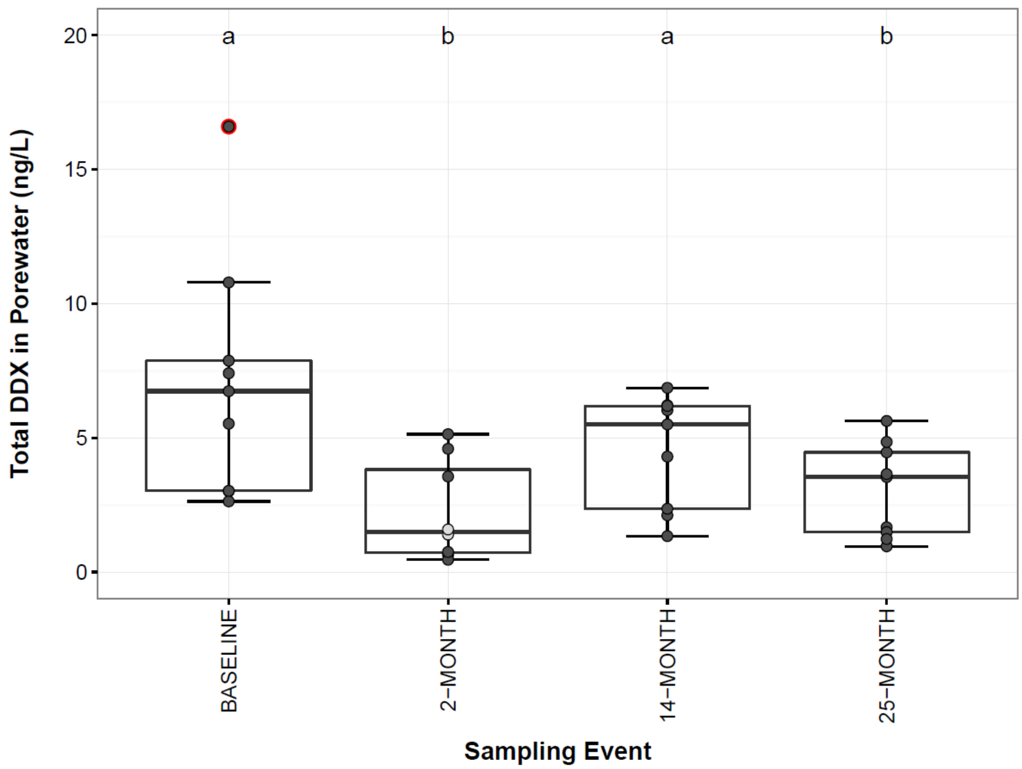

Figure 11. Comparison of Total DDX Concentrations in Surface Porewater (0–2 cm, 2–5 cm, 5–7 cm) for On-cap Stations (2, 3, and 5). Significant differences ($p < 0.05$) represented as different letters above boxes. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted with a red outline (as specified by Tukey). Notes: Stations 1 and 4 do not have baseline results and were excluded from this graph. Two samples were not detected during the 2-month event and are plotted as grey points.

5.6.8 Sediment Profile Imagery

In the short-term (two-months post-placement), sediment profile images showed little-to-no evidence that biological processes such as bioturbation were occurring. The redox potential discontinuity (RPD) appeared dominated by physical processes. Small tubes were observed at half the stations and fecal pellets, likely from bivalves, were observed at several stations. Oligochaetes were dominant at less than one-third of stations. Gas voids occurred at half the stations and were the most obvious signs of biogenic activity. There was no evidence in the sediment profile images that biological processes contributed to sediment mixing.

Bioturbation, a primary mixing process in marine sediments, is not an important factor in transitional or tidal freshwater benthic habitats (Diaz 1994). In general, conditions were equivalent with successional Stage 1, indicating benthic recolonization has not occurred to a great degree in the short-term (baseline observations were Stage 2 or 3 at nearly half the stations).

In the first annual post-placement monitoring event, observations at each station continued to be equivalent to Stage 1, indicating benthic recolonization had not occurred substantially. The RPD was shallower at stations where resuspension-deposition likely occurred, and the deepest RPD values were observed in sandy, porous sediment, primarily a function of porewater circulation driven by current or wave action pumping oxygenated water into the sediment (physical processes).

The results for the final monitoring event (two years following placement of TLC) were not available at the time this document was prepared.

Overall, the SPI results were most useful for observations related to cap placement, deposition and mixing, and of limited use for the assessment of benthic community health.

5.6.9 Benthic Community Census

Data was evaluated using four biological indices commonly used to assess benthic community health: total abundance, taxa richness, species diversity, and species evenness. Additionally, the benthic index of biotic integrity (B-IBI) methodology derived by Llansó (2002) was used to determine overall health of the location. Figures 12 to 16 present the results of the benthic community census.

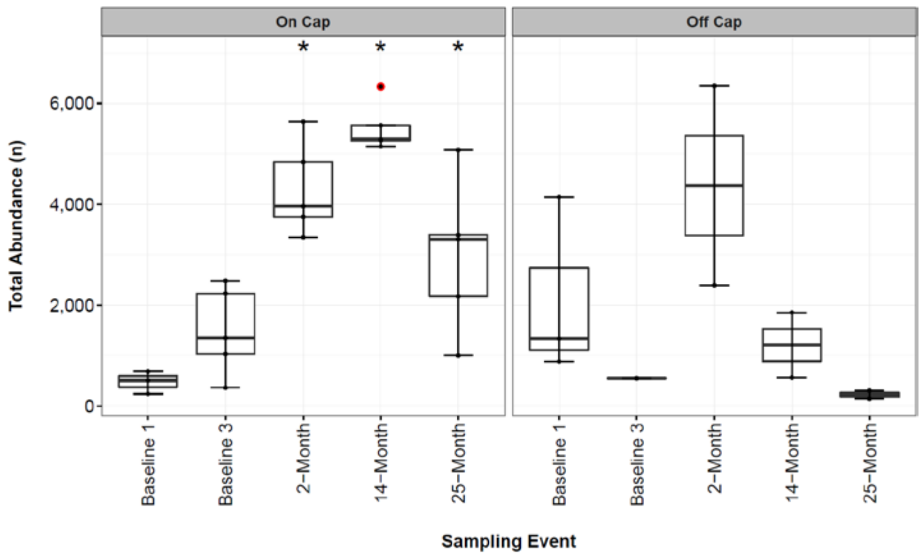

Figure 12. Total Abundance from the Benthic Community Census, Separated by Stations On and Off the Cap Footprint. Significant differences ($p < 0.05$) from either baseline event represented as a star (*) above box. Results for 25-month event are significantly greater than baseline 1 but not baseline 3. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

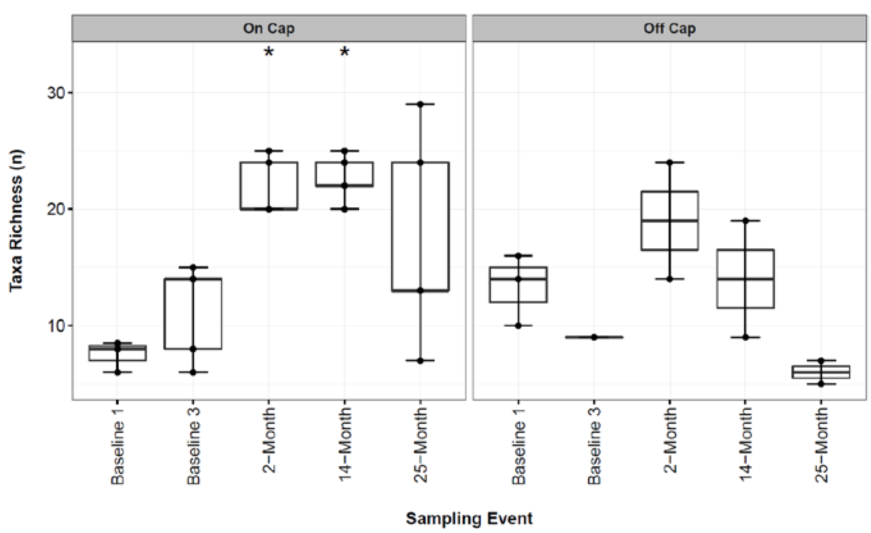

Figure 13. Taxa Richness from the Benthic Community Census, Separated by Stations On and Off the Cap Footprint. Significant differences ($p < 0.05$) from either baseline event represented as a star (*) above box. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

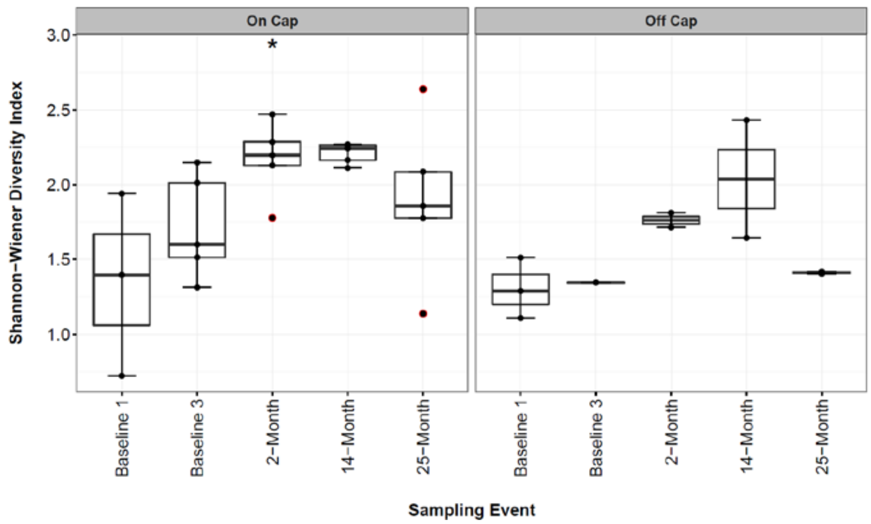

Figure 14. Shannon-Wiener Diversity Index from the Benthic Community Census, Separated by Stations On and Off the Cap Footprint. Significant differences ($p < 0.05$) from either baseline event represented as a star (*) above box. Results for 2-month event are significantly greater than baseline 1 but not baseline 3. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

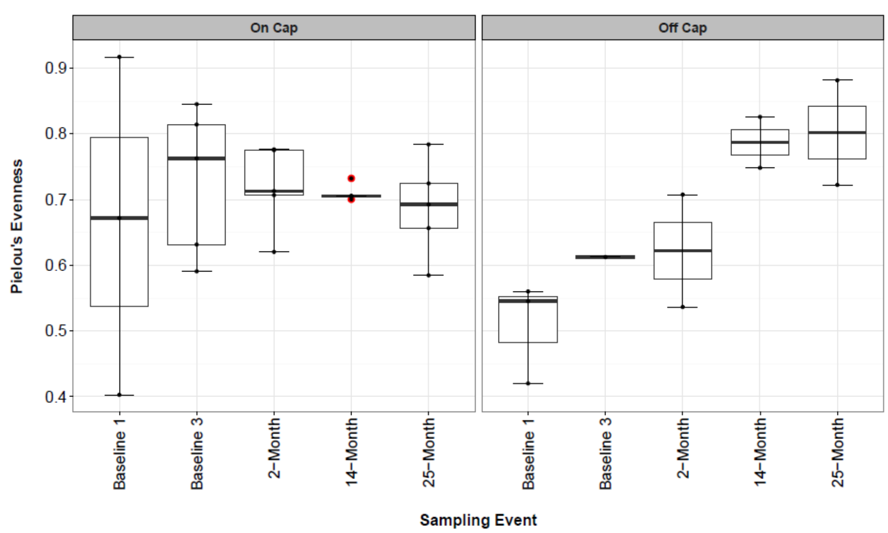

Figure 15. Pielou's Evenness Index from the Benthic Community Census, Separated by Stations On and Off the Cap Footprint. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

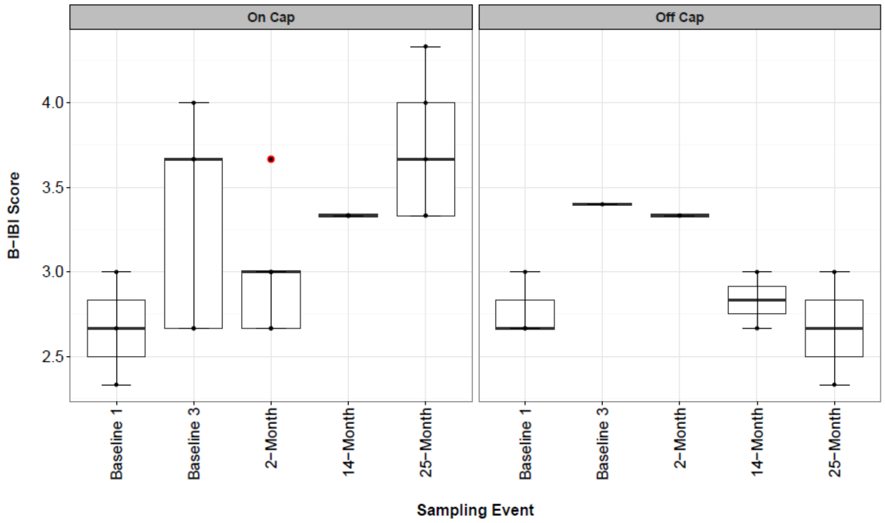

Figure 16. B-IBI Scores from the Benthic Community Census, Separated by Stations On and Off the Cap Footprint. Results are plotted as the median (horizontal bar), IQR (limits of boxes are 25th and 75th percentiles), and error bars extend from the IQR to the lowest value within 1.5 * IQR. Data beyond the end of the whiskers are outliers and plotted as red points (as specified by Tukey).

6.0 PERFORMANCE ASSESSMENT

A summary of the performance assessment for each of the POs is presented below along with whether each objective was met and the data supporting these conclusions. The Final Technical Report describes the performance assessment for this project in greater detail.

Performance Objective 1 was the evaluation of cap placement and determination of physical stability of the TLC. This demonstration showed that the TLC remained relatively stable over time based on by multiple metrics, including sediment core profiling, bathymetry, SPI, and SED-FSP. Sediment core profiling demonstrated an average cap depth of at least inches 6 inches at all stations (average of 10 inches in the most recent long-term monitoring event). The stability of the TLC was further supported by the current meter results indicating currents at the site were generally low relative to critical threshold velocities at both measurement stations and under flow conditions for two different seasons (spring and summer).

Performance Objective 2 was an evaluation of the extent of sediment and contaminant mixing. Multiple lines of evidence indicated that the dominant processes observed for sediment and cap mixing were some disturbance associated with the installation of the cap followed by longer term top-down mixing. The SPI camera results and the SED-FSP results provided a broader spatial context, while the visual analysis, TOC, grain size, and bulk sediment chemistry provided a more detailed and quantitative assessment of the focus stations at the site. While the long-term trends indicate ongoing and wide-spread top-down mixing, the material depositing at the site appears to be relatively low in concentration, and thus the top-down mixing is not expected to result in a loss of performance of the EMNR remedy. Importantly, the multiple lines of evidence also indicated the relatively limited amount of bottom-up mixing. This critically effects the performance of the TLC, as bottom-up mixing could bring higher concentration sediments into the surface zone where biological exposure is much more likely.

Performance Objective 3 was the evaluation of reductions in surface sediment chemical concentrations. Bulk sediment chemistry found reductions in concentration of total DDX below the PRG of 650 µg/kg, dw, significant reductions over time, and significantly lower concentrations in the TLC compared to underlying native sediment. On average, reductions for on-cap stations were greater than off-cap stations for all events. Sediment traps indicated relatively high deposition rates of material with lower concentrations in the post-placement events compared to baseline.

Performance Objective 4 was the evaluation of reductions in chemical bioavailability and bioaccumulation. Significant reductions in concentrations of total DDX in *L. variegatus* tissue (lipid weight basis) was observed in short- and long-term events (on average). Reductions in concentrations of total DDX in *C. fluminea* tissue were also observed in short-term and long-term events on average, with significant reductions in the short-term event. Concentrations of total DDX in surface sediment porewater were reduced in all events compared to baseline, with significant reductions in the short-term monitoring and most recent long-term monitoring event.

Performance Objective 5 was an evaluation of the rate of benthic recovery following TLC placement. Benthic macroinvertebrate census data following cap placement indicated increases in abundance, richness, and diversity. Additionally, the benthic-index of biotic integrity (B-IBI), which integrates multiple metrics into a single score, was in the highest category during the final long-term monitoring event, above values from pre-cap surveys.

Future Projections

Recovery of surface sediment concentrations with EMNR (thin-layer Habitat Enhancement Cap) provides physical isolation of the impacted sediments to the benthic community and prevents resuspension or transport of impacted sediments. As shown in Figure 17, reduction in concentrations of DDX in surface sediments with the EMNR remedial option occurs in a shorter timeframe compared to MNR. The measured concentrations in surface sediment decreased from an average of 573 µg/kg, dw in 2009 (57 months prior to TLC placement) and 264 µg/kg, dw in 2012 (20 months prior to TLC placement). After EMNR placement, measured concentrations in the 2-, 14-, and 25-month events show the concentration reaching 51 µg/kg, dw (average surface sediment) and projected to reach concentrations similar to off-cap measurement within 60 months or sooner. Concentrations in surface sediment with MNR remedy are projected to continue to decline, but at a much slower rate of recovery. The rate of recovery under MNR was estimated based on reductions in DDX concentrations for the two off-cap stations from 57 months pre-placement to 25 months post-placement (assuming a linear rate of decline). This rate of decline was applied to surface concentrations measured at the time of cap placement to derive the MNR curve.

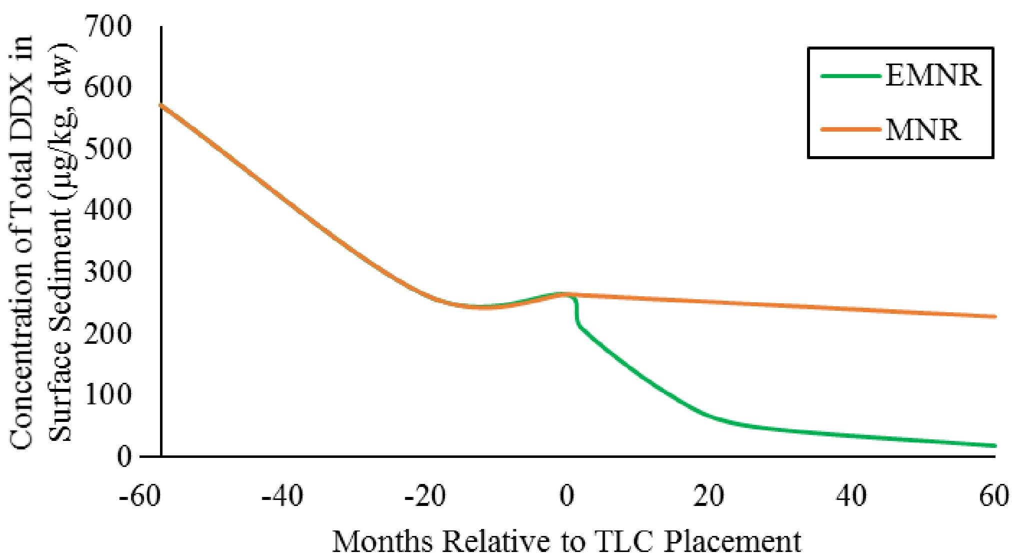

Figure 17. Illustration of EMNR and MNR Performance Relative to Total Sediment DDX Concentrations.

7.0 COST ASSESSMENT

Cost issues critically influence the evaluation and acceptance of innovative technologies. As a component of demonstrating and validating the performance of EMNR as a sediment remedy, this project will develop and validate the expected operational costs of the proposed remedy. Relevant costs will be detailed during the demonstration project so that the operational costs of EMNR implementation can be documented.

7.1 COST MODEL

The demonstration area at Quantico Embayment is 10.9 acres and includes placement of a minimum of six inches over the target area. To place a cap with a minimum thickness of six inches, an average of 9–12 inches of material needed to be placed over the remedial footprint (NAVFAC WA 2011). Therefore, this cost assessment conservatively assumes placement of 12 inches of material. Costs and assumptions presented below are based on estimates derived in the Quantico Embayment Feasibility Study (Battelle, et al., 2007) and the Record of Decision (NAVFAC 2011) and have not been adjusted to reflect subsequent inflation. The costs associated with placement of the TLC include materials, labor, equipment, and subcontracts associated with design, construction, oversight/quality control, and baseline monitoring (Table 13). Additionally, it was assumed that annual monitoring and maintenance will occur in years 1 to 5, followed by monitoring and maintenance every five years for 30 years. The present worth cost is the sum of the capital cost and the present worth of the monitoring and maintenance costs for 30 years.

Table 12. Cost Model for a Thin-layer Sand Cap for a 10.9 Acre Area.

Cost Element	EMNR Thin-Layer Cap Costs	
Construction cost	Materials Labor Equipment Subcontracts **Total**	$950,000 $540,000 $620,000 $240,000 **$2,340,000**
Design costs	Materials Labor Equipment Subcontracts **Total**	$20,000 $300,000 $40,000 $30,000 **$390,000**
Construction oversight & QC costs	Materials Labor Equipment Subcontracts **Total**	$30,000 $230,000 $100,000 $100,000 **$460,000**
Contingency	**25% of above costs**	**$800,000**
Post-construction (baseline) monitoring	**Materials, Labor, Equipment and subcontracts**	**$80,000**
Total Capital Costs	**Total**	**$4,070,000**
Annual monitoring & maintenance, Years 1–5	Monitoring Maintenance **Total**	$110,000 $10,000 **$120,000**
Annual monitoring & maintenance, Years 6–30	Monitoring Maintenance **Total**	$20,000 $10,000 **$30,000**
Present Worth O&M	**Total**	**$770,000**
Total Present Worth[1]	**Total**	**$4,840,000**

Note: Present worth was calculated assuming a 7% discount rate.

7.2 COST DRIVERS

Cost drivers to consider in selecting this technology include:

- **Material** costs will vary by amount required and the location of the project relative to the source of cap material. Estimates for the purchase and shipment of sand for this project were assumed to be $30/ton, but deviations from this can significantly impact overall costs.
- **Placement** costs can vary significantly based on the complexity of the site, including considerations for bathymetry, currents, infrastructure, regulatory requirements, and other considerations such as site access and logistical considerations.
- **Monitoring** and maintenance costs for EMNR largely depend on the monitoring plan and are controlled by the labor rates and number of personnel required to operate field equipment, analyze data, and generate the documentation associated with the project. Other operating costs include analytical laboratory costs and consumables.

7.3 COST ANALYSIS

The cost analysis will evaluate and compare the costs of EMNR thin-layer capping with monitored natural recovery (MNR) and traditional remedy alternatives, including installing a four-foot thick isolation cap and dredging to three feet with offsite disposal of dredged material (assumed to be non-hazardous). With the exception of dredging, all options require long-term monitoring at the site to ensure remedy effectiveness. Long-term monitoring costs are driven by labor, equipment, laboratory analyses, supplies, and transportation costs, but are not expected to vary significantly among MNR, EMNR, and isolation capping. Because dredging is assumed to meet remedial goals during sediment removal, no substantial long-term monitoring costs are incurred.

The estimated costs presented in this assessment are prepared for alternative comparison and are based on the information available at the time of the estimate (2007). The actual costs of remediation depend on many variables, including quantity of contaminated sediments, disposal fees, health and safety regulations, and labor and equipment costs. So that cost estimates best reflect the differences between alternatives and relative costs, a number of assumptions are necessary regarding project scope, especially for design, construction oversight, and long-term monitoring. These assumptions are described in greater detail in the Final Technical Report for this project.

Table 14 presents the comparative analysis of remedial alternatives for Quantico Embayment. Overall, MNR is the least expensive option because no construction activities are involved. Most costs for MNR are incurred during long-term monitoring. MNR long-term monitoring costs are estimated to be less than both EMNR and isolation capping because no maintenance is required (saving approximately $10,000 per maintenance event). Though the costs for EMNR are greater than those for MNR, EMNR is two to three times less expensive than isolation capping and dredging, which both require substantially higher capital costs.

Table 13. Cost Assessment for EMNR Thin-layer Cap Compared to MNR, Isolation Cap and Dredging for a 10.9 Acre Area.

Cost Element	EMNR Thin-Layer Cap	Monitored Natural Recovery	Isolation Cap	Dredge and Off-site Landfill
Construction Costs	$2,340,000	$0	$6,851,000	$10,035,000
Design Costs	$397,000	$204,000	$523,000	$473,000
Oversight & QC Costs	$456,000	$0	$876,000	$825,000
Contingency (25%)	$798,000	$51,000	$2,063,000	$2,833,000
Post-Construction (Baseline) Monitoring	$76,000	$76,000	$76,000	$76,000
Total Capital Costs	**$4,070,000**	**$330,000**	**$10,400,000**	**$14,200,000**
Annual Monitoring & Maintenance Years 1-5	**$123,000**	**$113,000**	**$123,000**	**$0**
Annual Monitoring & Maintenance Years 6-30	**$32,000**	**$23,000**	**$32,000**	**$0**
Present Worth O&M	$770,000	$650,000	$770,000	$0
Total Present Worth	**$4,840,000**	**$980,000**	**$11,200,000**	**$14,200,000**

Note: Present worth was calculated using a discount rate of 7%.

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8.0 IMPLEMENTATION ISSUES

Although conventional isolation caps have demonstrated effectiveness in the management and remediation of chemically impacted sediment, rigorous demonstration and validation of the effectiveness of EMNR remains limited (USEPA 2005). Ongoing questions regarding the application, performance, and ecological impacts of EMNR have limited its widespread implementation. To address these implementation issues, the following relevant questions were posed, and their evaluation is based on the literature compiled and the demonstrations conducted as part of this project.

Is artificially increased sediment deposition via TLC placement an effective strategy for enhancing MNR and accelerating natural system recovery rates?

The effectiveness of the TLC strategy for accelerating MNR appears to be a viable remediation approach depending on site conditions. From a process perspective, key aspects of the success of the TLC and the overall EMNR approach are that: (1) the TLC remains relatively stable above the sediment to be isolated; (2) any new deposition is relatively clean compared to surface sediment goals, even if the rate of deposition is low; (3) bottom-up mixing of the TLC is limited to the extent that the elevated levels of contamination in the underlying sediment do not unduly influence the exposure in the surface sediments following placement of the TLC; (4) advection rates through the cap are not so significant that they lead to a high level of porewater movement from below the TLC into the TLC; and (5) the remedy should demonstrate direct reduction in bioavailability over the short-term and long-term. For the Quantico Embayment site where we conducted our demonstration, these conditions were documented as satisfied. Multiple measures of cap thickness and elevation indicated that the cap material remained relatively stable and within design guidelines. New deposition, as characterized by sediment traps and surface sediment interval samples, was generally low in DDX. Bottom-up mixing was documented to be limited based on multiple lines of evidence. While advection rates were not directly measured, porewater measurements at critical intervals within the cap showed that advection was not significant enough to unduly influence the concentrations within the cap. Finally, direct measurements of bioavailability including uptake in organisms and porewater concentrations generally indicated significant reductions over both short and long-time periods out to two years.

How sensitive is EMNR performance to the accuracy of TLC placement?

Sensitivity of the EMNR performance to the accuracy of TLC placement appears to be relatively high due to the thinness of the layer applied (the same order of magnitude in thickness as the bioactive zone of the sediments). To be effective, the TLC must also accommodate a certain degree of bottom-up mixing that likely occurs either during the installation or due to physical or biological disturbance over time. Thus, key aspects of the sensitivity to placement include the relative thickness of the TLC compared to the bioactive zone and the degree of bottom-up mixing that is expected based on construction methods and site-specific likelihood of physical and biological disturbance following placement. For the demonstration at Quantico Embayment, the bioactive zone was relatively shallow because of the freshwater, riverine nature of the site. Also, it was observed that the installation of the TLC generally achieved target thickness throughout the site so that there were few areas where biological activity was likely to interact with the underlying sediments. In addition, physical disturbance of the TLC appeared to have been limited to localized resuspension during the installation of the cap, resulting in some interleaving of native sediments with the cap material, but not to the extent that it interfered with the effectiveness of the remedy over the two years of observations.

What are the short-term construction (risk-of-remedy) effects associated with EMNR and to what extent does TLC application influence benthic community survival?

The primary risks related to the construction of the TLC appear to be potential short- to mid-term effects on the benthic community, along with some amount of disturbance of the native sediment associated with the depositing of the TLC material. The effects on the benthic community are expected to be a function of both the initial covering of the native sediments that can result in smothering of the existing infaunal community, as well as the potential that the community could be degraded over the mid-term because of the differing grain size and TOC characteristics of the TLC material. From our laboratory treatability studies, we observed significant smothering effects from placement of thin layers of sand over infaunal organisms. However, at the demonstration site at Quantico Embayment, we observed relatively rapid recovery of the benthic community following construction of the TLC. While the sand material may not have provided optimal habitat initially, it was observed that over time, top-down mixing of relatively clean sediment deposits into the surface layer tended to improve the habitat characteristics, and a general improvement in benthic community health was observed relative to the pre-construction conditions.

Under what range of physical, biological, and chemical conditions will EMNR be effective?

The range of effectiveness of EMNR was not completely explored in this project. However, general considerations for the selection of EMNR are becoming well established. From a physical perspective, the remedy should generally be applied at relatively quiescent sites and not subject to significant physical disturbance that would disrupt or penetrate the cap to a degree that the underlying sediments would be re-exposed or significantly mixed into the TLC. The native materials must also have the physical strength to support the TLC so that gravitational mixing does not lead to its failure. From a biological perspective, the TLC thickness should consider the nature and scale of bioactivity in the surface sediments, and the expected route of exposure for the risk endpoints under consideration. From a chemical perspective, EMNR is generally viewed as being most effective at sites where MNR would be effective, but deposition rates are potentially too low to reach the desired clean-up goals in a reasonable amount of time. Thus, most sites where EMNR has been applied have exposure levels that are near risk thresholds, as opposed to higher concentration hot spots. For the Quantico Embayment site, our results reflect these physical, biological, and chemical conditions. The site is in a relatively protected embayment, the bioactivity was limited due to the freshwater nature of the site, and the concentrations (other than in areas targeted for removal) were relatively close to the target PRG.

With respect to grain size, TOC content, and other biogeochemical parameters that influence habitat quality, how can EMNR design be optimized?

This remains a key question that was not thoroughly addressed in this project. Follow-on studies have been proposed to address this optimization question. In general, EMNR has been carried out using TLCs constructed with sand, which is optimal from a stability and construction perspective, but not necessarily optimal from a habitat or environmental protection perspective. Because sand materials lack consistency with the grain size characteristics of the native sediments, they create a habitat inconsistent with the site conditions. In addition, the sand material contains essentially no TOC, which may create a less optimal habitat while also providing little to no binding capacity for contaminants.

While the traditional sand TLC was shown to be effective over two years at the Quantico Embayment site, future development of a more comprehensive approach and guidance for the selection and optimization of EMNR that addressed this question would be highly beneficial to the broader implementation of the remedy.

How effective is EMNR in reducing chemical mobility and biological exposure potential in surface sediment?

Overall, review of the historical literature and our experience with the Quantico Embayment site indicated that EMNR can be highly effective in reducing exposure in surface sediments. EMNR remedy effectiveness seems to be a function of three primary considerations, including careful consideration of site condition for the selection of EMNR, proper design of the EMNR remedy to meet site-specific conditions, and adequate monitoring to assure remedy success and address any potential defects in the TLC. For the Quantico Embayment site, the EMNR remedy was effective in reducing exposure in surface sediments as measured by bulk sediment total DDX concentrations, porewater DDX concentrations, and direct measurement of bioaccumulation in two site-exposed benthic organisms.

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