TECHNICAL REPORT 1983
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Enhanced Monitored Natural Recovery (EMNR) Case Studies Review

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SSC Pacific
San Diego, CA 92152-5001

SSC PACIFIC
San Diego, California 92152-5001

M. T. Kohlheim, CAPT, USN
Commanding Officer

C. A. Keeney
Technical Director

ADMINISTRATIVE INFORMATION

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Released by
D. Bart Chadwick, Head
Environmental Sciences
Branch

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M. Machniak, Head
Advanced and Applied
Sciences Division

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EXECUTIVE SUMMARY

This report initially presents three detailed Enhanced Monitored Natural Recovery (EMNR) case studies for the following sites: 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. After discussion of sediment management at these sites, other sites are discussed that may prove informative for sediment remediation through EMNR.

The three principal sites discussed in this report represent locations in which EMNR has been implemented as a component of a mature site remedy, and for which the success of implementation can be assessed through available placement and post-placement monitoring data.

EMNR was selected for those portions of each site 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 recolonization, while not causing widespread disturbance to the existing habitat.*

For Wyckoff/Eagle Harbor, Ketchikan Pulp, and Bremerton, overall site remedies also variously included dredging, construction of confined disposal facilities, isolation capping, debris removal, and monitored natural recovery.

For sites discussed in this report, remedial action objectives (RAOs) varied considerably. RAOs were defined as specific risk-based cleanup targets (for Eagle Harbor), biological indicators such as community structure and function that may demonstrate improvements in benthic habitat quality (for Ketchikan), and concentration-based targets derived from cost considerations and recovery rate modeling (for Bremerton). While all these objectives provide reasonable routes towards site remediation, variability exists in the extent to which improvements can be shown to have occurred within the time frame allotted for system recovery. Although not all remedies can be said to have equally achieved stated remedial goals (and cannot therefore be considered as equally successful), all sites discussed in this report do demonstrate improvements in surface sediment concentrations of at least some chemicals after remedy implementation.

Sites of further interest include examples in which a landslide created conditions similar to the placement of a thin layer cap, sites in which thin layer cap placement constituted a pilot project with monitoring goals focused on implementation rather than demonstration of long-term stability or risk reduction, and sites in which limited placement and/or monitoring data are available for assessing progress towards meeting site-specific RAOs.

Several of the principal sites at which thin layer capping has been pilot-tested have also included field testing of reactive amendments. Reactive amendments include materials such as resins, organic carbon, or other solids that are added to capping material or sediment. The materials sorb or react with chemicals to increase chemical transformation or decrease chemical availability. Results from the site using the addition of reactive amendments to thin layer chromatography will be discussed in the context of cap placement and system recovery metrics. However, the specific function and/or composition of the reactive amendments themselves will not be discussed in depth in this review. The use of geotextile mats or fabrics that aid in the support of the cap or provide a way to disseminate low-density sorptive amendments will also not be discussed in this review.

As noted above, post-placement monitoring of pilot sites was designed to evaluate the short-term integrity, performance, and biological impact of the installed cap. Because of this distinct short-term focus, pilot studies of thin layer capping provide insight into factors associated more directly with remedy implementation, including the effect of thin layer cap placement on water quality and/

or the benthic community structure and/or composition. Where data are available to support the discussion, these topics are considered in assessing the strengths and limitations of thin layer capping.

CONTENTS

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ACRONYMS AND ABBREVIATIONS

ARARs	Applicable or relevant and appropriate requirements
CDF	Confined Disposal Facility
cm	centimeter
cm/d	centimeters per day
cm/s	centimeters per second
cm/yr	centimeters per year
CSO	Combined Sewer Overflow
CY	cubic yards
DDT	Dichlorodiphenyltrichloroethane
DoD	Department of Defense
EBDRP	Elliott Bay/Duwamish Restoration Program
EMNR	Enhanced Monitored Natural Recovery
HAET	High Apparent Effects Threshold
HEC	Herrera Environmental Consultants
km	kilometer
KPC	Ketchikan Pulp Company
MCULs	Minimum Cleanup Levels
mg/kg	milligrams per kilogram
m	meter
m^2	square meter
mg/m2	milligrams per square meter
mm	millimeter
OC	Organic Carbon
OU	Operable Unit
OU B	Open Water Unit
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyl
RAOs	Remedial Action Objectives
ROD	Record of Decision
TOC	Total Organic Carbon
µg/kg	microgram per kilogram
USEPA	United States Environmental Protection Agency
WW	Whatcom Waterway

1. INTRODUCTION

This case study review was prepared as part of a Navy-led project to foster broader understanding and acceptance of the Enhanced Monitored Natural Recovery (EMNR) remedy through demonstration and validation of performance and cost-effectiveness at Department of Defense (DoD) contaminated sediment sites. EMNR is a hybrid remedy that generally relies on the combined effects of a thin layer cap (enhancement) and natural recovery, and is verified over time through monitoring. This case study review is a resource for site managers who are considering EMNR as a remedy. The ENMR project will perform a field demonstration based on this review.

Conventional in situ sediment capping involves the controlled placement of uncontaminated material over contaminated sediment. Capping is a relatively mature, proven technology recognized by the U.S. Environmental Protection Agency (USEPA) (2005a). USEPA (2005a) identifies the following three primary cap functions: physical isolation, stabilization/erosion protection, and chemical isolation.

Physical and chemical isolation separate contaminants from the surrounding environment, protect human or ecological receptors from chemical exposures, and minimize the potential for resuspension and transport. Materials commonly used in conventional sediment caps include clean sediment, sand, or gravel (Palermo et al., 1998a; EPRI, 2004) that can be dredged from nearby waterways or obtained from upland sources, including commercial quarries. In certain instances, a more complicated engineered capping system can involve geosynthetics (e.g., geomembranes or geotextiles), multiple layers of various materials, or specialty amendments (Palermo, Maynord, Miller, and Reible, 1998a).

Early use of isolation capping commonly involved the placement of 1 to 3 m of sediment to securely bury and isolate chemically impacted sediment. This approach has been based on relatively conservative design criteria that included providing sufficient cap thickness to isolate benthic organisms to a given bioturbation depth; reduce contaminant flux to achieve specific sediment, pore water, or water column target concentrations; establish sufficient armoring to stabilize cap material in response to specific storm or flood flow return periods; limit mound elevation to meet navigation or erosion constraints; and account for changes in cap thickness caused by consolidation after placement (Palermo et al., 1998a; 1998b; ERPI, 2004; Bailey and Palermo, 2005).

Today, thinner caps are increasingly employed to enhance ongoing natural recovery processes and to minimize impacts to the aquatic environment (e.g., to lessen the loss of aquatic habitat caused by cap displacement). These thinner caps commonly involve the placement of 10 to 30 cm of clean sediment, and have are called “thin layer caps.” Optimum thin layer cap thickness is based on site-specific characterization information, natural recovery characteristics, and remedial action objectives (RAOs).

In contrast to isolation caps, thin caps used for EMNR are not intended to provide a complete seal over the chemically impacted sediment as in a conventional isolation capping operation (Brannon et al., 1985). Instead, the thin layer cap provides a surface layer of cleaner sediment, which results in an immediate reduction in surface chemical concentrations that facilitates the re-establishment of benthic organisms, minimizes short-term disruption of the benthic community, and accelerates the process of physical isolation continued over time by natural sediment deposition (NRC, 2003; USEPA, 2005a). Depending on the rates of natural sedimentation and erosion, bioturbation mixes thin layer cap material with underlying chemically impacted sediment, thereby encouraging natural recovery processes such as chemical transformation (where appropriate). Natural sedimentation physically isolates chemically impacted sediment and the thin layer cap from biological exposures at the sediment surface, disrupting exposure pathways to benthic organisms.

This report examines sediment management projects that have employed thin layer capping/ EMNR as a component of remedial design. Optimum thin layer cap thickness is determined based on site-specific characterization information, natural recovery characteristics, and RAOs. A thin layer cap thickness of 15 cm was the most commonly employed design thickness for the EMNR case studies summarized in this report, although cap thicknesses between 15 and 45 cm are considered “thin layer caps” and are included in the discussion throughout this report.

The three case studies discussed in detail are presented in Section 2 of this report. Section 3 presents additional sites that may prove informative for implementing thin layer capping as a remedy. Conclusions and an overview of lessons learned during this implementation are provided in Section 4. References are provided in Section 5.

2. MNR CASE STUDIES

2.1 WYCKOFF/EAGLE HARBOR SUPERFUND SITE, WASHINGTON

2.1.1 Site Overview and RAOs

The Wyckoff/Eagle Harbor Superfund Site is a 200-hectare (500-acre) marine embayment located in central Puget Sound, Washington, on the east side of Bainbridge Island (Figure 1). The significance of the Wyckoff/Eagle Harbor Superfund Site is in the successful placement of a 15-cm cap over sediment containing elevated concentrations of mercury and polycyclic aromatic hydrocarbons (PAHs). Lessons learned through post-placement monitoring include (1) broadcasting the cap material in multiple low-volume lifts results in uniform and consistent placement of material, (2) interpretation of post-placement bathymetric surveys may be hindered by the resolution of instrumentation, and (3) incomplete source control near the thin layer cap has increased surface sediment mercury concentration in the cap material over time.

Chemicals in Wyckoff/Eagle Harbor sediment largely originate from industrial activities of a former wood-treating facility and an adjacent shipyard. The wood-treatment facility and the shipyard operated throughout much of the 20th century. In the East Harbor Operable Unit (OU), the principal chemicals of concern are PAHs. In the West Harbor OU, chemicals of concern in intertidal and subtidal sediment include mercury, arsenic, cadmium, copper, lead, zinc, and PAHs. The presence of elevated concentrations of metals in West Harbor sediment resulted from the use of antifouling agents and paints in the shipyard. Within the West Harbor OU, concentrations of mercury in subtidal sediment exceeded concentrations from other locations in Eagle Harbor by more than an order of magnitude, and sediment concentrations greater than 5 mg/kg were defined as the "principal threat" (USEPA, 1992).

RAOs for the West Harbor OU include (1) achieving the State of Washington Sediment Quality Standards or minimum cleanup levels (MCULs) (0.59 mg/kg for mercury) in the top 10 cm of the sediment throughout the West Harbor OU within 10 years after the completion of active sediment remediation, and (2) reducing chemical concentrations in fish and shellfish to levels protective of human health and the environment. Risk-driven remedial decisions for the West Harbor OU2 have thus been driven by both ecological and human health concerns.

2.1.2 Remedial Design and Implementation

Remedies implemented in the West Harbor OU between 1992 and 2002 (USEPA, 2007) include the following:

- *Dredging of sediment containing greater than 5 mg/kg mercury and disposal of dredged sediment in an onsite confined disposal facility (CDF).* This concentration threshold represents the site-specific delineation of the "hot spot," removal of which is expected to prevent potential resuspension and redistribution of mercury from the OU area. The highest mercury concentration measured within the hot spot was 95 mg/kg.
- *Placement of a thick cap (~1 m) over "high concern" sediment containing concentrations of mercury greater than 2.1 mg/kg.* This concentration represents the High Apparent Effects Threshold (HAET), above which amphipod and oyster larvae exposed to sediment fail site-specific acute toxicity tests, and benthic organisms may demonstrate chronic exposure effects.
- *EMNR through placement of a 15-cm thin layer cap over sediment of "moderate concern" that either (1) exceeded the mercury MCUL of 0.59 mg/kg but did not exceed the HAET of 2.1 mg/kg, or (2) was shown on a site-specific basis to require remediation to reduce biological exposure and/or the potential for sediment redistribution.* The thin layer cap was designed to reduce the

concentration of chemicals in the biologically active zone of the sediment without causing significant, widespread disturbance to existing habitat.

- *Sediment armoring.*
- *Long-term monitoring of areas not excavated, including capped and uncapped areas (natural recovery).*
- *Construction of an approximately 180-m tidal barrier (completed August 2006) between the CDF and the adjacent estuary*. The barrier was required because seeps emanating from the initial tidal barrier contained elevated concentrations of copper and zinc.

The thin layer cap installed as a component of EMNR was defined in the Record of Decision (ROD) as the placement of shallow layers or windrows of clean sediment in areas of low natural sedimentation (USEPA, 1992). Thin layer capping was implemented in approximately 10% of the West Harbor OU, in a shallow water area between 1 and 11 m of water depth and minimal bottom slope. This area was generally defined as experiencing low to moderate near-bed velocities and a low background sedimentation rate (USEPA, 1992). As the limit of the thin layer capping area was explicitly defined as a function of sediment chemical concentrations, no site physical characteristics were specifically identified in the ROD as limiting (or supporting) a particular thin layer capping area delineation.

Placement of the cap material was specified in the ROD as occurring through hydraulic washing from the deck of a barge (effective for dispersing a thin layer of sand over a wide area) or windrow placement from a split-hull hopper dredge (USEPA, 1992).[1] Windrows were designed as longitudinal ridges of sand at approximately 60-m spacing on center. In the area receiving sand through hydraulic washing, final cap thickness was projected as a fairly uniform 15 cm, although interpretation of post-placement confirmation surveys has been somewhat hindered by the resolution of bathymetric survey instrumentation. In the area receiving windrow placement, it was expected that cap thickness would range from 30 cm along the centerline of the windrow to approximately 7 cm at a distance halfway between adjacent windrows. Although the time required for placement of the thin layer cap could not be confirmed, 6 months were projected for full cap implementation in the West Harbor OU (USEPA, 1992). As full implementation entailed placement of 275,000 cubic yards (CY) of medium-grained sand over a 22-hectare (54-acre) area, the time required for implementation of the thin layer cap over 1.8 hectares (4.5 acres) was likely on the order of 3 weeks. As thin layer and thick cap placement throughout the West Harbor OU involved cost-related overlap in mobilization and materials requirements, it is impossible to separate the line-item cost for thin layer cap placement from the overall cost of capping in the West Harbor OU (estimated at ~ $1M). The cost of the cap material itself was estimated at $15/CY.[2]

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[1] The range of possible cap placement techniques has been thoroughly and recently reviewed (Bailey and Palermo, 2005; http://el.erdc.usace.army.mil/elpubs/pdf/doerr9.pdf). In this narrative, cap placement strategies will therefore be discussed only in the context of site-specific placement decisions.

[2] Robert Zisette, Consulting Engineer, or Mary Jane Nearman, Project Manager, USEPA Region 10. Conversations with Karen Merritt on 24 March 2008 (Zisette and Nearman) and 16 May 2008 (Zisette).

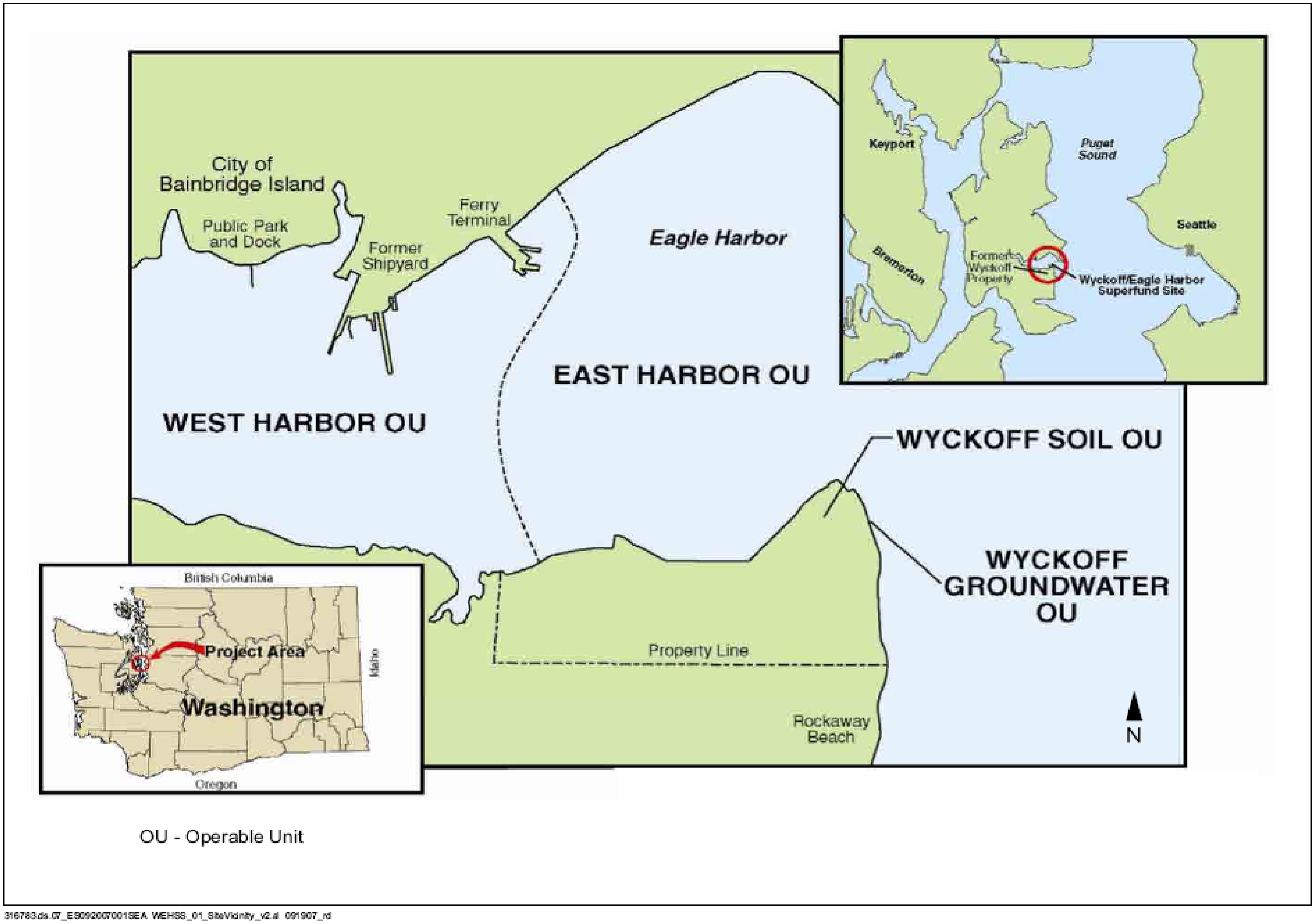

Figure 1. Wyckoff/Eagle Harbor, Washington.

Strengths and weaknesses of the thin layer cap design in the West Harbor OU were discussed with the USEPA project manager and consulting engineers at Herrera Environmental Consultants (HEC), the engineering firm responsible for placement and post-placement monitoring of the thin layer cap. No significant technical problems arose during cap placement.[2]

With projected system recovery, it was assumed that biological recovery after thin layer cap placement would occur over several years. Chemical recovery of the site, as defined by the time required for surface sediment chemical concentrations to decrease to below the remedy-specific threshold levels (i.e., the MCULs), was defined as 10 years. As recovery is therefore predicated on a specific sediment chemical concentration, achieving remedy success is highly dependent on effective source control.

2.1.3 Monitoring

The thin layer capped area in the West Harbor OU has undergone various post-remediation monitoring events between 1999 and 2007. Monitoring of the thin layer cap area has focused on two objectives: (1) environmental fate and transport monitoring, and (2) remedy goal monitoring (USEPA, 2007).

The extent to which cap placement has reduced the transport/redistribution of mercury within Eagle Harbor has been assessed by comparing surface sediment chemical concentrations with pre-remediation conditions (1994), Year 0 post-remediation conditions (1997), and RAOs based on Washington State Sediment Management Standards. Remedy goal monitoring within the thin layer cap areas has focused on sampling in Year 2 (1999), Year 4 (2001), and Year 8 (2005).

Monitoring has included (1) mercury analysis in surface water, groundwater, and intertidal seeps; (2) mercury analysis in surface and suspended sediment; and (3) comparison of current sediment chemical concentrations with site-specific sediment bioassay MCULs. Site-specific bioassay MCUL had been previously determined for amphipod, polychaete, and bivalve larvae tests conducted during the interval prior to remedy implementation.

Sediment sampling has included surface sediment (0 to 2.5 cm) and deeper sediment (0 to 10 cm). Surface sediment mercury concentrations are compared against the Washington State Sediment Quality Standards benchmark (0.41 mg/kg) to evaluate the extent to which mercury concentrations in recently deposited sediment demonstrate successful (upgradient) source control. Sediment mercury concentrations defined in the 0- to 10-cm depth interval are compared against MCUL criteria (0.59 mg/kg) to verify that recontamination of the sand cap from the underlying sediment is not occurring. Bathymetric surveys have also been conducted at the same sampling intervals to verify continued sediment surface elevation and to monitor for evidence of cap erosion.

Monitoring results generally confirm that capped areas are remaining in place and chemicals of concern are remaining below criteria, although interpretation of post-placement bathymetry has been somewhat limited by the resolution of the chosen survey instruments (which is approximately equivalent to the thin layer cap thickness). Overall costs for monitoring between 1999 and 2005 are estimated at $225,000.[3] This total includes three sampling intervals, with the price per interval ($75,000) divided between sediment sampling and chemical analysis ($25,000) and bathymetric survey work ($50,000).

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[3] Robert Zisette, conversation with Karen Merritt on 16 May 2008.

Results from 2005 monitoring (USEPA, 2007) of the thin layer cap area include (1) surface water dissolved mercury concentrations remain below surface water criteria; (2) the MCUL was exceeded in the 0- to 10-cm interval samples from 20% of stations (n = 2) within the thin layer cap zone, resulting in a statistically significant increase in mercury concentrations in 2005 relative to what was observed in 1999 and 2001; (3) the MCUL was exceeded for 100% of stations (n = 2) in reference station zone; and (4) there was a statistically significant increase in mercury concentrations in the 0- to 2.5-cm depth interval between the 2001 sampling and the 2005 sampling.

Results from the Year 8 (2005) data summary report suggest that although there has been no significant evidence of cap failure or erosion, mercury concentrations within the thin layer cap zone are increasing somewhat in surface sediments (HEC, 2006). This increase is likely caused by multiple processes, including deposition or mercury-enriched flocculent material from the water column (i.e., likely resulting from lateral transport from elsewhere in Eagle Harbor), and internal mixing of the cap sediment with underlying sediment (i.e., bioturbation). Based on monitoring results, the 2007 USEPA Five-Year Review concludes that the implemented remedy is achieving the objectives laid out in the ROD and all Applicable or Relevant and Appropriate Requirements (ARARs) (USEPA, 2007).

2.1.4 Lessons Learned

Currently, it appears that thin layer capping has been implemented successfully as a component of the larger remedial effort at Eagle Harbor and that the thin layer cap has remained stable during 10 years of monitoring. Placement of the thin layer cap was restricted to those locations within the harbor that were of “moderate concern,” with surface sediment mercury concentrations ranging from 0.59 to 2.1 mg/kg. The zone receiving a thin layer cap was significantly smaller in areal extent than the larger area in the West Harbor OU receiving remediation through other means (including dredging and thick capping).

Monitoring results in Eagle Harbor specifically highlight the importance of source control, particularly when remedy success has been defined as a specified surface sediment chemical concentration. A fraction of thin layer cap sampling stations indicate recontamination from lateral transport of chemicals in the absence of wider harbor source control. The extent to which such recontamination is of significant concern for overall site remediation depends on the areal extent of the cap and the magnitude of sediment recontamination in the context of the recovery achieved by the multiple remedy components employed at this site.

2.2 KETCHIKAN PULP COMPANY (KPC), KETCHIKAN, ALASKA

2.2.1 Site Overview and RAOs

The former KPC facility is located on the northern shore of Ward Cove, a marine embayment approximately 7.5 km north of Ketchikan, Alaska (Figure 2). The KPC facility conducted sulfite pulping operations between 1954 and 1997 and pulp mill effluents were discharged to Ward Cove. As organic-rich deposits are up to 1.5-m thick in some locations of Ward Cove, the resultant change in the physical structure of the sediment has negatively affected habitat quality for benthic organisms.

Chemicals of concern at this site include ammonia, sulfide, and 4-methylphenol. None of these chemicals are bioaccumulative and ecological exposures are dominated by diffusive uptake pathways. Diffusion of chemicals from underlying sediment was identified as the dominant mode of chemical transport responsible for toxicity to organisms in surface sediment. Because human health and ecologic risks at this site were within acceptable regulatory limits, the complete isolation afforded by placement of a thicker armored cap was not required. The area of site remediation in Ward Cove incorporates an approximately 32-hectare (80-acre) subtidal zone with water depths ranging from 4.5 to greater than 35 m (Figure 3a–b). Although the tidal range in Ward Cove exceeds 4.5 m, there is little freshwater inflow to the Cove and both bottom shear velocities and background sedimentation rates are low in the area of concern.

RAOs for sediment in the Ward Cove area of concern include (1) reducing the potential for chemical exposure and resultant toxicity to benthic organisms in surface sediment, and (2) enhancing recolonization of sediment by a healthy and diverse benthic community, with the goal of ultimately supporting a healthy community of marine organisms (USEPA, 2000b). Remedial criteria are based on biological indicators that support attainment of these objectives, rather than specific threshold concentrations of chemicals in sediment or pore water.

2.2.2 Remedial Design and Implementation

According to the Five-Year Review (USEPA, 2005b), remedial implementation has included the following:

- Institutional controls
- Removal of approximately 680 tons of sunken logs from within dredge footprint
- Dredging of sediment within a 1.2-hectare (3-acre) area for navigational purposes
- Thin layer cap (15 to 30-cm thickness) placement within an 11-hectare (27-acre) area
- Monitored natural recovery within a 20-hectare (50-acre) area, where thin layer cap placement was initially considered impractical
- Long-term monitoring

Locations in which thin layer capping was considered impractical during remedial design included areas with the following characteristics:

- A very high density (greater than 200 logs/acre) of sunken logs that formed pyramids exceeding 10 ft in height
- Water depth exceeding 30 m
- Bottom slopes exceeding 40%
- Organic-rich sediment with inadequate bearing capacity (less than 6 pounds per square foot) to support a sediment cap
- Routine maintenance dredging operations

EMNR was selected to achieve RAOs by providing a new sediment surface that (1) limits chemical exposures from now buried sediment, and (2) improves sediment physical structure/habitat quality to enhance benthic recolonization.

In terms of engineering design, the specified thin layer cap material was defined as fine-grained to medium-grained sand with non-plastic silt (Hartman Consulting Corporation, 2000a). Fine-grained sand was defined with a particle diameter between 0.08 and 0.43 mm. Medium-grained sand was defined with a particle diameter between 0.43 and 2.0 mm. Non-plastic silt was defined with a particle diameter between 0.005 and 0.08 mm, with a plasticity index of less than 4 as determined by the Atterberg limit tests (ASTM D4318). For the area within the barge access channel, capping employed moderately coarse-grained sand with a particle diameter between 2 and 4 mm. Various methods were tested for the uniform distribution of capping materials, and a framework was developed for initiating alternate remediation strategies if implementation fails.

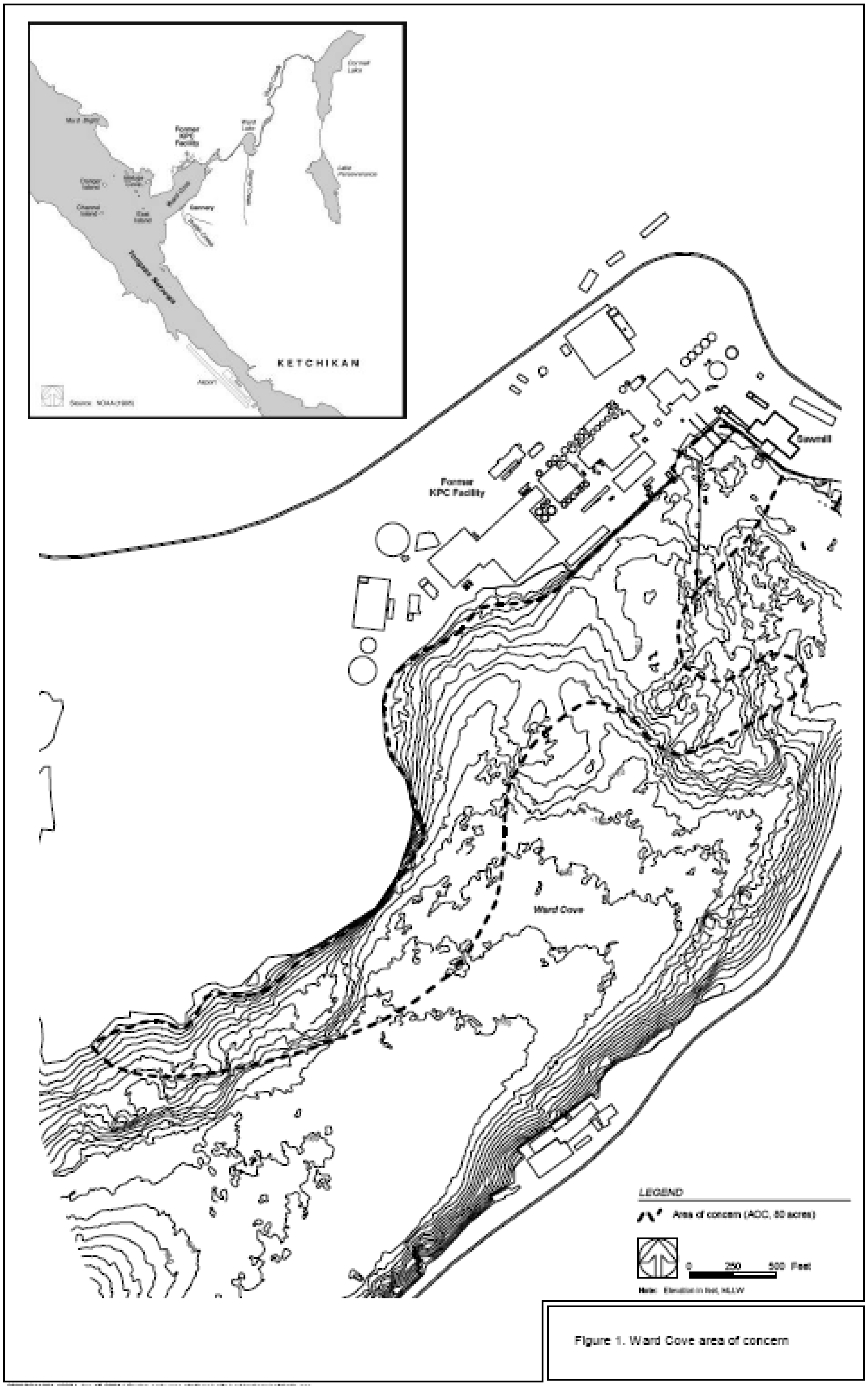

Figure 2. Ward Cove area of concern, Ketchikan Alaska.

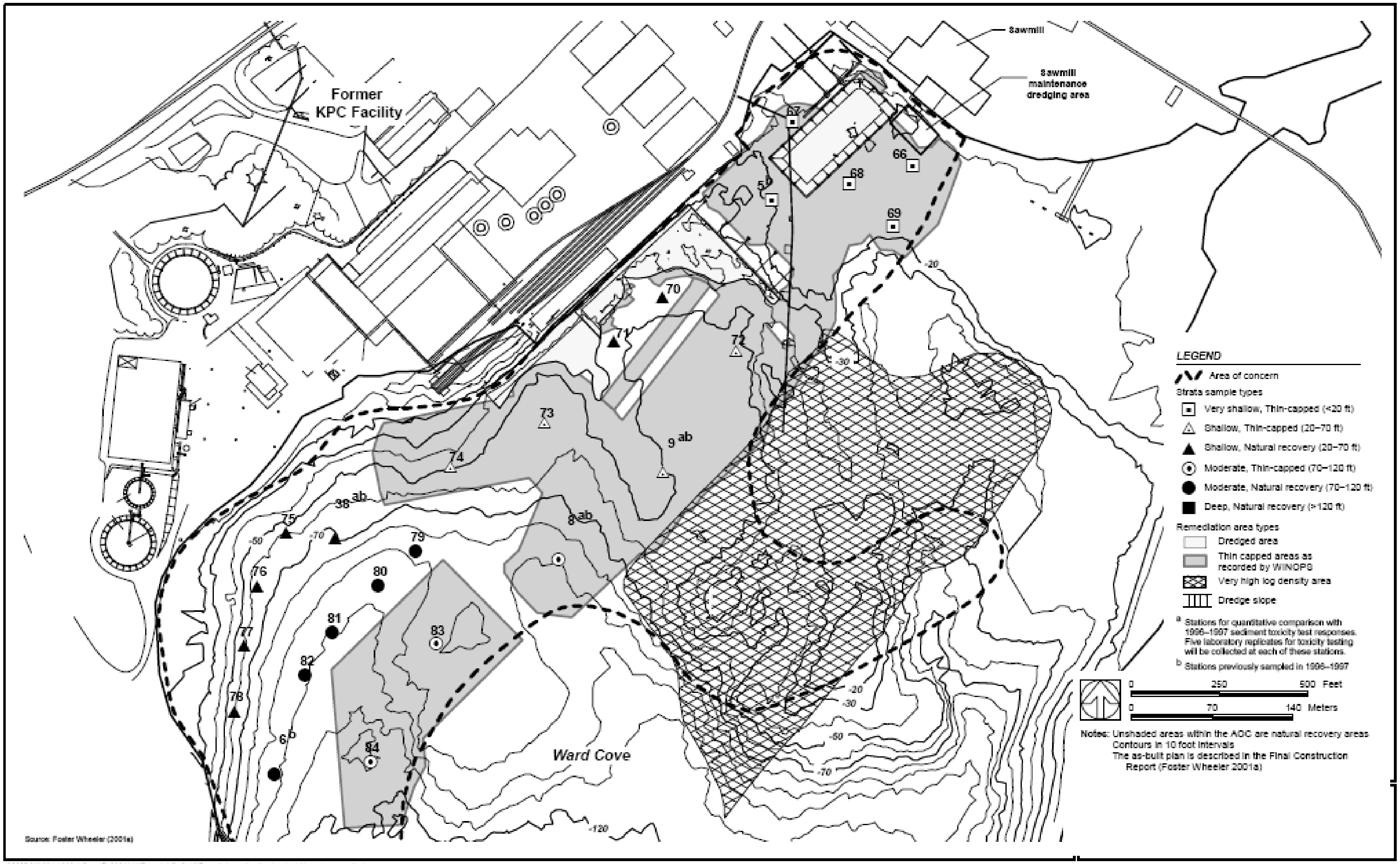

Figure 3a. Stations for long-term monitoring within the Ward Cove area of concern, Ketchikan Alaska.

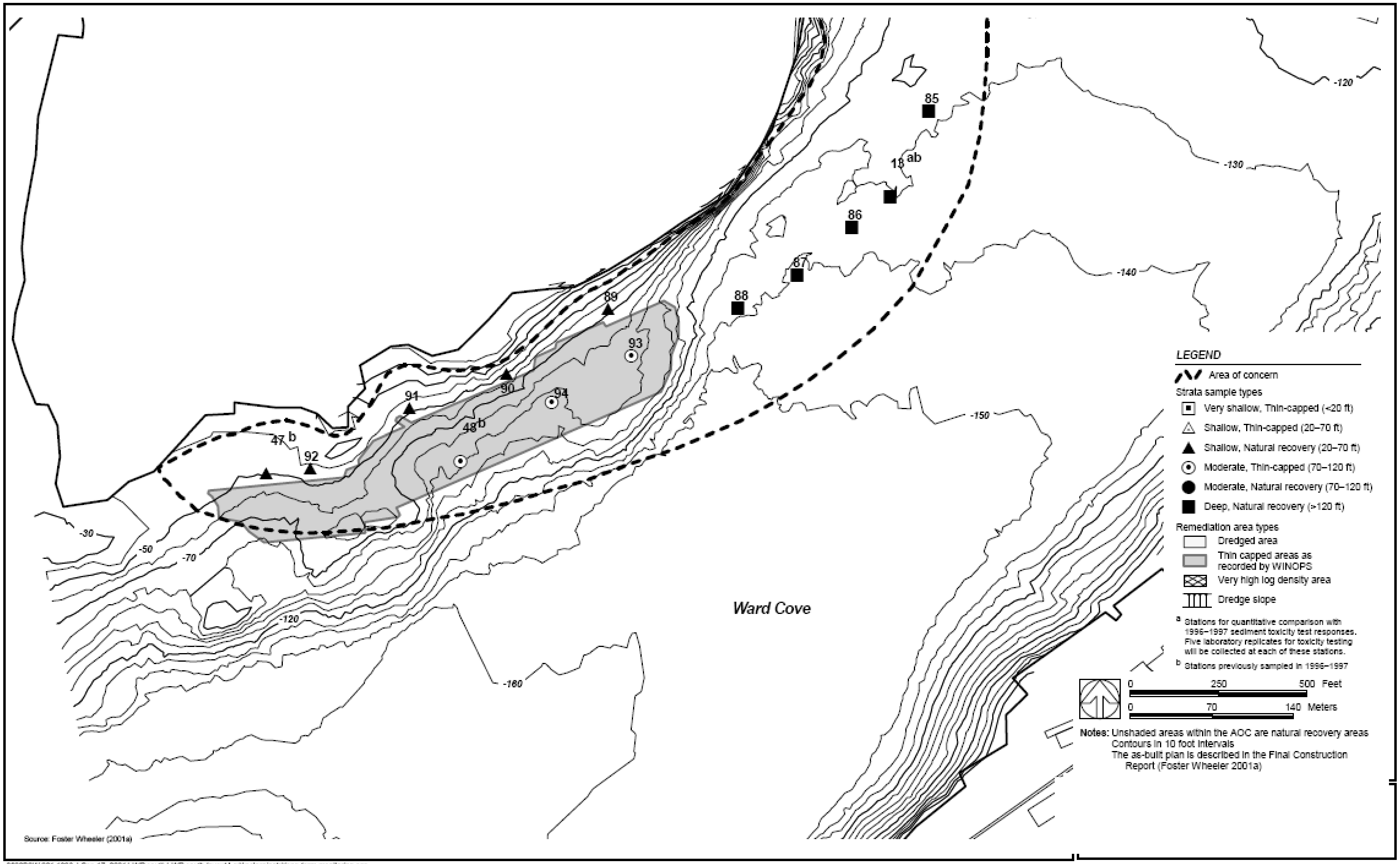

Figure 3b. Stations for long-term monitoring within the Ward Cove area of concern, Ketchikan Alaska.

The placement of the thin layer cap over an 11-hectare (27-acre) area required 24,000 CY of sand and was completed in ~30 days (Foster Wheeler, 2001). The remedy was successfully implemented using a derrick barge and modified cable arm re-handling bucket. Various methods of cap placement were tested because of the concern for uniform placement of cap material in the deep water of Ward Cove. According to the project manager, the most consistent and uniform means of distributing sand was to use a barge and bucket, with the bucket swung over the capping area and the release rate of sand controlled by the bucket operator.[4] This method of cap placement proved superior to more refined methods, including the use of diffusers, underwater pipes (i.e., Tremie tubes), or the release of sand from the bucket while swinging the bucket underwater. Moreover, although the remedial design specified that cap placement would be limited to water depths less than 30 m, field experience suggested that placement of a medium-grained to coarse-grained sand cap could be successful at even greater water depths.

Implementation costs for the thin layer capping portion of the overall site remedy (including capping, dredging, and log removal) are not currently available, although the cap material price was estimated at $18/CY (USEPA, 2000b).

Successful cap placement was defined as the grain size distribution and target total organic content (TOC) of the new sediment surface. The targeted sand content of post-capping surface sediment was 32% by weight. Success was therefore defined as achieving greater than 40% sand content in at least 80% of collected samples, with no more than 20% of the samples at less than 13% sand content (Hartman Consulting Corporation, 2000b). Success targets were also defined for TOC content, with a post-placement goal in surface sediment of 15% TOC by weight. The targeted TOC content was equivalent to a 40 to 50% reduction in the TOC content of the underlying surface sediment (Hartman Consulting Corporation, 2000b). Verification of these targets was obtained via sediment grab sampler, diver-deployed push core, or underwater video survey. It is important to note that the implementation standard did not focus on achieving a specified cap thickness because RAOs for this site could be achieved with either complete cap cover or a partial cap cover plus mixing of cap material with underlying, organic-rich sediment. In application, however, the cap was approximately 15- to 30 cm thick.

2.2.3 Monitoring

Monitoring (2001–2010) of the Ward Cove thin layer cap site has included the following:

- Sediment toxicity comparison in thin layer capped areas and natural recovery areas versus reference areas elsewhere in Ward Cove.
- Comparison of benthic community structure and composition in thin layer capped areas and natural recovery areas versus reference areas elsewhere in Ward Cove.
- Evaluation of temporal trends in sediment toxicity in thin layer capped and natural recovery areas.
- Evaluation of temporal trends in macroinvertebrate benthic community structure and composition in thin layer capped and natural recovery areas (i.e., confirmation that recovery is progressing via the classic colonization pattern of “pioneering” species followed sequentially by “equilibrium” species).

[4] Karen Keeley, Project Manager USEPA Region 10, conversation with Karen Merritt on 27 March 2008.

- Surface sediment analysis for ammonia, 4-methylphenol, grain size distribution organic content, and total solids (because sediment chemistry and physical structure can influence composition and health of benthic communities).

Visual inspection of the sediment surface during and after cap placement confirmed that placement was consistent in both areal distribution and uniform thickness. Post-placement monitoring has also confirmed that factors relating to the nature of the underlying sediment (e.g., organic enrichment, prone to gas generation, poor structural stability) have not compromised the physical integrity or stability of the thin layer cap. Of particular significance in successful thin layer cap placement in Ward Cove is that, although the Project Manager for the KPC site described the surface sediment in the cove as having the appearance and consistency of "black mayonnaise," the placement of a 15- to 30-cm sand cap did not exceed the bearing capacity of underlying native sediment, and the cap has not created conditions promoting the buildup and destabilizing discharge of gaseous byproducts from the underlying sediment. In terms of post-placement cap failure, a binding strategy has also been developed to redress any damage to the cap caused by activities such as dredging. Consistent with this strategy, projects deemed to have "erode[d] or displace[d] large portions of the cap will be required to repair or replace the cap" (Exponent, 2001b).

Costs for the 2004 monitoring interval were estimated at $200,000 to $300,000, with the expectation that costs would decrease for future monitoring events (USEPA, 2005b). According to the 2005 Five-Year Review (USEPA, 2005b), the selected remedies are functioning as intended in Ward Cove and environmental conditions are improving. Evidence of improved conditions has been documented by the following metrics:

- The thin layer sand cap was observed at all stations and does not appear to have been incorporated into the underlying soft sediment.
- The broadcast method of cap placement was successful, and thus appropriately chosen for this site.
- Based on the results of nine standard assessment metrics, a high diversity and abundance of benthic organisms now exist within Ward Cove. In comparison to pre-remedy evaluations in 1992, communities sampled in 2004 indicate twice as many taxa, with a more even distribution of individuals among taxa. No statistical differences were detected for benthic community metrics between thin layer cap (TLC) areas and reference areas, suggesting ecological recovery is proceeding.
- For those areas with thin layer cap placement, concentrations of ammonia and 4-methylphenol (which are volatile and readily diffusible chemicals of concern) are now below site-specific sediment quality values within the biologically active zone of the capped sediment.
- There is high (greater than 90%) survival of amphipods in toxicity tests conducted in surface sediment from capped areas, with toxicity testing having focused on a 10-day test with the chemically sensitive, burrowing amphipod, *Eohaustorius estuarius*.

Overall site remediation will be complete when there is no longer any statistically significant difference between toxicity and benthic community structure and/or composition for any of the thin layer capped or natural recovery areas versus the reference areas (Exponent, 2001a). An overview of the process for evaluating monitoring data in the context of this objective is presented in Figure 4. Results of the 2005 Five-Year Review suggest that if monitoring results from 2007 (not yet available) are consistent with or better than 2004 monitoring results, monitoring of benthic communities may be discontinued in Ward Cove.

2.2.4 Lessons Learned

Currently, the KPC site has demonstrated (1) successful placement of a thin layer cap is possible in deep water (greater than 30 m), (2) placement of a thin layer cap over organic-enriched sediment does not necessarily require specialized sediment broadcasting equipment, (3) it is technically feasible to place a thin layer cap in a manner that does not exceed the bearing capacity of organic-enriched sediment, and (4) the cap does not appear to have created conditions promoting the buildup and destabilizing discharge of gaseous byproducts from the underlying sediment. The placement of a thin layer cap was successful in reducing toxicity in surface sediment because it limited the extent to which benthic organisms were in direct contact with pore water containing elevated concentrations of dissolved chemicals. Ecological recovery is occurring as benthic communities colonize the thin layer cap. Overall remedial goals are being achieved.

2.3 BREMERTON NAVAL COMPLEX, BREMERTON, WASHINGTON

2.3.1 Site Overview and RAOs

Bremerton Naval Complex is located on the Sinclair Inlet of Puget Sound at Bremerton, Washington (Figure 5). The Bremerton Naval Complex has been in operation since the 1890s and currently consists of (1) the Bremerton Naval Station, serving as deep-draft port for aircraft carriers and supply ships, and (2) the Puget Sound Naval Shipyard that provides maintenance and repair services to the naval fleet.

The area of concern in the Bremerton Naval Complex is defined by approximately 154 hectares (380 acres) of upland and 105 hectares (260 acres) of submerged land. The upland areas consist of a relatively low-lying marsh created through filling of marshes and tidelands. The submerged area extends from the shoreline of Sinclair Inlet to a distance of approximately 450 m offshore.

Various fleet support activities, including ship building, maintenance, and mooring, have contributed chemical inputs to the Bremerton Naval Complex. Moreover, waste disposal, spills, and leaks of industrial materials, including metal plating waste, metal filings, electrical transformers (containing PCBs, batteries, paint (containing heavy metals), acids, and caustic materials have led to elevated concentrations of numerous chemicals in the surface and subsurface sediment of Sinclair Inlet. Although most chemical sources to Sinclair Inlet are historic, ongoing minor releases appear to result from erosion of upland soils and direct stormwater discharge to the inlet.

Primary chemicals of concern in Sinclair Inlet include PCBs and mercury. Although ecological risks resulting from PCB and mercury exposure at this site are not considered significant, PCBs and mercury pose unacceptable risks to human health. For sediment samples collected in the open water area of concern, baseline PCB concentrations exceeded the Washington State Sediment Quality Standard of 12 mg/kg OC (concentration normalized to organic carbon content) in a significant number of stations (no percentage given), with a maximum measured concentration of 61 mg/kg OC. Mercury concentrations exceeded the Sediment Quality Standard of 0.4 mg/kg at 88% of stations sampled in the open water unit (OU B), with a maximum measured concentration of 12 mg/kg.

RAOs were defined for six OUs in Sinclair Inlet, including OU B. OU B is an approximately 220-acre subtidal section of the inlet, with water depths generally less than 15 m. For OU B, RAOs focused principally on the reduction of human health risk by reducing the concentration of PCBs in the biologically active zone of sediments (0 to 10 cm).

A site-specific remedial action objective was defined for OU B to reduce area-weighted average surface sediment PCB concentrations to below 3-mg/kg OC (minimum cleanup target). The 3-mg/kg OC target was selected as the result of a numerical modeling exercise that suggested this target sediment concentration could be reached within 10 years of remedy implementation if the area-weighted surface sediment concentration of PCBs declined to 4.1 mg/kg OC after remedy implementation.

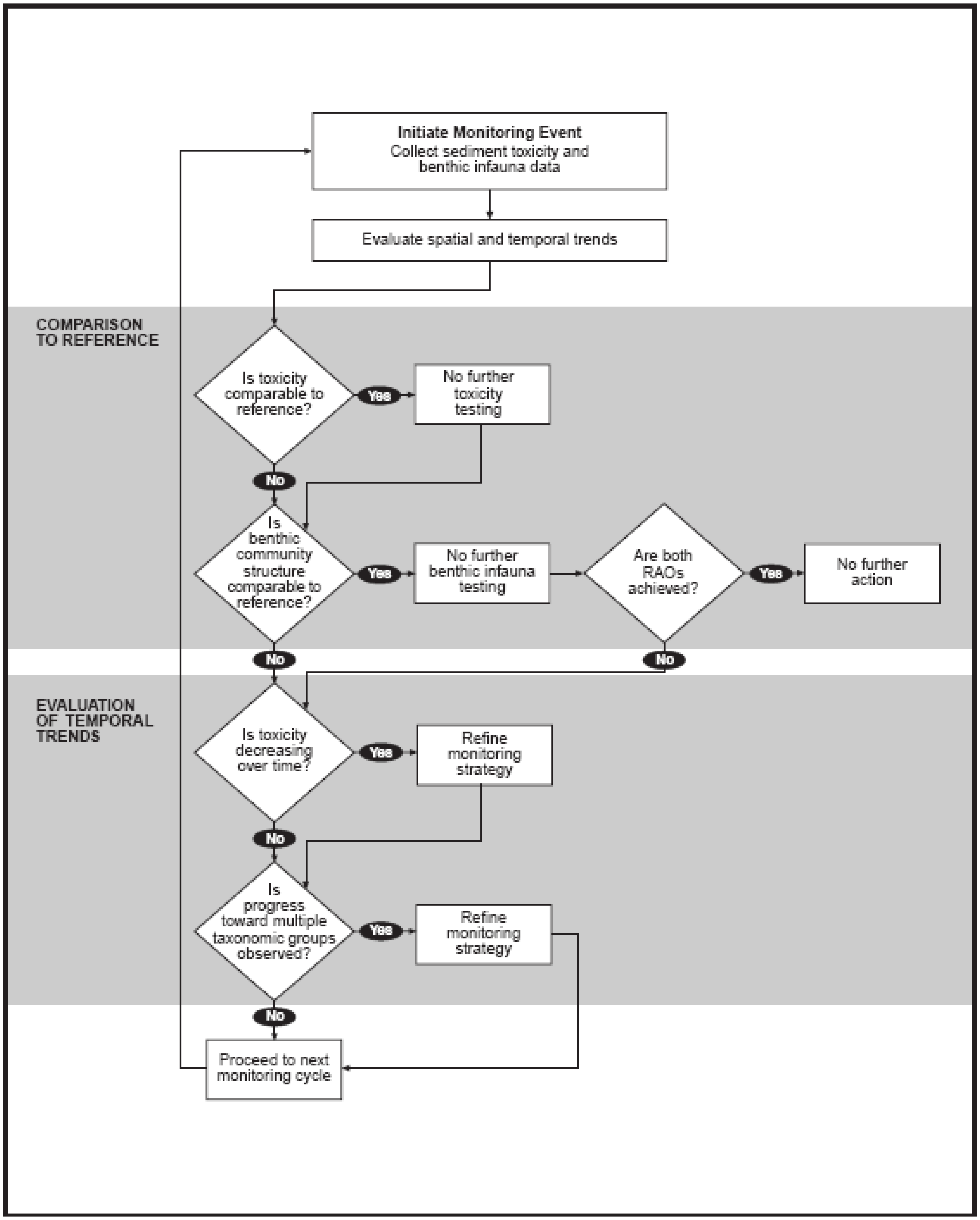

Figure 4. Overview of monitoring data evaluation process.

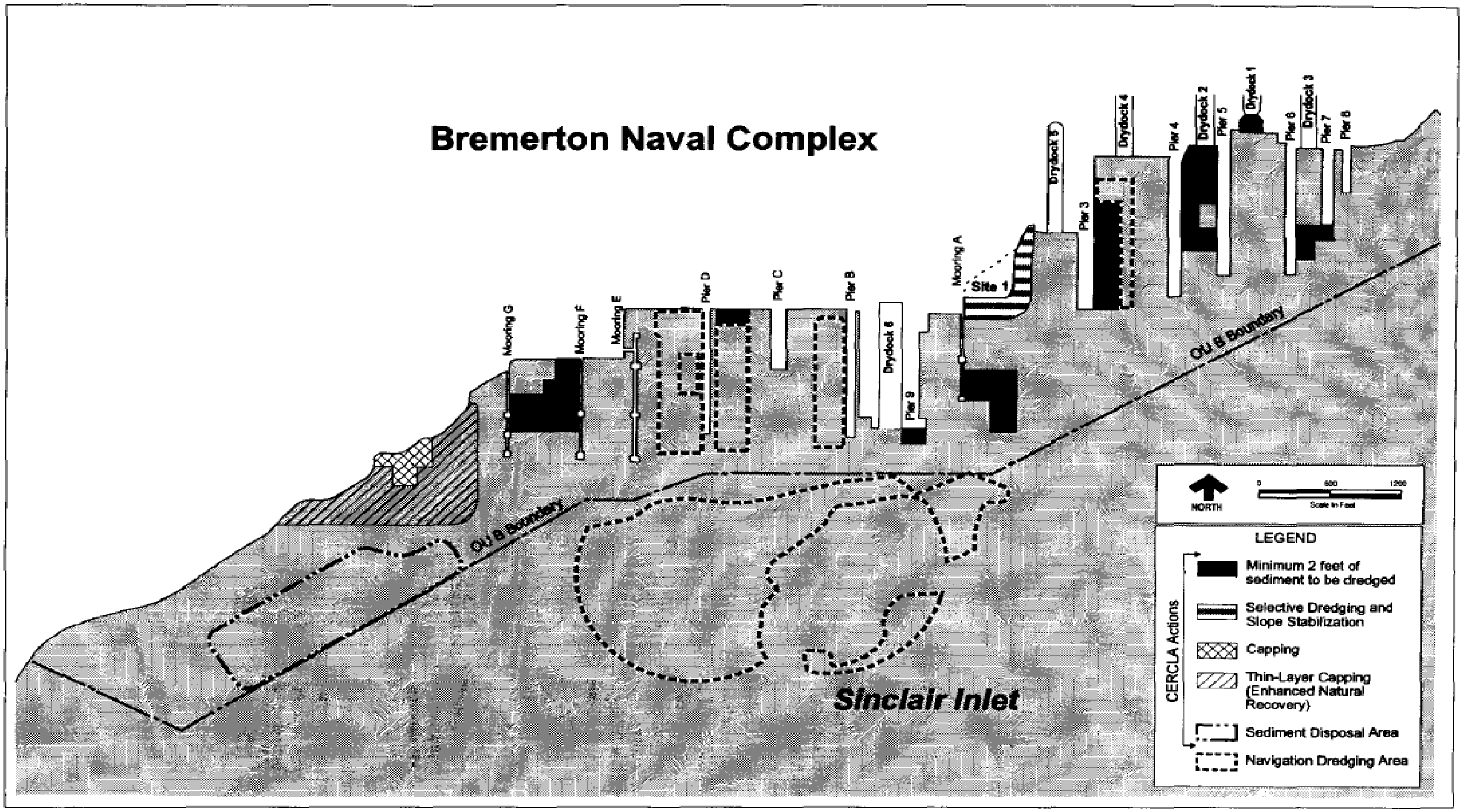

Figure 5. Planned OU B sediment cleanup for Bremerton Naval Complex.

The long-term remedial goal for OU B was defined as achieving a sur face sediment PCB concentration of 1.2 mg/kg OC, consistent with reference area concentrations in Sinclair Inlet. As areas of elevated PCB concentration were often also characterized by elevated concentrations of mercury, reducing the concentration of PCBs in surface sediment provided the ancillary benefit of simultaneously reducing the surface sediment concentrations of mercury.

Near-shore sediment in Sinclair Inlet is dominated by silt and clay. Analysis of tidal currents suggests that current speeds are below 10 cm/s more than 90% of the time, regardless of specific location, season, or water depth (USEPA, 2000a). This low current velocity and low associated shear stress does not appear to resuspend bottom sediment in Sinclair Inlet and suggest that PCB and mercury contaminated sediment are not likely to be significantly flushed from the inlet by natural processes. Sedimentation rates in the area of OU B have been estimated at between 0.5 and 0.75 cm/yr (USEPA, 2000a).

2.3.2 Remedial Design and Implementation

Remedy components for OU B (USEPA, 2000a) include the following:

- Dredging and disposal in a CDF of sediment with PCB concentrations greater than 12 mg/kg OC.
- Shoreline stabilization to reduce erosion of contaminated sediment.
- EMNR, including thin layer capping (thickness of 15 to 20 cm), for 6.5 hectares (16 acres) of subtidal sediment with PCB concentrations greater than 6 mg/kg OC.

The PCB concentration breakpoint for dredging (12 mg/kg OC) was selected for cost-effectiveness (USEPA, 2000a), while the concentration breakpoint for EMNR (6 mg/kg OC) was selected as an average concentration between the dredging-related breakpoint and the 90th percentile sediment PCB concentration for reference area sediments (i.e., 1.2 mg/kg OC) (USEPA, 2000a).

The area designated for EMNR in Sinclair Inlet is outside of several zones identified by high erosion potential. These zones include the inlet navigational channel, the Port Washington Narrows, and the intertidal area of the area of concern (which was ultimately capped with gravel rather than sand). For those areas in Sinclair Inlet deemed appropriate for EMNR, lines of evidence supporting placement of a thin layer cap include (1) evidence that the system is currently gaining sediment through natural deposition, and (2) the comparatively low concentration of PCBs (less than 1 mg/kg OC) in sediments currently entering the system. It is expected that, combined with the dredging and disposal actions, EMNR will reduce the OU B area-weighted average PCB concentration to below 3 mg/kg OC within 10 years and to 1.2 mg/kg OC within approximately 30 years (USEPA, 2000a).

Placement of the thin layer cap in Sinclair Inlet was accomplished by positioning a split-hull hopper barge over the target area and releasing a long, low-relief ridge of medium sand as the barge was towed across the site. Subsequent passes with the barge were positioned to place new ridges of material adjacent to existing ridges. Cap placement with clean sand was calculated to require an approximately 50% volume contingency for overlap and consolidation of material. The total estimated placement volume for the capping area in OU B was 20,000 CY. The estimated materials cost for the sand cap was approximately $4/CY (USEPA, 2000a). Successful cap placement was verified via multi-beam bathymetric surveys and sub-bottom profiling. These techniques were selected to allow differentiation of the cap material from underlying native sediment and to confirm the placement and thickness of the sediment cap.

2.3.3 Monitoring

The monitoring plan for OU B included a baseline evaluation in 2003, and continued monitoring in 2005, 2007, 2012, and 2017. Although no monitoring costs are available, the ROD estimates monitoring costs of $165,000 for the initial post-placement survey, and $30,000 for each subsequent sampling interval (USEPA, 2000a).

System recovery is being monitored with the following:

- Bathymetric profiling to monitor for cap erosion and document active sedimentation.
- Sediment sampling (including total PCBs, mercury, TOC, grain size, and moisture content) to confirm that surface PCB concentrations are consistent with expectations after thin layer cap placement.
- Benthic community analysis (photo-documentation) to confirm recolonization and ecological recovery following cap placement.
- Tissue sampling of English sole to evaluate the success of remediation in lowering tissue concentrations of chemicals of concern for a species likely consumed by humans. For PCBs in fish tissue, the remediation goal of 0.023 mg/kg wet weight represents the 90th percentile concentration of PCBs in English sole tissue sampled from a reference location defined as a non-urban embayment (USEPA, 2000a).

Monitoring conducted in 2003 yielded the following observations (NAVFAC, 2006a):

- As the clean sediment chosen for the thin layer cap was similar in physical properties to the underlying native sediment, neither bathymetric surveys nor sub-bottom profiling could clearly differentiate the cap material from the underlying sediment. The resultant imagery did not allow assessment of cap settling or displacement within a resolution of 30 cm, or the extent to which thin layer cap material was mixing with underlying sediment. Thus, confirmation of the placement of the thin layer cap (between 15 and 20 cm) could not be accurately verified.
- Benthic recolonization was actively occurring within the capping zone.
- For the surface sediment samples collected from within the thin layer capping zone, PCB concentrations ranged from 3.7 to 5.2 mg/kg OC, and mercury concentrations ranged from 0.32 to 0.79 mg/kg.
- Within the EMNR zone, mercury concentrations in surface sediments appear to have decreased more significantly after cap placement than PCB concentrations, suggesting that source control of PCB inputs may not have been fully achieved near the EMNR zone.
- English sole tissue concentrations were unchanged from pre-remediation sampling.

Monitoring conducted in 2005 yielded the following observations (NAVFAC, 2006b):

- Within the thin layer cap area, evidence of bathymetric change was minimal, and the extent of deposition of fresh material onto the cap or erosion of the cap material itself could not be well resolved.
- For the surface sediment samples collected from within the thin layer capping zone, PCB concentrations ranged from 3.9 to 5.0 mg/kg OC and were essentially unchanged from concentrations measured in 2003.
- Mercury concentrations ranged from 0.31 to 0.84 mg/kg and were also essentially unchanged from 2003 monitoring data.

The 2005 monitoring report concluded that it was unlikely that the RAOs were going to be met within the 10-year window predicted by pre-implementation monitoring (NAVFAC, 2006b). The

2005 monitoring report also concluded that the 2007 monitoring would likely follow a revised sampling and analysis plan (NAVFAC, 2006b). Revisions to the previous monitoring plans were suggested to reduce the variability in replicate sample data and to improve the overall representativeness of chosen sampling locations.

While the 2007 monitoring report has not yet been published, 2007 data were discussed with the NAVFAC Project Manager[5] Results of the 2007 monitoring interval include the following:

- For the surface sediment samples collected from within the thin layer capping zone, PCB concentrations ranged from 2.2 to 4.0 mg/kg OC and appeared to have declined from concentrations measured in 2005.
- For all monitoring stations within OU B, while the arithmetic mean carbon-normalized sediment PCB concentration was essentially unchanged in 2007 relative to 2003 (9.5 mg/kg OC in 2003 versus 9.9 mg/kg OC in 2007), the geometric mean PCB concentration declined over the same interval from 6.7 to 4.6 mg/kg OC. Neither the geometric nor the arithmetic mean sediment OC content varied over this interval.
- For the surface sediment samples collected from within the thin layer capping zone, mercury concentrations ranged from 0.3 to 1.3 mg/kg and were essentially unchanged from 2005 data.
- For all monitoring stations within OU B, the arithmetic mean sediment mercury concentration declined from 0.86 to 0.77 mg/kg and the geometric mean sediment mercury concentration declined from 1.0 to 0.86 mg/kg over the 2003 to 2007 monitoring interval.
- Arithmetic mean English sole PCB tissue concentrations declined from 0.085 to 0.033 mg/kg between 2003 and 2007. Maximum English sole PCB tissue concentrations declined from 0.15 to 0.046 mg/kg over this same interval. All PCB tissue concentrations are defined on a wet weight basis.

2.3.4 Lessons Learned

Overall conclusions for the Bremerton Naval Complex site are that placement of long, low-relief ridges of sand within the cap area footprint is an effective way to distribute cap material, and though surface sediment mercury concentrations have appeared consistently lower in cap material relative to native sediment over time, incomplete source control near the thin layer cap resulted in little net change in surface sediment PCB concentrations over the first two intervals of post-remedy monitoring. Preliminary 2007 sampling results, however, demonstrate that surface sediment PCB concentrations have declined, though it is difficult to predict the extent to which the reduction in sediment PCB concentrations between 2005 and 2007 demonstrates an increased likelihood for achieving the 10-year remedial targets. The observations of initially low net change in surface sediment PCB concentrations over the first several years of remedy implementation demonstrate the need for source control near a capped area and highlight general difficulties in reaching remedial success targets that may have been based on incomplete or inaccurate models of chemical transport dynamics in the area of concern.

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[5]Dwight Leisle, NAVFAC project manager; conversation with Karen Merritt on 3 June 2008.

3. OTHER SITES

While the case studies discussed in Section 2 represent sediment remediation projects in which full-scale field implementation of thin layer capping has occurred and monitoring data are available, other examples exist that (1) demonstrate a natural (landslide) simulated placement of a thin layer cap, (2) entail placement of a thin layer cap as a component of a pilot or demonstration project, or (3) are characterized by limited assessment of progress toward meeting site-specific RAOs and/or the thin layer capped area is not well segregated from adjacent areas receiving thicker isolation caps.

3.1 SAGUENAY FJORD (QUEBEC, CANADA)

At the Saguenay Fjord in Quebec, Canada, a landslide simulated the effect of a sediment cap placement. Between 1947 and 1976, a chlor-alkali facility that operated in Arvida on the Saguenay River discharged mercury to the Saguenay Fjord. After closure of the facility, mercury concentrations in surface sediment of Saguenay Fjord decreased from greater than 10 mg/kg in the late 1970s to less than 1 mg/kg in the mid-1990s. In July 1996, an extended rain event led to the failure of multiple dikes along the Saguenay River. The resultant flooding generated a mass flow event that deposited between 20 and 50 cm of postglacial marine clay in the fjord. As the clay deposit was characterized by significantly lower concentrations of mercury and other trace metals than the underlying native sediment, its rapid emplacement is generally analogous to the placement of an engineered sediment cap.

Following the hypothesis that the flood layer would isolate the underlying sediment from the water column and benthic and pelagic biota, researchers at McGill University (Dr. Alfonso Mucci) and University of Quebec at Rimuski (Dr. Emilien Pelletier) analyzed surface and underlying sediment in Saguenay Fjord yearly between 1996 and 2002. Research objectives were to (1) monitor the extent to which the flood layer served as a naturally emplaced sediment cap, (2) monitor the extent to which the presence of the flood layer affected the speciation of mercury (inorganic versus methylmercury) and its distribution between the particulate and pore water phases, and (3) assess the extent to which the flood layer may influence the methylation rate of inorganic mercury in the underlying native sediment. Sediment total mercury analyses were conducted on depth-sectioned cores collected annually between 1996 and 2002. Analysis of pore water total mercury and all methylmercury analyses (sediment and pore water) were conducted on cores collected from 2000–2002.

Several important observations resulted from these analyses (Pelletier et al., 2003; Bernier, 2005), as follows:

- Emplacement of the flood layer led to a significant decrease in the total mercury and methylmercury concentration in surface sediments relative to the concentration in underlying sediment.
- There was little evidence of post-depositional mixing of the flood deposit with the underlying sediment over time.
- After emplacement of the flood layer, there was an increase in the pore water concentration of inorganic mercury in sediment underlying the flood material that likely resulted from the dissolution of the iron oxides phases with which that mercury had originally been associated.
- Transport of dissolved inorganic mercury from underlying sediment into the flood deposit occurred as a result of the pore water concentration gradient that developed between the underlying native sediment and the flood deposit.

- Although methylation of inorganic mercury was occurring within the flood deposit, diffusion of methylmercury from the sediment into overlying water was hindered by adsorption of methylmercury to particulate phases (such as organic matter) at the new sediment–water interface or active demethylation of methlymercury in the surficial oxic layer.
- Methylation activity appeared dominant at the oxic-suboxic transition in the sediment with the depth of this transition zone fluctuating as a function of biological processes rather than being directly and clearly linked to sediment composition (i.e., the transition zone migrated upward into the flood deposit from its original location within the underlying native sediment).

3.2 THIN LAYER CAP PILOT STUDIES

Other sites of interest include locations in which thin layer caps have been implemented as a demonstration project or on a pilot scale. These sites include the Palos Verdes Shelf site off Los Angeles, California; the Anacostia River in Washington, DC; and the Grasse River in Massena, New York. For these sites, the mechanics of successful cap placement have not differed significantly than at sites in which thin layer caps have been implemented as a component of a mature field remedy. Differences between these sites and those discussed in Section 2 of this review result instead from the fact that with pilot or demonstration-scale projects such as these, placement of a thin layer cap may not be consistently guided by the identification or development of site-specific RAOs. That is, as monitoring for demonstration projects may be focused more specifically on understanding how the cap (or cap amendment) works rather than assessing the extent to which system recovery is occurring consistently with RAOs, success may be defined differently for demonstration- or pilot-scale projects than for the projects designed and implemented as a mature field remedy. These sites therefore present opportunities for examining topics such as high-resolution implementation monitoring, including use of innovative equipment including sediment profile cameras (SPCs), and the effect of remedy implementation on short-term benthic community structure.

3.2.1 Palos Verdes Shelf (Los Angeles, California)

The Palos Verdes Shelf site is located off the coast of Los Angeles, California, and is characterized by sediment with elevated concentrations of PCBs and dichlorodiphenyltrichloroethane (DDT). Contaminated sediments are located on the continental shelf (1- to 6-km wide) and continental slope, at water depths reaching 100 m. Input of chemicals to this site likely originated from the Los Angeles Country Sanitation District ocean outfall. The outfall discharges approximately 3 km offshore at 60 m of water depth and historically included industrial and commercial discharges to the Sanitation District sewer system.

At this location, the primary functions of the sand cap are to physically stabilize sediment, limit the potential for biotic transfer of chemicals from sediment into benthic organisms, and reduce the flux of chemicals from sediment pore water into the water column (Palermo et al., 1999). Capping approaches identified to achieve these targets include (1) placement of a thin layer cap to reduce the exposure of benthic invertebrates to contaminated sediment, and (2) placement of an isolation cap to effectively segregate contaminated sediment from the food chain.

To this end, a pilot study involving cap material dredging and transport, cap implementation, and placement monitoring was conducted between May 2000 and March 2001. Approximately 135,000 CY of capping material was dredged from the Long Beach Harbor entrance channel or sand borrow areas outside of the harbor breakwaters and placed in four 300-m × 600-m pilot cells. Placement of cap material occurred principally by two methods: (1) conventional placement in which the hopper doors on a dredge were fully opened at predetermined locations for complete and rapid discharge of sand, and (2) spreading placement in which the hopper doors were partially opened and sand was released as the dredge traversed a linear track line. The rate at which sand was released from the hopper during spreading placement was adjusted by flushing sand from the hopper with variously positioned water jets.

Field monitoring of cap placement was conducted through sediment profile imagery, bathymetric surveys, sediment coring, water column monitoring (chemistry and turbidity), and material placement monitoring. Principal objectives for implementation monitoring included assessment of (1) the likelihood of uniform cap thickness at either 15 or 45 cm, (2) the extent to which cap placement disturbed in-place sediment, (3) the extent to which cap surface chemical concentrations reflected placement, (4) cap stability during placement, and (5) consistency between cap placement and model predictions.

Results from the implementation survey supported the conclusion that placement of a sand cap of 15- or 45-cm thickness effectively isolates chemically-impacted sediment on the Palos Verdes Shelf (Fredette et al., 2002). Specific observations included the following:

- Placement of a cap of uniform and predetermined thickness (15 or 45 cm) was possible using conventional point placement or spreading/broadcast methods for more uniform dispersal of cap material.
- Physical disturbance or mixing of the underlying sediment with the cap material during cap placement was limited to the top 5 cm of the sediment, and was diminished when cap materials were spread through broadcast methods rather than conventional point placement.
- Elevated suspended solids and chemical concentrations in the water column resulting from discharge of cap material from the hopper returned rapidly to background concentrations with little evidence of lateral migration of resuspended materials.
- Chemical concentrations in the surface sediment of cores collected after cap placement indicated that recontamination of the cap surface was minimal after placement (as would result if placement resulted in the resuspension of significant contaminated sediment).
- There was no evidence of cap instability or underlying sediment deformation resulting from cap placement.

As noted, confirmation of cap thickness was aided by using sediment profile imagery. The SPC is a monitoring tool that allows for high-resolution inspection of near-surface sediment (Figure 6). The camera is mounted within a frame that, in the case of deep water sites such as the Palos Verdes Shelf, is lowered from the deck of a support vessel. In shallow water locations, the SPC may be lowered to the sediment surface by hand. The SPC has two principal aspects: a camera enclosed in pressure housing and a prism with a beveled edge to facilitate penetration into the sediment.

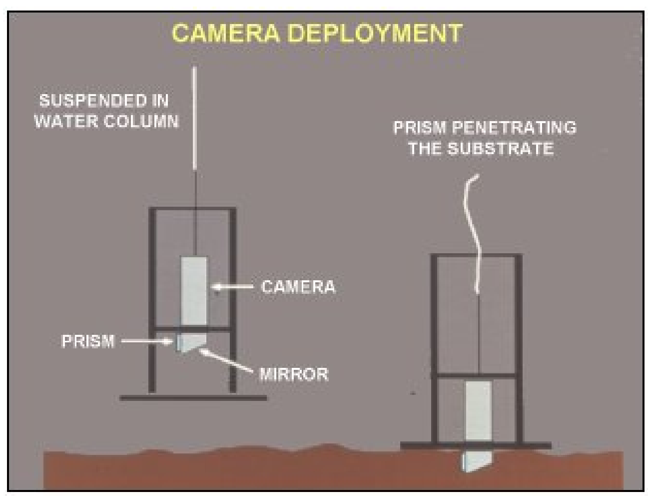

Figure 6. Deployment of SPC for surface sediment observation (source: www.csc.noaa.gov).

The camera housing contains a clear (Plexiglas®) faceplate, a light source (strobe), and a mirror so that images of the sediment are illuminated and reflected to the camera. The prism is pushed into the sediment through the combined action of lead weights and a hydraulic damping piston, so that sediment disturbance during deployment is minimized. Typical sediment penetration depths reach 20 cm, and are influenced by surface sediment characteristics such as the presence and density of rooted vegetation and grain size. Because the camera may penetrate to sufficient sediment depth to capture the vertical extent of a thin layer cap, this technique may be employed to monitor cap thickness, benthic biological response to cap placement, and the extent to which an emplaced cap has mixed with underlying sediment during or after placement. SPC images for the Palos Verdes Shelf site are presented in Figure 7. Image A in the figure presents a 4-cm thick surface layer of gray sand overlying background sediment. The gray sand is cap material dredged from Queen’s Gate channel. Image B presents deposition of a brown-toned, fine-grained sediment over the sand cap layer. Photographs in Figure 7 are from “Monitoring Results from the Field Pilot Study of In Situ Capping of Palos Verdes Shelf Contaminated Sediments: Appendix J” by Fredette et al. (2002), which is available at http://el.erdc.usace.army.mil/publications.

For the Palos Verdes Shelf site, monitoring objectives at this site have focused specifically on questions of implementation and do not address long-term goals or RAOs. Thus, limited data have been collected for the Palos Verdes Shelf site to quantify the rate of system recovery or to verify the extent to which the observed rate is consistent with initial assumptions or model inputs, confirm changes in abundance or community development for benthic invertebrates, or confirm that water column, surface sediment, and/or tissue chemical concentrations are declining over time.

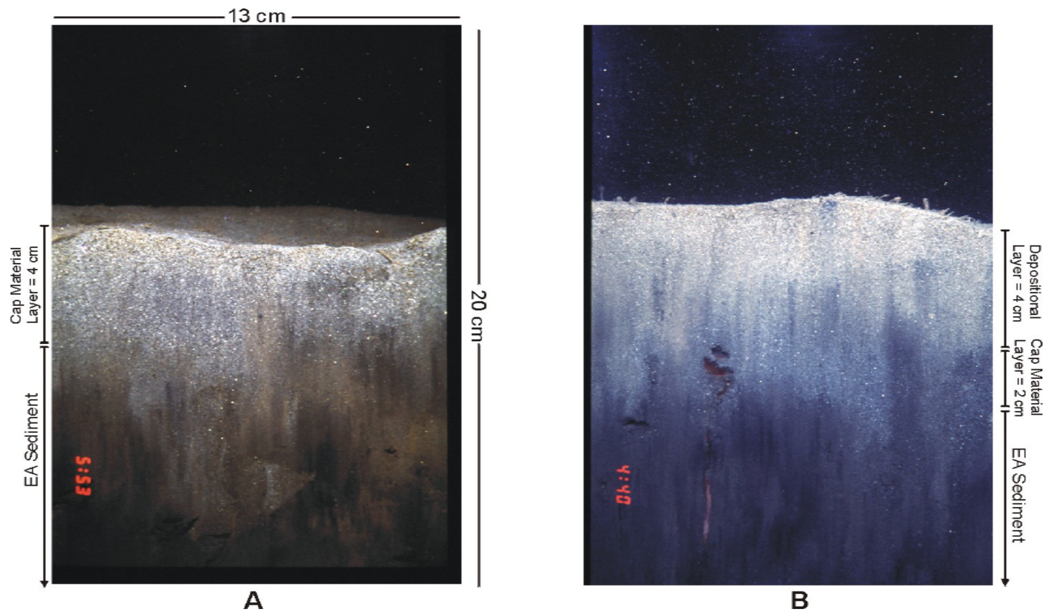

Figure 7. SPC images from Station O17 of the Palos Verdes Shelf site. (A) September 2000. (B) Supplemental survey, February 2001.

3.2.2 Anacostia River (Maryland and District of Columbia)

The Anacostia River is a freshwater tidal system draining an urban watershed in Maryland and the District of Columbia. As a function of its location and general industrial usage, sediment in the Anacostia River contains elevated concentrations of a range of organic (i.e., PAHs, PCBs, and pesticides) and inorganic (metals including lead and zinc) chemicals. In the spring of 2004, a series of pilot-scale engineered caps were placed along the near-shore zone to evaluate the effectiveness of various reactive capping amendments. Caps included a 15-cm sand-only cap, and layered caps that included 15-cm AquaBlok™[6] covered by 15-cm sand, 15-cm coke breeze (byproduct of coke manufacturing) and 15 cm of sand, and 15-cm apatite (a calcium phosphate mineral) and 15-cm sand. The total area under study is approximately 0.3 hectacres (0.75 acres) and was divided into four 24-m x 30-m pilot cells. A control area was also established in which no cap was placed.

In the Anacostia River, post-placement monitoring has been designed to evaluate the integrity, performance, and biological impact of the reactive caps, with biological impact defined by the rate and extent of biological recruitment of the cap surface. Monitoring occurred at 1 month, 6 months, 18 months, and 30 months after placement and has included bathymetric surveys to document areas of net accretion and/or erosion on the cap surface, chemical monitoring in surface sediment and within the reactive cap layers, and biological monitoring to document the extent and rate of benthic recolonization after cap placement.

In terms of cap thickness and stability, monitoring has verified the continued physical stability and integrity of the reactive material caps and has confirmed that cap materials have not been scoured or eroded by propeller wash or storm waves. The physical stability of the amended caps is confirmed by sediment coring, with core profiles documenting net sediment accretion on cap surfaces over the 30-month monitoring interval. Changes in cap thickness over time appear greater, however, when assessed by bathymetric survey than by sediment coring, with variation over time ranging between 15 cm (as determined by bathymetric survey) and 6 cm (as determined by sediment coring) (Horne Engineering Services, 2007a). These differences in observed cap thickness between monitoring strategies likely result from measurement uncertainties, including limitations on the resolution of bathymetric survey instrumentation, and the accuracy of spatial identification of sampling locations employed in time-series core collection. Moreover, as consolidation of underlying sediment is likely to occur after placement of a sand cap, not all documented variation in bathymetry is attributable to changes in cap thickness.

Chemical concentration profiles within the sediment caps appear to indicate that chemicals of concern are not migrating vertically into the cap layers. Vertical migration may result from the physical mixing of sediment by organisms or abiotic processes, or through advective or diffusive pore water transport upward into the cap. As surface sediment appears to exhibit higher chemical concentrations than are measured within the cap layer itself, resuspension and lateral transport of material onto the cap surface are likely responsible for the observed sediment chemical profiles.

For benthic community structure, nine taxonomic groups were identified in sediment samples collected from all capped and control areas. The dominant taxonomic group was oligochaete worms, with taxa numbers decreasing in the following order: control area (10), coke cap (8), apatite cap (7), AquaBlok™ cap (6), and sand-only cap (6). Other taxa consistently present included chironomid midges, nematodes, tubificid worms, and gastropods.

Although recolonization includes a significant percentage of deposit feeding organisms, their activity does not appear to have negatively affected cap integrity. In terms of benthic recolonization, organism densities appear to have increased since cap placement, but remain lower than observed in the initial 2003 pre-cap survey (Horne Engineering Services, 2007b). Mean organism densities[7] across all experimental plots ranged from 29,421 to 44,649 per m^2 in 2003, 320 to 1,748 per m^2 in

[6] AquaBlok® is a proprietary clay polymer that is designed to swell upon hydration, forming a continuous and impermeable isolation barrier between underlying sediment and the water column. Application of AquaBlok® is designed to isolate sediment chemicals from the water column.

[7] Organism densities are defined per m^2 as presented in Horne (2007b). Density per m^2 may be converted to density per ft^2 by multiplying by 10.8.

2005, and 741 to 3,230 per m^2 in 2006 (Horne Engineering Services, 2007b). Reductions in faunal density relative to pre-capping densities may be partially explained by the use of sand as the uppermost layer on all caps, as sand is not an ideal habitat for the deposit feeding organisms that dominate the benthic taxa. It may be assumed that faunal density in the capped areas will continue to improve over time as organic-rich materials continue to be deposited at the sediment surface, thereby improveing habitat quality. These results highlight a likely time frame for benthic recolonization, and demonstrate how the pace and direction of biological recovery may be influenced by the characteristics (i.e., grain size and organic matter content) of the cap material. Additionally, it suggests that clean native sediment may be a better substrate for cap material in terms of benthic community re-establishment.

3.2.3 Grasse River (Massena, New York)[8]

The Grasse River, located in upstate New York, is principally impacted by PCBs used historically in transformers and hydraulic systems. In the summer of 2001, a series of pilot-scale caps were placed along the lower Grasse River to evaluate installation strategies for amended caps and monitor the effect of cap placement on various environmental parameters, either during or after cap placement. Pilot cap thickness was targeted at between 22 and 60 cm, with 30 cm defined as optimal thickness. Metrics for monitoring and evaluation included the effectiveness of cap coverage, cap material stability, surface sediment PCB concentrations after capping, water quality during placement, and the recovery/recolonization rate of the cap surface by benthic organisms. Post-placement monitoring occurred late in 2001, and again in 2002 and 2003.

Pilot caps were placed along a 230-m × 120-m reach of the river defined by steep side slopes, a relatively flat bathymetry, low erosion potential, minimal groundwater seepage, and the minimal presence of coarse-grained sediment (cobbles) or debris on the river bottom. Native river sediment was defined as primarily silts and sands with moderate organic matter content. The test area was divided into placement cells, with the pilot project divided into two operational stages. Stage I was designed to screen capping materials and application methods, and Stage II was designed as a full-scale field application of the optimum material/application combination selected after Stage I testing. Capping materials screened in Stage I included a 1:1 sand/topsoil mixture, granulated bentonite clay, and AquaBlok™. Placement strategies for capping material included surface and subsurface (i.e., underwater) placement of material by mechanical clamshell, subsurface placement by Tremie tube, and surface placement by pneumatic broadcasting (limited to the bentonite clay). Measured thicknesses after placement ranged from 15 to 62 cm.

For Stage I testing, results suggested that placement of the sand/topsoil cap via a clamshell bucket deployed at the water surface or underwater resulted in optimal placement technique. Optimal placement was defined by the ability to distribute cap material uniformly and consistently where required, with no significant mixing of the cap material with underlying sediment and minimal sediment resuspension. In terms of application rate, the sand/topsoil mix was placed at a rate between 43 and 50 CY/hr for Stage I testing, and between 58 and 66 CY/hr for Stage II testing. The placement rate was not significantly affected by the placement method (release from the clamshell bucket at the surface of the water, release underwater, or whether material was placed in a single or multiple passes). Although application by clamshell bucket was defined as optimal in terms of uniform and consistent distribution of cap material, clamshell bucket and Tremie placement consistently met targeted cap thicknesses.

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[8] All data available at http://www.thegrasseriver.com/CapProjDesc.htm unless otherwise noted.

In terms of water column concentrations of PCBs and total suspended solids, water quality impacts associated with pilot cap placement were negligible. Within and adjacent to the test cells, average PCB concentration during cap placement were within the range of concentrations (less than 240 ng/L) historically measured at a nearby monitoring station, and corrective action trigger levels were never reached. For total suspended solids (TSS), water column concentrations were somewhat elevated at the point of capping during material placement (although remained less than 20 mg/L), but concentrations returned to baseline concentrations (less than 10 mg/L) a short distance beyond the silt curtain. Although TSS concentrations' downgradient of the pilot test site were slightly elevated (increasing by ~ 1 mg/L) relative to concentrations at upgradient monitoring stations, modest increases in TSS were not correlated with increased PCB concentration in suspended solids. TSS and PCB data were not correlated in monitoring station data, which suggests that resuspension of bed sediment was not responsible for the increased TSS concentration observed at downgradient monitoring stations. A post-placement water quality survey conducted in Winter 2001 confirmed that the cap placement had no residual effects.

For sampling conducted in Winter 2001 (i.e., approximately 3 months after cap placement), 17 benthic species were identified in the capped area (GET I.D.s), including three species not present in the pre-capping baseline survey. For sampling conducted in 2002, results for the four test cells were compared with results from an adjacent (uncapped) reference cell (McShea et al., 2003 in EPRI, 2004; Bailey and Palermo, 2005). Results for the three Stage II test cells, as well as the Stage I test cell receiving the 1:1 sand/topsoil mixture with or without AquaBlok™ were as follows:

- The number of organisms per cell ranged from 26 to 104 (with a mean of 69), as compared to 78 organisms in the adjacent (uncapped) reference cell.
- The number of taxa per cell ranged from 8 to 13 (with a mean of 11.2), relative to 12 in the reference cell.
- Total biomass per cell ranged from 3673 to 5893 mg/m^2 (with a mean of 4774 mg/m^2), relative to 3119 mg/m^2 in the reference cell.
- Diversity index values ranged from 2.3 to 3.0 within test cells relative to 2.9 within the reference cell (diversity index values range from 0 to 4, with a higher number indicating greater diversity).
- Tolerance index values ranged from 6.1 to 7.1 within test cells, relative to 8.8 in the reference cell (tolerance index values range from 0 to 10, with a higher index value indicating a higher percentage of pollution-tolerant organisms).

Relative to conditions defined for the reference cell at this location, these results highlight a relatively rapid benthic recolonization rate after cap placement and suggest that the addition of topsoil to a sand cap may improve the characteristics of this material for potential benthic habitat quality.

Data collection in 2002 also included sediment coring to assess the extent to which cap placement led to decreased surface sediment PCB concentrations over time. Results indicated that a layer of low-density solids settled on the cap surface. While PCB concentrations in that surface layer (mean concentration of 0.2 mg/kg) were elevated relative to concentrations in the cap material, PCB concentrations in surface sediment remained significantly lower than concentrations in underlying (pre-cap) sediment (mean concentration of 6.8 mg/kg). PCB concentrations within the cap material were generally below analytical detection limits (typically 0.05 mg/kg, although not defined).

Results from 2003 sediment sampling documented significant cap erosion, likely resulting from the formation of an ice jam upriver from the pilot test location. Because ice jams can constrict the channel cross-sectional area and may clear rapidly from the river, their presence may lead to increased flow velocities, scour, and/or flow surges, all with potentially negative impacts on bed stability.

3.3 OTHER RELEVANT SITES

A third category of sites for discussion include those for which limited placement and/or monitoring data are available for assessing the extent to which (1) thin layer capping has resulted in progress towards meeting site-specific RAOs, or (2) the thin layer capped area can be segregated from adjacent areas receiving thicker isolation caps. Examples of thin layer cap sites briefly considered in this section include the Duwamish Waterway in Seattle, Washington; the Georgia Pacific Log Pond in Bellingham Bay, Washington; the U.S. Navy Manchester Annex, Manchester, Washington; Pacific Sound Resources in Seattle, Washington; and the Pier 64 area in Seattle, Washington. Because the placement of thick (greater than 1 m) isolation caps is inconsistent with the objectives of EMNR, sites defined by isolation capping are not considered here.

3.3.1 Duwamish Waterway (Seattle, Washington)

The Duwamish Waterway empties into Elliott Bay in Seattle, Washington, and defines the estuary of the Duwamish River. Chemicals of concern in the Duwamish Waterway include PAHs, PCBs, phthalates, and mercury. Between November 2003 and March 2004, the Elliott Bay/Duwamish Restoration Program (EBDRP) implemented a 2.8-hectare (7-acre) sediment remedy near the Duwamish Combined Sewer Overflow (CSO) and the City of Seattle Diagonal Way Storm Drain outfall. The remedy included removal of between 1 and 1.5 m of contaminated sediment from two areas (Areas A and B), followed by isolation capping in these areas to restore the pre-dredging bathymetry. Area A is approximately 2 hectares (5 acres) in extent and is located immediately offshore of the CSO and storm drain outfalls. Area B is approximately 0.8 hectares (2 acres) in extent and is located offshore of a sewage treatment plant that ceased operation in 1969.

The overall site monitoring plan defined eight principal objectives to ensure that (1) water quality standards were met during remedy implementation, (2) remedy implementation was performed in accordance with specifications, (3) sediment containing PCB concentrations in exceedance of 50 mg/kg would be disposed of in a Toxic Substances Control Act-approved landfill, (4) capping materials were chemically screened prior to placement, (5) dredging of contaminated sediment did not lead to increases in sediment chemical concentrations outside of the remedial areas, (6) it was unlikely that the sediment outside of the remedial areas would recontaminate the isolation cap, (7) potential ongoing point source discharges to the Waterway are identified and controlled to the extent possible, and (8) the cap remains stable over time. The site monitoring schedule included baseline sampling (within 3 months of cap placement), yearly monitoring until Year 5, and long-term monitoring (after Year 5) at a frequency defined by the recontamination rate observed during the first 5 years (KCDNRP, 2003).

After remedy implementation in Area B, the concentration of PCBs in sediment surrounding Area B increased as a consequence of dredge operations by an approximate factor of 4, from 0.5 to 2.0 mg/kg (EcoChem, 2005). As a result, a 15-cm thin layer cap was placed over 1.6 hectares (4 acres) of sediment surrounding Area B. The placement of the thin layer cap was accomplished using a 16 CY skip box on a hydraulic excavator. The 1.6 hectare (4 acre) area was divided into 9-m x 15-m cells, with each cell receiving approximately 42 CY of medium sand.

Monitoring conducted concurrent with thin layer cap placement confirmed that a minimum cap thickness of 15 cm was readily achieved across the 1.6-hectare (4-acre) area via the chosen placement method. Post-placement surveys with a SPC confirmed the presence of sand at every sampling location, with sand thickness consistently greater than the depth of camera penetration (typically between 5 and 15 cm) (Anchor Environmental, 2007). Post-placement bathymetric monitoring has also been conducted by visually inspecting marked, flexible stakes that were emplaced prior to remedy implementation.

Long-term monitoring goals for the thin layer capping zone focus on decreasing surface sediment chemical concentrations to below sediment management standards. For the post-placement baseline sampling, concentrations of PCBs in surface sediment ranged from below detection to 32 µg/kg, concentrations of bis-2-ethylhexyl phthalate ranged from 9 to 70 µg/kg, and concentrations of mercury were all below detection (Anchor Environmental, 2007). These low chemical concentrations suggest that significant remobilization of underlying sediment did not occur during thin layer cap placement. Although monitoring data were slated to be collected annually beginning in 2005, results from recent monitoring surveys are still unavailable.

3.3.2 Georgia Pacific Log Pond (Bellingham Bay, Washington)

The Whatcom Waterway (WW) Area is composed of intertidal and subtidal habitat in Puget Sound near Bellingham, Washington. The WW Area includes the Whatcom and I&J Street Waterways, the mouth of Whatcom Creek, the Georgia-Pacific Log Pond, and subtidal locations near the Georgia-Pacific biotreatment lagoon. The WW Area is contaminated with mercury originating from a chlor-alkali facility operated by Georgia-Pacific, phenolic compounds originating from pulp mill discharges to the waterway, and other compounds, including metals (copper, nickel, and zinc), growth inhibitors (tributyltin), and PAHs. Significant mercury discharge has occurred principally in the Log Pond area, and sediment mercury concentrations in this area commonly exceeded the Washington State Sediment Quality Standards.

As an Interim Action, a sediment cap was placed over the Log Pond area in 2000 (RETEC, 2006). The cap was implemented by the U.S. Army Corps of Engineers and included containment measures to remediate impacted sediment and restoration activities to enhance inter-tidal and (shallow) sub-tidal habitat. As the result of cap placement, approximately 1 hectare (2.7 acres) of shallow subtidal habitat and 1.2 hectares (2.9 acres) of low intertidal habitat were created. The thickness of the emplaced cap ranged from 15 cm ft to greater than 1 m, with the more thinly capped areas lying along the perimeter of the Log Pond area. In 2005, monitoring conducted in the Log Pond area confirmed that 5 years after placement, cap thickness over the majority of the remediated area still exceeded 1 m. The single sediment core collected along the perimeter of the cap was logged as containing 60 cm of cap material (RETEC, 2006).

Except for the south (S) corner of the cap (discussed below), surface sediment mercury concentrations measured in 2005 have remained consistently below Washington State Sediment Quality Standards (RETEC, 2006). For the sampling stations located in the thinner (less than 1 m) regions of the cap, surface sediment mercury concentrations have increased from 0.12 mg/kg to 0.35 mg/kg (W corner), from 0.07 to 0.09 mg/kg (E corner), and from 0.05 to 2.65 mg/kg (S corner). In general, these overall low concentrations of mercury in cap sediments 5 years after placement suggests that the cap is functioning as intended and there is little evidence of vertical or horizontal migration of mercury-impacted sediment in the Log Pond area. The exception to this general conclusion is apparent at the cap's south corner, in which wave energies appear to have been sufficient to trigger cap erosion and redistribution of mercury-impacted sediment from the area immediately adjacent to the Log Pond (RETEC, 2006).

Sampling conducted within 6 months of cap installation documented a developing benthic community in the capped area (Bingham, Clothier, and Matthews, 2001). When compared to benthic community structure in an adjacent location (inner Chuckanut Bay reference site), the number of species was similar, with similar diversity and species distribution, as well as similar overall invertebrate biomass between the Log Pond cap and the reference site (Bingham, Clothier, and Matthews, 2001). The principal difference between the Log Pond capped area and the Chuckanut Bay reference site was in dominant species, with the Log Pond cap dominated by polychaete annelids and Chuckanut Bay dominated by crustaceans.

Sampling at 18 months after placement revealed that (1) annelid species still appeared to be over-represented at the Log Pond cap site, and (2) the degree of in-site variability (i.e., variability between stations) was greater for the Log Pond site than the reference site. This greater variability across the Log Pond stations (n = 3), was attributed to the physical disturbance induced by the cap placement and was hypothesized to stabilize over time as the full invertebrate community developed (Bingham, Clothier, and Matthews, 2006). Benthic community sampling conducted 5 years after placement confirmed that biomass, samples collected from both locations demonstrated similar representation (by weight) of crustaceans, annelids, and mollusks, with overall biomass being higher at the Log Pond site than in the reference area. In terms of number of invertebrate species, species diversity and species evenness, results from the test location and the reference location continued to converge; however, data variability between stations at the Log Pond site remained apparent 5 years after placement (Bingham, Clothier, and Matthews, 2006).

3.3.3 U.S. Navy Manchester Annex (Manchester, Washington)

The Manchester Annex site is located along the western shoreline of Clam Bay, near Manchester, Washington. This site, also known as the Old Navy Dump/Manchester Laboratory Site, consists of a former fire training area, a landfill, and a former submarine net and boat depot (the Net Depot). Chemicals of concern associated these activities included dioxins and furans, PCBs, metals, vinyl chloride, and asbestos (USACoE, 2004). Site remediation has included the construction of a landfill cap and shoreline protection system, an intertidal sediment cap, and removal of shore-side structures and soil. The intertidal cap was approximately 2 hectares (5 acres) in extent and between 15- and 30-cm thick (USACoE, 2004).

The intertidal cap was designed to enhance natural recovery of the cove by reducing PCB, metal, and 2,4-dimethylphenol concentrations in surface sediment to below remedial target levels. Cap placement was viewed as providing immediate benefit to cove invertebrates, as it lowered filter-feeder exposure (particularly for clams) and separated sediments with elevated chemical concentrations from the zone of biological activity. Intertidal clams were highlighted in the development of the post-placement monitoring plan because they exhibited the most consistently elevated tissue chemical concentrations among biota sampled in the bay. Although the RAO for this site (i.e., reducing chemical concentrations in the biologically mixed zone of sediment to below cleanup levels) was likely achieved immediately after implementation of the remedy, neither confirmation monitoring nor monitoring within the 5-year review period were undertaken (USACoE, 2004). Limited data collection during the initial 5 years after placement hinders interpretation of recovery trends.

3.3.4 Pier 64 (Seattle, Washington)

A thin layer cap was placed in the Duwamish River Turning Basin in 1994, covering approximately 1.6 hectares (4 acres) at the site of Pier 64/65, with between 30 and 45 cm of sand. Chemicals of concern at this location included metals, PAHs, PCBs, and benzoic acid. Thin layer capping was employed at this site to enhance the natural recovery rate at this site and to reduce the potential for sediment and chemical resuspension during the pile-driving phase of an adjacent pier expansion project. Pier expansion entailed the removal of old creosote-impregnated piling and placement of new concrete piling. Because of the potential for sediment disturbance during these activities, cap material was placed around the piling area.

Sampling conducted after placement (1994), as well as in 1997 and 2002, has generally demonstrated a decline in surface sediment chemical concentrations in the capped area, except for several elevated PAH concentrations in the 2002 sampling. Elevated PAH concentrations in 2002 likely resulted from the piling work and were reflected in benthic tissue data collected from within the area of re-contamination (Polaris Applied Sciences, 2003). Sampling conducted in 2004 confirmed a continued mean cap thickness of 45 cm and demonstrated that the cap was continuing to isolate underlying sediment with chemical concentrations elevated above Washington State Sediment Management Standards (Polaris Applied Sciences, 2004).

4. LESSONS LEARNED

This report focuses primarily on case studies in which EMNR has been implemented as a component of mature remedial design. The three principal case studies examined—Eagle Harbor Washington; Ketchikan, Alaska; and Bremerton, Washington—present various conditions and challenges for thin layer cap placement. Other sites of interest discussed include locations in which thin layer caps have been implemented as a demonstration project or on a pilot scale. For these sites, the mechanics of successful cap placement have not differed significantly than at sites in which thin layer caps were implemented as a component of a mature field remedy.

Differences between these demonstration sites and sites characterized by full-field implementation arise principally from the differences in monitoring objectives and long-term goals. That is, for demonstration projects, placement of a thin layer cap may not be consistently guided by or narrowly restricted to fulfilling site-specific RAOs. Monitoring for demonstration projects is generally more focused on understanding how the cap or cap amendment works (pure science and engineering), whereas the three principal case studies focused mainly on assessing the extent to which risk-based RAOs were achieved. Neither approach is incomplete for their respective goals, although examining both types of case studies allowed a comprehensive overview of TLC.

Generally, EMNR has been implemented with the generally stated goals of reducing the concentration of chemicals in the biologically active zone of sediment in a manner that enhances the potential for benthic recolonization, while not causing widespread disturbance to existing habitat. EMNR sites are characterized by moderately elevated sediment chemical concentrations and relatively quiescent near-bed conditions, but are limited to varying degrees in their capacity for rapid natural recovery because of low background sedimentation rates.

Cap placement results presented in this report demonstrate various successful placement strategies, including hydraulic washing of capping material from a barge; aerial, surface, or underwater discharge from a swinging cable arm bucket; use of a split hull hopper barge; or underwater discharge using Tremie tubes. As noted in Section 2, the range of possible cap placement techniques, including but not limited to those presented in this discussion, has been thoroughly and recently reviewed elsewhere (Bailey and Palermo, 2005). Other successful cap placement strategies not documented in this case study review, but discussed in Bailey and Palermo (2005), include hydraulic spraying of sand slurry from a barge (Soda Lake, Wyoming) and use of a spreader barge/diffusive plate assembly (Mocks Pond, Indiana).

For the principal case studies considered here, results further highlight that significant water depth, bottom slope, and organic enrichment of the sediment do not necessarily preclude the placement of a stable and successful thin layer cap. Although post-placement bathymetric surveys have been conducted at several of the sites, bathymetric monitoring appears to currently offer minimal benefit for caps of 30 cm or less in thickness (the three thin layer caps examined in the case studies were from 15- to 30-cm thick). For the KPC site and the Bremerton Naval Complex site, visually inspecting the cap is a superior way to verify cap integrity over time. Among the case studies surveyed, the availability of appropriate monitoring tools and techniques limited monitoring thin layer cap stability over time as well as the process of thin layer cap material mixing with underlying sediment. However, ongoing improvements in the capabilities of multi-beam bathymetry suggest that resolution on the scale required for monitoring the stability of thin layer caps may soon be possible.

Alternately, sediment profile imaging, as used at the Palos Verdes and Duwamish field sites discussed in Section 3, has proven itself as a useful tool for high-resolution inspection of near-surface sediment. For all EMNR sites, cap stability should be monitored during the time period expected for

EMNR to occur, although the interval in question is poorly defined because of the paucity of fundamental research on thin layer cap mixing rates. Verifying mixing rates for thin layer caps is therefore a research need that will allow the time period for stability monitoring to be framed.

Source control issues should be monitored at sites at which EMNR is applied. Notably, all sediment remedies, including dredging, conventional capping, and monitored natural recovery, are confounded by incomplete source control. At both the Eagle Harbor and Bremerton sites, where the sediment chemistry at the cap surface has been monitored after placement as an indication of remedy, some early recontamination of the new (capped) sediment surface was observed. Monitoring data coupled with knowledge of sediment chemical concentrations in surrounding areas suggests that recontamination at both locations resulted from incomplete source control near the cap, rather than failure or erosion of the cap itself.

This conclusion is significant for all sediment remedies in that it highlights the natural processes of sediment movement—deposition, resuspension, and transport—that occur in aquatic environments. The extent to which these processes compromise the success of a given remediation project will depend on site-specific factors such as the size of the cap versus the fraction of its extent that has been recontaminated and the extent to which chemical concentrations and transport pathways from surrounding media (including soil that may erode into a harbor) are understood and have been addressed.

A key research need for EMNR is to investigate the relevance of ongoing “top-down” sources of contamination to thin layer caps versus the “bottom-up” sources of contamination as thin layer cap material mixes with underlying contaminated sediment. The concentration of contaminants in all thin layer caps will likely increase with time. Understanding the source of those increases is both a fundamental research need for refining the application of thin layer caps as well as a potential monitoring need for all sites with significant ongoing source control issues.

For the principal sites discussed in this report, the nature of the defined RAOs varied considerably between sites. Objectives were defined alternately in terms of specific risk-based cleanup targets (for the Eagle Harbor site), biological indicators such as community structure and function that may demonstrate improvements in benthic habitat quality (for the Ketchikan site), and concentration-based targets derived from cost considerations and ecological recovery rate modeling (for the Bremerton site).

While all these objectives provide reasonable routes towards site remediation, variability exists in the extent to which improvements can be shown to have occurred within the time frame allotted for recovery. For example, for the portion of the Ketchikan site that was capped, attainment of remedial goals was defined as a benthic recolonization rate—a process readily occurring within the time frame of a standard 10-year, long-term monitoring plan. In contrast, for the Bremerton site, the attainment of remedial goals may be unlikely within the modeled 10-year interval because of issues such as incomplete source control. While all sites discussed here demonstrate improvements in surface sediment concentrations of at least some chemicals after remedy implementation, not all remedies have equally achieved the projects’ stated remedial goals.

For those sites attempting to link sediment remediation to specific reductions in ecological or human health risks, multiple factors may complicate the ability to demonstrate the clear linkage between remedy implementation and a measurably reduced risk of exposure as defined by decreasing concentrations in biota. Complications in this relationship arise from variations in recovery rates for different organisms, exposure potential, organism size or age, and species site/home range (site fidelity) and the elapsed time between the inception of remedial activities and the cessation of chemical discharge to the site. This second point is important in that it is not uncommon to measure a decrease in tissue concentrations of chemicals in the aftermath of industrial closures (presumably resulting from a decrease in the surface water concentration of those chemicals), that does not follow consistently into continued appreciable declines in tissue concentrations after implementation of sediment-based remedies (e.g., Francesconi, Lenanton, Caputi, and Jones, 1997; Southworth, Peteson, and Bogle, 2002; Paller and Littrell, 2007). For example, RAOs for the Bremerton site acknowledge that organism recovery rates may be on a different timeline than sediment recovery rates such that English sole tissue concentrations will not be measured during each monitoring interval that includes sediment sampling. The ability to define remedial success for sites such as Bremerton may be complicated by the inclusion of both fish tissue and sediment goals, as the time course toward achieving these goals probably progresses at differing rates and may not provide timely benchmarks for determining whether an alternate remedial action plan may be warranted.

Risks associated with remedy implementation remain an uncertainty with EMNR. Because the benthic community plays a key fundamental role in EMNR performance by mechanically mixing the sediment (i.e., bioturbation), a hypothesized advantage of EMNR over isolation capping or dredging is the low-impact of thin layer cap placement on the existing benthic community.

This hypothesis has not been rigorously tested, however, and the time frame for recovery from any adverse effect is unknown. For example, the Ketchikan site monitoring, as well as pilot study results from the Grasse River, suggest that recovery may take place within 5 years, whereas results from the Log Pond site suggest that significant variability in community structure can remain apparent 5 years after implementation. Because variability in community recovery between stations may result from variability in physical factors, including light penetration, hydrodynamics, sediment characteristics, and larval delivery success, the convergence of benthic community data at a site may be significantly influenced by station selection and the extent to which success is defined by station-specific versus integrated metrics of community structure.

A better understanding of the recovery time frame after cap placement would be useful from a research perspective, and would, in turn, allow a more precise estimation of the loss of ecosystem services considered as a component of site feasibility studies. Moreover, because differences in physical factors (including sediment grain size) are likely to alter extant benthic communities, addressing the effects of thin layer capping materials such as sand on benthic community recovery remains a critical research need for EMNR. This is particularly true if benthic community recovery is defined as a site RAO or is a principal concern for site stakeholders.

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6. AUTHORS

K. Merritt
J. Conder
V. Magar
ENVIRON Corporation

V. J. Kirtay
D. B. Chadwick
SSC Pacific

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

ENVIRON Corporation
136 Commercial Street, Suite 402
Portland, Maine, 04101

SSC Pacific
San Diego, CA 92152-5001

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Environmental Security Technology Certification Program
901 North Stuart Street, Suite 303
Arlington, VA 22203

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14. ABSTRACT

This case study review was prepared as part of a Navy-led project to foster broader understanding and acceptance of the Enhanced Monitored Natural Recovery (EMNR) remedy through demonstration and validation of performance and cost-effectiveness at Department of Defense contaminated sediment sites. EMNR is a hybrid remedy that generally relies on the combined effects of a thin layer cap (enhancement) and natural recovery, and is verified over time through monitoring. This case study review is a resource for site managers who are considering EMNR as a remedy. The EMNR project will perform a field demonstration based on this review.

15. SUBJECT TERMS

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