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Long-Term Monitoring Strategies For Contaminated Sediment Management

Space and Naval Warfare Systems Center Pacific
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ENVIRON International Corporation

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Acronyms

CAD	Contained Aquatic Disposal
CAMU	Corrective Action Management Unit
CDF	Confined Disposal Facility
CSM	Conceptual Site Model
DoD	Department of Defense
DQO	Data Quality Objective
GIS	Geographic Information Systems
GPS	Global Positioning System
Hg	Mercury
ISRAP	Interactive Sediment Remedy Assessment Portal
MCSS	Major Contaminated Sediment Sites
MNR	Monitored Natural Recovery
NAPL	Non-aqueous Phase Liquid
NAVFAC	Naval Facilities
NRC	National Research Council
OBS	Optical Back Scatter
OC	Organic Carbon
OU	Operational Unit
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PSD	Particle size distribution
RAO	Remedial Action Objective
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
RPM	Remedial Project Managers
SPI	Sediment Profile Imaging
VOC	Volatile Organic Carbon
USEPA	United States Environmental Protection Agency

Glossary

advection: the process of transfer of fluids (vapors or liquid) through a geologic formation in response to a pressure gradient that may be caused by changes in barometric pressure, water table levels, wind fluctuations, or infiltration.

benthic: adjective describing the biologically active sediment zone, generally at the sediment surface at the bottom of a water body such as an ocean, lake, or river (e.g., benthic organism, or sediment benthic layer).

bioaccumulation: the process by which chemicals are taken up by an organism either directly from exposure to a contaminated medium or by consumption of food containing the chemical.

bioavailability: degree or ability of a chemical to be absorbed and to readily interact in organism metabolism.

bioconcentration: the process by which there is a net accumulation of a chemical directly from an exposure medium into an organism.

biodegradation: a process by which microorganisms transform or alter (through metabolic or enzymatic action) the structure of chemicals introduced into the environment; usually refers to chemical decomposition. See also biotransformation.

biomagnification: the process of bioaccumulation and biological transfer by which tissue concentrations of chemicals in organisms at one trophic level exceed tissue concentrations in organisms at the next lower trophic level in a food chain.

biota: species of all plants and animals present within a certain region or area.

biotransformation: alteration of the structure of a compound by a living organism or enzyme.

bioturbation: the natural activity of living organisms, such as worms, to move particles and pore water from inside soil or sediment beds toward the surface and circulate them in the upper layers of the sediment bed.

capping: an engineered sediment remedy involving the placement of a subaqueous covering or cap of clean material over contaminated sediment that remains in place to physically isolate contaminated sediment sufficient to reduce exposure due to direct contact, and to stabilize contaminated sediment and protect against contaminated sediment erosion, suspension, and transport.

chemical precipitation: formation of a separable solid substance from solution, either by converting the substance into an insoluble form or by changing the composition of the solvent to diminish the solubility of the substance in it.

chemical sequestration: a chemical process by which a compound or metabolite is locked away so as to not to be readily available. For example, long-term hydrophobic sorption of organic chemicals can lead to their sequestration from the environment and from biological exposures.

contaminant: any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil.

degradation: to reduce the complexity of; to impair in respect to some physical property.

dilution: process of reducing the concentration of a solute in solution, usually simply by mixing with more solvent.

diffusion: the movement of suspended or dissolved particles (or molecules) from a more concentrated to a less concentrated area. The process tends to distribute the particles or molecules more uniformly.

dispersion: to spread or distribute from a fixed or constant source.

dredging: the mechanical removal of subaqueous sediments from the aquatic environment.

ecological risk: the likelihood that adverse ecological effects are occurring or may occur as a result of exposure to one or more stressors.

ecosystem: the interacting system of a biological community and its non-living environmental surroundings.

erosion: the wearing away of land surface by wind or water, intensified by land-clearing practices related to farming, residential or industrial development, road building, or logging.

flux: the rate of transfer of fluid, particles, or energy across a given surface

geographic information system: a computer system designed for storing, manipulating, analyzing, and displaying data in a geographic context.

hot spot: an area of contamination in which the level of contamination is significantly greater than in neighboring regions in the area.

human health risk: the likelihood that a given exposure or series of exposures may have damaged or will damage the health of individuals.

in situ: in its original place; unmoved unexcavated; remaining at the site or in the subsurface.

isotope: a variation of an element that has the same atomic number of protons but a different weight because of the number of neutrons. Various isotopes of the same element may have different radioactive behaviors, some are highly unstable.

kinetics: referring to the rate of physical or chemical reactions

monitored natural recovery (MNR): an engineered remedy for contaminated sediment sites that involves leaving contaminated sediments in place and allowing ongoing aquatic, sedimentary, and biological processes to reduce the bioavailability of the contaminants in order to protect receptors. Generally includes long-term monitoring to ensure protection of ecological and human receptors.

monitoring: the collection of data over space or time to evaluate physical, chemical, or biological trends or to compare the physical, chemical, or biological state with a predetermined goal or regulatory requirement.

organic: referring to or derived from living organisms; in chemistry, any compound containing carbon.

oxidation: process through which oxygen is added to a compound; the atomic or molecular loss of electrons in biochemical or geochemical electron-transfer reactions; always accompanied by reduction. See also reduction.

phytoremediation: the use of plants to contain, sequester, remove, or degrade organic or inorganic contaminants in soils, sediments, surface water and groundwater.

reduction: process by which electrons are added to a compound; the atomic or molecular gain of electrons in biochemical or geochemical electron-transfer reactions; always accompanied by oxidation. See also oxidation.

sedimentation: process by which sediment is deposited into surface waters such as streams and lakes.

sorption: the process in which one substance takes up or holds another (either through hydrophobic or electrochemical bonding).

volatilization: the conversion of a chemical substance from a liquid or solid state to a gaseous or vapor state.

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1 Introduction

Content: *This section introduces the subject of long-term monitoring for contaminated sediment sites, and identifies the goals of this Navy Guidance on sediment long-term monitoring.*

As estuarine and coastal sites fall under increasing scrutiny, the number of contaminated sediment sites nationwide continues to increase along with the potential volumes of sediment requiring some form of remedial action (Nadeau, 2005). The same trend is being observed among Department of Defense (DoD) sites. Based on more than 200 identified sites, the estimated cost to complete remediation of the Navy's contaminated aquatic sediments is more than one billion dollars. This does not include the costs associated with the post-remediation monitoring efforts.

Monitoring requirements, remedy performance, and risk reduction are not well-understood, particularly at large-scale sediment sites. Of the relatively few sites where remedies have been implemented, limited monitoring data provides little information regarding the long-term effectiveness of sediment remedies to reduce human health or ecological risks. Even among the United States Environmental Protection Agency (USEPA) Superfund sites that have undergone remedy implementation, short- and long-term monitoring data are often insufficient to fully evaluate the effectiveness of the remedy in meeting the remedial action objectives (RAOs) (USEPA, 2003a). The cost of monitoring at these sites varies widely due to differences in scope, magnitude, and duration of monitoring plans, thereby making it difficult to project potential monitoring costs for DoD sites.

There is a clear need for the development of improved methods for assessing ecosystem recovery at contaminated sediment sites to better understand the impact of remedial management strategies on the ecosystem. There is also a need for guidance that standardizes long-term monitoring methods and approaches and which supports the Navy policy on sediment investigations and response actions (CNO, 2002). Navy policy (CNO, 2002) states:

> *A monitoring plan with exit strategies shall be developed before collecting the first monitoring sample. Monitoring is critical to successful implementation of remedies that leave contaminants in place, including monitoring of remedial activities, natural recovery or capping. If a monitoring alternative is selected in conjunction with or in place of a cleanup action a monitoring plan must be completed before the first monitoring sample is collected. The DQO process must be employed to design the monitoring plan. The monitoring plan must have the number, type (biota or bulk chemistry), location, and duration of all samples. Exit strategies must be included in all monitoring plans.*

An underlying need for the development of improved monitoring methods and protocols to document the long-term performance and effectiveness of remedial actions has been identified by the Navy (Regulatory and Base Operations: EEC-5: Cost-effective methods for identifying, analyzing, and managing environmental constraints related to current and projected regulatory impacts) and USEPA in its Contaminated Sediment Research Multi-Year Implementation Plan (2005a). To date, little is known about the long-term efficacy of sediment remediation efforts. Most site owners are eager to close their sites and reluctant to implement long-term monitoring programs that may last decades after spending millions of dollars on sediment remedies. In an atmosphere of industry criticism regarding the uncertain effectiveness of sediment dredging, and public uncertainty about the long-term stability and effectiveness of in situ remedies, there is an increasing need for a more effective, standardized and accepted long-term monitoring framework to evaluate the effectiveness of sediment remedial actions.

As DoD sediment sites move toward remedy implementation, a uniform approach for the design and implementation of long-term sediment monitoring programs is needed. Such an approach should ensure that long-term monitoring is clearly tied to remedial action objectives and that clear exit criteria are established to facilitate timely and cost-effective site closure while protecting human health and the environment. Though several resources identify general monitoring needs and approaches for sediment sites, few provide a framework with detailed information about when and how to apply various monitoring tools to address those needs, and no formal guidance exists to support evaluation and selection of appropriate monitoring tools and approaches suited to site-specific data quality objectives (DQOs) and monitoring goals.

The Navy (under the 0817 program) developed this contaminated sediment monitoring guidance document for sediment sites that undergo remediation. The goal of this contaminated sediment monitoring guidance document is to provide an optimized, cost-effective framework to bridge the gap between detailed monitoring tool descriptions and general guidelines that identify monitoring needs. The guidance includes remedy-specific validation and monitoring matrices that relate monitoring tools to specific monitoring needs for dredging, capping, and monitored natural recovery (MNR), to help remedial project managers (RPMs) focus on key issues associated with site-specific monitoring needs and tools and to facilitate the design of cost effective and meaningful monitoring plans. It is envisioned that this guidance will be useful to RPMs at a variety of stages in the Remedial Investigation/Feasibility Study (RI/FS) process, but will be particularly useful in understanding and developing monitoring programs and plans to monitor remedy performance following remedy implementation at contaminated sediment sites.

This guidance also serves as a detailed reference companion for the Interactive Sediment Remedy Assessment Portal (ISRAP). The ISRAP presents the remedy-specific validation and monitoring matrices (included in this document as Appendix B) as an online, interactive tool. Presenting the matrices as an interactive tool facilitates navigation of the large volume of information in the matrices, and allows technical contents to be updated and modified over time. Thus, in addition to the matrices being in a much more user-friendly form, the ISRAP represents a living, updatable version of Appendix B.

The guidance described in this document supports the Navy policy on sediment investigations and response actions (CNO, 2002), and is consistent with the Navy's *Implementation Guide for Assessing and Managing Contaminated Sediments at Navy Facilities* (NAVFAC, 2005a), as well as USEPA's *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (2005b). This framework is also consistent with USEPA's Directive 9355.4-28, *Guidance for Monitoring at Hazardous Waste Sites: Framework for Monitoring Plan Development and Implementation* (2004), and USEPA's

Data Quality Objectives (DQO) process (2000b). The publication of the USEPA *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (2005b) attests to the maturity of sediment remedial options discussed in this document and the need for monitoring remedy effectiveness.

1.1 Role of Monitoring in Sediment Remediation

EPA's *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (2005b) identifies the following reasons for long-term monitoring: 1) to assess compliance with design and performance standards; 2) to assess short-term remedy performance and effectiveness in meeting sediment cleanup levels; and 3) to evaluate long-term remedy effectiveness in achieving remedial action objectives (RAOs) and in reducing human health and/or environmental risk. Additionally, as stated in the USEPA (2002) *Principals for Managing Contaminated Sediment Risks at Hazardous Waste Site, Step 11,* "a physical, chemical and/or biological monitoring program should be established for sediment sites in order to determine if short-term and long-term health and ecological risks are being adequately mitigated at the site and to evaluate how well all remedial actions objectives are being met. Monitoring should normally be conducted during remedy implementation and as long as necessary thereafter to ensure that all sediment risks have been adequately managed". Monitoring data usually are needed to complete the five-year review process frequently called for by records of decision (RODs).

Monitoring provides empirical data to evaluate the extent to which sediment remedial actions achieve short- and long-term goals. Monitoring also can provide information on changing conditions that can impact the remedy, external influences on ecosystem recovery, background sources that can influence or mask recovery, and sedimentation processes that can accelerate recovery. Monitoring may focus on chemical concentrations in various physical (e.g., sediment or water) or biological (e.g., benthic animals, plants, fish, or other relevant receptors) media, physical processes such as hydrodynamics or sedimentation, ecosystem recovery and biological population dynamics, remedy stability, or combinations of these metrics.

Monitoring of environmental restoration recognizes that uncertainty is inherent to any cleanup activity and must be managed through data collection and uncertainty mitigation (i.e., using monitoring data, probabilistic modeling, and contingency planning to counteract the impacts that may arise from unexpected conditions) (DOE 1997, 1999). Sources of uncertainty may include:

- The vertical and lateral extent of sediment contaminants and their exposure pathways to ecological receptors.
- The dynamics of contaminant transport in aquatic environments, including partitioning rates and magnitude, soluble transport, sedimentary transport, and biological transport kinetics.
- Future sedimentation rates.
- Sediment stability and resistance to erosion.

- Future hydrodynamic conditions, which may be influenced by external, perhaps unpredictable factors.
- Future changes to site use and subsequent impacts on sedimentation, sediment stability, and chemical stability.
- Remedy effectiveness and remedy impacts on aquatic ecology.
- Background contaminants and ecological stressors, whether or not they are related to the primary contaminants of concern.
- Adequacy of source control.

If all uncertainties could be eliminated prior to remedy implementation, there would be no need for post-implementation monitoring (DOE, 1999). In fact, cleanup decisions typically are made with incomplete data, and uncertainties always exist in remedy selection, design, and implementation. For this reason, monitoring may be required at various levels of the sediment remedial implementation process. During implementation, monitoring helps ensure that remedy implementation meets design specifications, while post-remedy long-term monitoring is used to determine the extent to which the conceptual site model and remedy selection achieve long-term RAOs identified in the ROD.

When developing a monitoring plan, it is important to maintain consistency with the numerical cleanup levels or action levels for sediment and or other media established in the ROD, and with narrative RAOs that relate to reducing risk (USEPA, 2005b). Establishing clearly defined monitoring goals and corresponding exit criteria is central to a well defined and well managed monitoring program. All data should be collected with an understanding of how the data will be used and how they contribute to a validation of remedy performance and success. This document provides guidance on how to identify long-term monitoring goals, select monitoring tools and methods to achieve these goals, and document remedy success.

1.2 Remedy-Specific Monitoring Packages

This guidance adopts a framework based on remedy-specific monitoring packages. The goal of this strategy is to develop a suite of integrated remedy, long-term monitoring, and validation packages for contaminated sediment management strategies including:

- Monitored Natural Recovery (MNR)
- Sediment Capping
- Dredging

Clearly, sediment remedies are not limited to MNR, capping, and dredging and may include combinations of these methods and a variety of other methods such as institutional controls, addition of sorptive or reactive sediment amendments, or habitat restoration. This guidance focuses on MNR, capping, and dredging because these three approaches currently dominate sediment remedy approaches.

The strength of a remedy-specific approach is that it focuses the monitoring program on the specific mechanisms utilized by a given remedy to achieve success. Ideally, these packages will serve to optimize long-term monitoring, provide integrated cost comparison data for remedies that include validation and monitoring, and reduce complexity and cost in the selection/application of proper monitoring approaches. The approach is not intended to serve as a "one-size-fits-all." A single approach is not appropriate for monitoring ecosystem response to all sediment remedial actions. Monitoring plans need to be flexible and adopt an adaptive site management strategy so that the data collected can be adjusted as necessary to meaningfully measure ecological recovery. The remedy-specific approach described in this document is intended to provide a systematic framework for designing and selecting monitoring alternatives, to increase consistency among Navy sites, to decrease uncertainties, and to cost-effectively document remedy success at contaminated sediment sites.

1.3 Document Organization

This guidance is organized as follows:

Section 1.0: *Introduction.*

Section 2.0: *Remedial Technology Descriptions*. This section provides background information describing the principal remedial strategies used for managing contaminated sediments and the mechanisms employed by each remedy to reduce human and ecological risks.

Section 3.0: *Establishing Monitoring Goals and Requirements*. This section introduces the basic elements required for developing a monitoring plan to assess remedy success during and after remediation.

Section 4.0: *Remedy-Specific Monitoring Approaches*. This section discusses the monitoring approaches most applicable to MNR, capping, and dredging.

Section 5.0: *References.*

Appendix A: *Overview of Sediment Monitoring Tools*: This supplementary section provides an overview of sediment monitoring tools, methods, and techniques.

Appendix B: *Monitoring Tool Matrices*: Remedy-specific matrices provide a decision-making framework for a comprehensive list of tools.

Appendix C: *Case Studies*: This section provides a brief description of monitoring approaches used at (or to be used) at two different sediment sites including the Puget Sound Naval Complex, Bremerton Site (Washington) and the Wyckoff/Eagle Harbor site (Washington). Also included is a validation and evaluation of the sediment monitoring tool matrices, conducted using a retrospective application of the matrices to the case studies.

Appendix D: *Example Statistical Resources for Experimental Design and Data Interpretation*: This Appendix provides an annotated bibliography of statistical resources useful in the experimental design of sediment remedy monitoring programs and interpretation of sediment remedy monitoring data.

2 Remedial Technology Descriptions

***Content:** This section provides a short description of the principal remedial strategies used for managing contaminated sediments –MNR, capping, and dredging as well as a brief discussion of source control as the first step in implementing any sediment remedial strategy. A short discussion of the mechanisms of risk reduction through which they work is provided. Comprehensive sediment cleanup information can be found via:*

- *Contaminated Sediments in Superfund website* (http://www.epa.gov/superfund/resources/sediment/).
- *Major Contaminated Sediment Sites (MCSS) Database, which was compiled to collect and organize, in one location, pertinent information on major contaminated sediment remediation projects in the United States (http://www.ge.com/en/citizenship/ehs/remedial/hudson/mcss/index.htm).*

Fundamental to establishing a clearly defined long-term monitoring plan is an understanding of the remedial action goals and the fundamental physical, chemical, or biological processes employed by the remedy. For example, in very general terms, dredging relies on mass removal to achieve risk reduction, while capping relies on burial and creation of a clean sediment surface, and MNR relies on natural processes (e.g., sedimentation and burial, chemical sequestration, and contaminant degradation or transformation) to achieve these goals. The primary mechanisms involved in each remedy will inform the selection of the physical/chemical/biological processes to monitor during and after remedy implementation.

The goal of all sediment remedies should be achievement of site-specific RAOs. Surface sediment contaminants pose the greatest risk of biological exposures, which occur at the sediment-water interface and in the biologically active zone of surface sediments where benthic animals flourish. At sites where deeper contaminated sediment is not currently bioavailable or bioaccessible, and that has been found to be relatively stable with analyses, buried contaminants are not likely to contribute to site risks (USEPA, 2005b). Thus, it stands to reason that most sediment remedies focus on eliminating complete exposure pathways for receptors exposed to contaminants at the sediment surface. Long-term monitoring should focus on the extent to which the implemented remedies successfully eliminate complete exposure pathways to sediment contaminants.

RAOs may include numeric contaminant-specific remedial goals, often targeting specific surface sediment contaminant concentrations in the benthic active zone, as well as ecological recovery goals that describe reduced risks to human health and ecological receptors. Contaminant-specific remedial goals tend to include both short- and long-term goals, while ecological recovery goals tend to be long-term goals; both types of goals should include the time frame over which when goals are expected to be achieved.

2.1 Source Control

Sediment remediation relies on source control to prevent the recontamination of the remediated area. Source identification and control are often critical to the effectiveness of sediment cleanup. Source control is defined as those efforts that are taken to eliminate or reduce, to the extent practicable, the direct or indirect release of contaminants into the water body under investigation. At some sediment sites, the original sources of the contamination may have already been controlled, but secondary sources such as contaminated upland soils, storm water discharges, and seeps of ground water or non-aqueous-phase liquids (NAPLs) may continue to introduce contamination to the site. At sites with significant sediment mobility, areas of higher contaminant concentration may impact less contaminated areas down gradient. In general, and consistent with Navy policy (CNO, 2002), upland sources should be controlled to the extent possible before sediment cleanup. Furthermore, before implementing a sediment remedy, the potential for recontamination should be considered and factored into the remedy selection process. A critical question often is whether an action in one part of the watershed is likely to result in significant and lasting risk reduction, given the probable timetable for other actions in the watershed (USEPA, 2005b). If a site includes a source that could result in significant recontamination, source control measures may be necessary as part of the overall response action.

Though the focus of this guidance is on monitoring sediment remedies, to the extent that source control is part of the response action, or where source control is uncertain, source control monitoring may be a component of the long-term monitoring program. Source control monitoring may be addressed directly at the source (e.g., monitoring treated effluent discharges) or indirectly at the site (e.g., monitoring surface sediment recontamination potential or, as in the case of MNR, reduced surface sediment contaminant concentrations with time.

2.2 Monitored Natural Recovery

Monitored natural recovery (MNR) depends on natural recovery processes, within the context of a carefully controlled and monitored site cleanup approach, to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods (USEPA, 1999). At most sites, where biological exposures occur primarily at the sediment surface, MNR relies on reduced contaminant mass, mobility, bioavailability and/or toxicity at the sediment surface. Processes that contribute to natural recovery include the following (Brown, 1999; Magar and Wenning, 2006):

- Physical processes: sedimentation and burial, advection, diffusion, dilution, dispersion, bioturbation, and volatilization.
- Biological processes: biodegradation, biotransformation, phytoremediation, and biological stabilization.
- Chemical processes: oxidation/reduction, sorption and chemical sequestration, chemical precipitation, or other processes that contribute to contaminant stabilization and reduced bioavailability.

MNR should be the result of a thoughtful decision-making process following careful site assessment and characterization (NRC, 1997; USEPA, 2005b). A primary goal of MNR is to not disturb natural processes that can contribute to risk reduction

(USEPA, 2001a; Magar and Wenning, 2006). Ecological recovery and risk reduction using MNR are achieved through the following processes:

- Natural deposition and burial resulting in the natural dilution of surface sediment chemical concentrations to create a cleaner sediment surface, and in time to achieve surface sediment chemical concentration goals.
- Chemical stabilization, sequestration, transformation, or degradation to reduce or eliminate contaminant mobility, bioavailability, and/or toxicity.
- Reduction of chemical flux from sediments to the water column over time through physical, chemical, or biological processes.
- Reduction of surface sediment pore water contaminant concentrations through physical, chemical, or biological processes.
- Reduction of surface sediment erosion potential with time through deposition, and natural sediment cohesion and compaction with time.

Because MNR relies on natural processes, it is likely to be most applicable to sites, or portions of sites, where human or ecological risks are not immediate or substantial. Depositional areas not susceptible to major erosional events are often seen as favorable for MNR, where long-term deposition following source reduction/elimination contributes to reduced surface sediment chemical concentrations with time. MNR also may be employed at sites that undergo more active remediation, where natural processes provide additional long-term recovery following active remediation, or at portions of sites that do not undergo active remediation.

MNR relies on monitoring to demonstrate achievement of RAOs. The parameters to be monitored, and the sampling frequencies and locations, are based on the conceptual site model (CSM), natural recovery processes that reduce or interrupt contaminant exposure pathways, and the uncertainties associated with the CSM and the kinetics of recovery processes (DOE, 1999). Conceptual site modeling and site-specific monitoring are integrated to provide a continuous feedback mechanism during operation of the remedy to demonstrate that attenuation processes are sufficient to meet performance objectives and are functioning within the envelope of acceptable time frames to achieve those objectives (DOE, 1999).

2.3 Capping

In situ isolation capping is the controlled, accurate placement of a clean, isolating material cover, or cap, over contaminated sediments without relocating or causing a major disruption to the original sediment bed (NRC, 1997).

Several guidance documents discuss various elements of capping, including capping design, and materials; physical and chemical stabilization components; geotechnical and operational considerations; and basic monitoring requirements (Palermo et al., 1998; USEPA, 2005b; NAVFAC, 2005b). Ecological recovery and risk reduction using capping are achieved through the following processes:

- Physical isolation of sediment contaminants.

- Structural stabilization of the sediment bed to reduce or prevent surface sediment erosion.
- Establishment of a clean sediment surface to achieve surface sediment chemical concentration goals.
- Creation of a healthier benthic habitat with improved sediment characteristics for benthic colonization.
- Reduction or elimination of chemical flux from sediments to the water column.
- Reduction of surface sediment pore water contaminant concentrations.

In addition to conventional in situ isolation caps, there are recent advances in two additional cap types: thin-layer caps and reactive caps. Thin layer caps are placed on top of the contaminated material to enhance natural recovery by rapidly establishing a relatively clean sediment surface. Reactive capping is a new technology that involves the addition of sorptive or reactive media to sequester or destroy chemicals of concern in surface sediments.

2.4 Thin-Layer Caps

Thin-layer caps are used to enhance ongoing natural recovery processes. A thin-layer cap can help accelerate natural recovery processes to provide a cleaner sediment surface and benthic environment. An optimum thin-layer cap thickness must be determined based on site-specific characteristics, including natural recovery rates, RAOs, benthic bioturbation rates and depths, and contaminant transport properties. Ecological recovery and risk reduction using thin-layer caps are achieved through the following processes:

- Dilution of surface sediment chemical concentrations to create a cleaner sediment surface and achieve surface sediment chemical concentration goals.
- Creation of a healthier benthic habitat with improved sediment characteristics for benthic colonization.
- Reduction of chemical flux from sediments to the water column.
- Reduction of surface sediment pore water contaminant concentrations.
- Reduction of surface sediment erosion potential.

2.5 Reactive Caps

Reactive caps, also called active caps, involve the addition of sorptive or reactive media to surface sediments to sequester or destroy chemicals of concern in surface sediments. These new technologies may be most suitable for sites where MNR is in process but has not had sufficient time to achieve long-term cleanup goals and risk reduction. Sequestering contaminants within organic or inorganic sediment matrices can enhance natural remediation processes. In the laboratory, it has been shown that this technique reduces pore water contaminant concentrations and contaminant bioavailability (Ghosh, et al., 2000, 2003; Bucheli and Gustafsson, 2000; Luoma, 1978).

In principle, the contaminant sorption capacity of natural sediments can be modified and enhanced by the addition of activated carbon for persistent organic pollutants; natural minerals such as apatite, zeolites, or bauxite and refined minerals such as alumina/activated alumina for metals or metalloids (Cao, et al., 2002; Apak, et al., 1998; Acurex, 1996; Yabe and De Oliveira, 2003; Aguilar, et al., 2004). Other reactive remedies remain untested but may include ion exchange resins for metals or other inorganic contaminants (Griffiths, 2002); and zero-valent iron (microscale or nanoscale) for PCB dechlorination. Since reactive caps can have ecological impacts in their own right, studies establishing the efficacy of these amendments are still ongoing.

Several types of reactive caps are being demonstrated as part of the USEPA's *Anacostia River Active Capping Demonstration Project* (http://www.clu-in.org/conf/tio/capping_031203/prez/1280x1024/ppframe.cfm?date=69&simul=1) and at the Navy's Hunters Point Shipyard site. At the Anacostia River, thin layer sand and reactive caps were used to study the performance of AquaBlok™, apatite, and an organo-clay sorbent. The reactive caps are compared with the thin-layer sand for their ability to stabilize or control sediment-bound contaminants. At the Hunters Point Shipyard site, activated carbon is being pilot tested to promote the sorption and chemical sequestration of PCBs in surface sediments. In principal, ecological recovery and risk reduction using reactive capping is achieved through the following processes:

- Binding or chemical transformation of contaminants to reduce chemical mobility, bioavailability, and toxicity in surface sediment and sediment pore water.
- Dilution of surface sediment chemical concentrations to create a cleaner sediment surface and achieve surface sediment chemical concentration goals.
- Creation of a healthier benthic habitat also may be possible, but may require the addition of a sand layer on top of the reactive cap to serve as a substrate for benthic colonization and growth.

2.6 Dredging

Environmental dredging involves the subaqueous removal of contaminated sediments and relocation to sites where sediment can either be contained via disposal or treated. The purpose of environmental dredging is the removal of contaminant mass from the aquatic environment above certain action levels while minimizing the spread of contaminants during the operation (NRC, 1997). Dredging can be classified as either mechanical or hydraulic. Mechanical dredges typically use either digging buckets (e.g., clamshell buckets) suspended by a cable from a crane, an excavator on a fixed arm, or dragline buckets suspended by cable from a crane. In hydraulic dredging the sediment is loosened first and mixed with water by cutter heads or hydraulic agitation. The loosened sediment is then pumped from the aquatic environment. Ecological recovery and risk reduction using dredging are achieved through:

- Mass removal and hot-spot removal to reduce contaminant mobility.
- Achievement of target surface sediment concentrations.

- Reduction of contaminated-sediment resuspension potential and downstream contaminant deposition.

Because dredging often has difficulty achieving target surface sediment contaminant concentrations (NRC 2007; Bridges et al. 2008), dredging commonly relies on natural recovery, backfilling, or capping to achieve surface sediment RAOs. Backfilling serves many of the same functions as conventional isolation capping or thin-layer capping.

Dredging resuspension is influenced by the dredging technique, dredging rate, surface water hydrodynamics, and the physical properties of the dredged sediment (e.g., finer materials are more likely resuspended than coarse grained materials). Containment barriers often are used during the dredging process in order to reduce the downgradient transport of resuspended contaminants during the removal process. Such containment barriers may include oil booms, silt curtains, silt screens, sheet-pile walls, cofferdams, and bubble curtains (USEPA, 1993). Since there is uncertainty regarding the efficacy of containment barriers, monitoring may be required to demonstrate their proper application.

A dredging operation generally requires debris removal, staging and transport, treatment (e.g., dewatering, treatment of decant and dewatering effluents, and possibly sediment treatment), transportation, and disposal for both liquids and solids. These additional components of the dredge operation require monitoring, mostly during remedy implementation.

2.6.1 Debris and Sediment Removal

Depending on the type of dredging equipment selected, certain situations may require debris removal before the actual operation takes place. Debris removal may incur similar risks to those of the actual dredging operation. These include increased contaminated sediment suspension and release, increased residuals production, and decreased dredging productivity. Therefore, plans for monitoring operations should account for these risks.

2.6.2 Sediment Dewatering

When sediment is first removed, the dredged material is generally too wet to be transported or placed at a disposal facility. Mechanical dredging can add up to 0.2 to 0.5 times the in-place sediment volume, and hydraulic dredging can add up to 5 to 10 times the in-place sediment volume as water (Palermo et al., 2006). Dewatering is performed routinely for the management of contaminated dredge sediments to reduce the weight and volume of sediment designated for off-site disposal, and to facilitate transportation and disposal. Dewatering technologies for dredged sediments include dewatering beds, mechanical dewatering, barge dewatering, and additives that enhance dewaterability. Short- and long-term monitoring plans should account for dewatering performance (i.e., the extent to which dewatering activities achieve design specifications with respect to the specified sediment-water content for transportation and disposal) as well as to monitor wastes generated by the dewatering process.

2.6.3 Sediment Disposal

Once removed, dredged sediment must be transported for disposal and appropriately disposed. Disposal may or may not require dewatering or treatment. Dredged material disposal options generally include land and aquatic disposal. Land disposal may involve on-site disposal in a corrective action management unit (CAMU) or off-site upland disposal. Aquatic disposal may involve disposal in a confined disposal facility (CDF) or contained aquatic disposal (CAD). Dredged material can be transported by floating barges, trucks, or rail. Transportation generally must adhere to Department of Transportation regulations.

Disposal alternatives are not covered in this guidance document. On-site landfill disposal or, in the case of an unregulated waste stream, disposal as non-regulated fill material, may be part of a long-term monitoring plan, but likely would require considerations from the in-situ aquatic monitoring program.

3 Monitoring Plan Design

***Content:** This section introduces the basic elements required for developing a monitoring plan to assess remedy success during and after remediation. Fundamental to this task is the Data Quality Objective (DQO) process, which is applied to identify key questions to define monitoring goals to facilitate the selection and implementation of the most effective monitoring tools.*

At the most basic level, successful sediment remedies are those that meet sediment remediation goals over time and reduce risks to human health and the environment to acceptable levels. The extent to which remedy objectives are achieved is evaluated through monitoring. Monitoring is the collection and analysis of repeated measurements to evaluate changes in conditions and progress toward meeting management objectives (USEPA, 2004).

3.1 Monitoring Phases

Whereas monitoring remedy success is important to the ultimate assessment of remedy success, assessing endpoints related to the construction and performance of the remedial strategy also is necessary to ensure that the remedy itself does not result in adverse impacts and that the technology has been implemented correctly (i.e., in accordance with design specifications) and performs to its full potential.

Monitoring phases are described below. Figures 3.1-3.3 depict the temporal arrangement of monitoring phases and remedy events for dredging, capping and MNR, respectively.

Baseline Monitoring. Baseline monitoring is used to augment the data on existing conditions following site characterization and remedial design activities conducted as part of the RI/FS. Baseline monitoring establishes a database for planning or future comparisons, and is a key part of the monitoring program associated with any remedy (Figures 3.1-3.3). The intent of baseline monitoring is to establish initial conditions against which changes can be compared, augmenting site characterization data.

Just as pre-remedial data provides a baseline for comparison with remedial goal monitoring post-remedy baseline conditions must be established immediately after remediation to establish post-remediation baseline conditions to compare with long-term recovery data. Depending on the site, it may be necessary to establish baseline conditions with respect to contaminant chemistry, ecological conditions, and physical conditions.

The quantity and quality of site characterization data must be evaluated prior to designing a monitoring program to ensure that the data are robust and the site is well characterized with respect to the endpoints of interest. Site characterization data collected during the RI/FS may need to be supplemented with additional data more aligned with long-term monitoring goals. RI data may need to be supplemented with new data for sites where RI data is old or at sites where the RI data does not adequately provide a baseline. To the extent possible, monitoring approaches (including monitoring tools) should be similar (or identical) in pre- and post-remediation monitoring programs to facilitate direct data comparison.

Construction Monitoring: Construction monitoring includes assessment of construction and operations activities, potential adverse conditions associated with remediation, and attainment of design criteria (i.e., in accordance with design specifications). ***Construction monitoring data is used to answer the question: Is the remedy constructed as designed?*** Construction monitoring occurs during active remediation, such as dredging or placement of a cap (Figure 3-1 and Figure 3-2). Construction monitoring usually ends following completion of dredging or cap placement, culminating in the verification that design criteria were met.

Performance Monitoring: Performance monitoring addresses the remedy mechanism itself, such as sediment isolation (capping and MNR) and natural recovery processes (MNR). Performance monitoring is absent from dredging, as there is no ongoing remedy mechanism responsible for risk reduction once construction activities are complete. ***Performance monitoring data is used to answer the question: Is the remedy mechanism performing as designed?*** Performance monitoring generally occurs after construction is complete. However, as the construction process slowly advances across the spatial extent of a site, performance monitoring can begin in areas where construction is complete while other areas remain under construction (Figures 3-1a and 3-1b).

Capping and natural recovery performance should be monitored over a broad range of physical, hydrological, and geochemical conditions over time in order to ensure that the cap continues to isolate sediments or that natural recovery processes continue to function (e.g., freshly-deposited sediments remain in place). A key focus is ensuring the physical, chemical, and ecological integrity of the remedy mechanism at the site. This is especially important following high energy disturbances at the site, such as storm events, in which the mechanism of the remedy can be damaged. For example, storm events can expose contaminated sediments that were capped or previously isolated via natural sedimentation.

Remedial Goal Monitoring. Often referred to as "long-term monitoring", remedial goal monitoring provides an assessment of the extent to which the sediment remedy achieves RAOs that are the ultimate goals of sediment management—namely, the reduction of human health and ecological risks (USEPA, 2005b). ***Remedial goal monitoring data is used to answer the question: Is the remedy achieving risk reduction?*** Monitoring components may include direct measurements of risk reduction (e.g., biological chemical concentrations or biological effects) or indirect measurements of risk reduction (e.g., sediment, pore water, or surface water concentration reductions) with time.

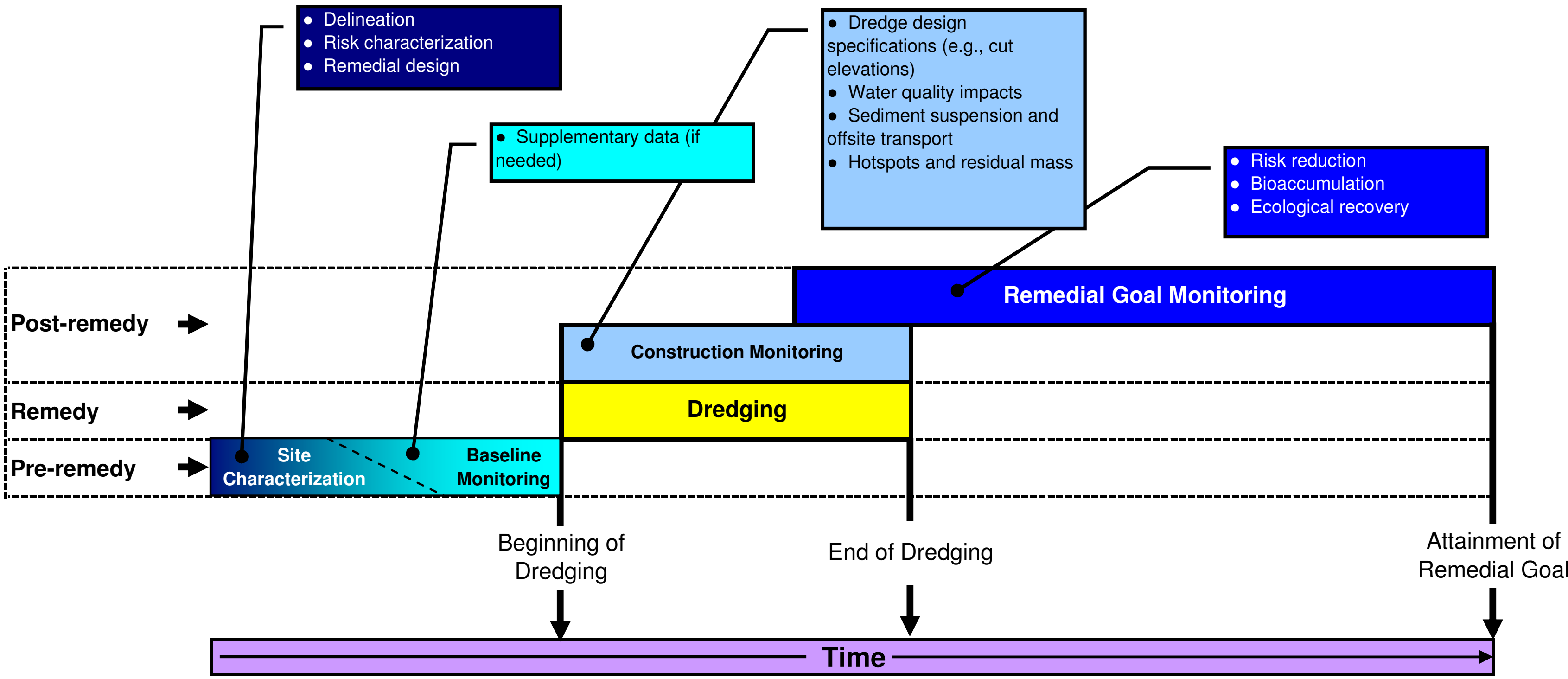

Figure 3.1. Timeline depicting the temporal arrangement of monitoring phases relative to dredging and pre-remedy activities.

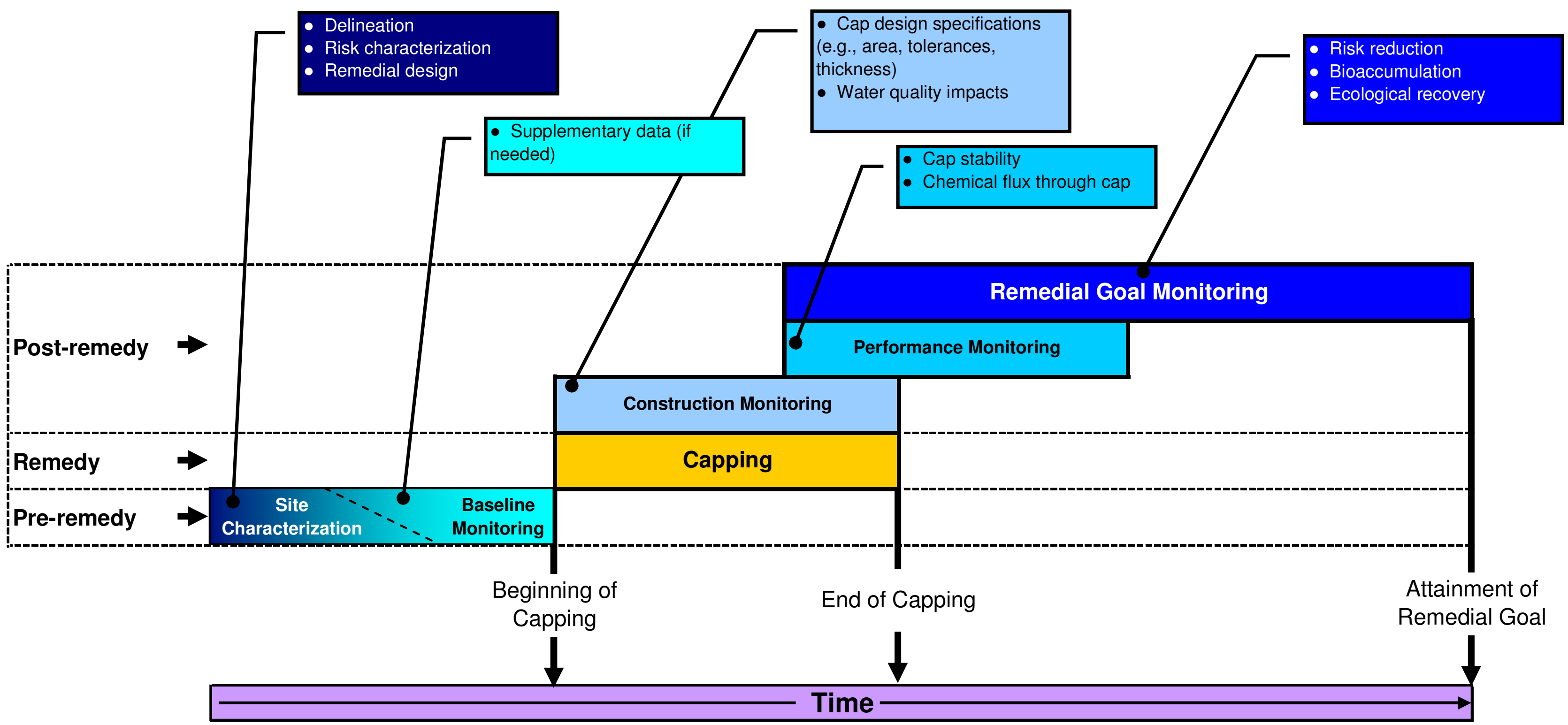

Figure 3.2. Timeline depicting the temporal arrangement of monitoring phases relative to capping and pre-remedy activities.

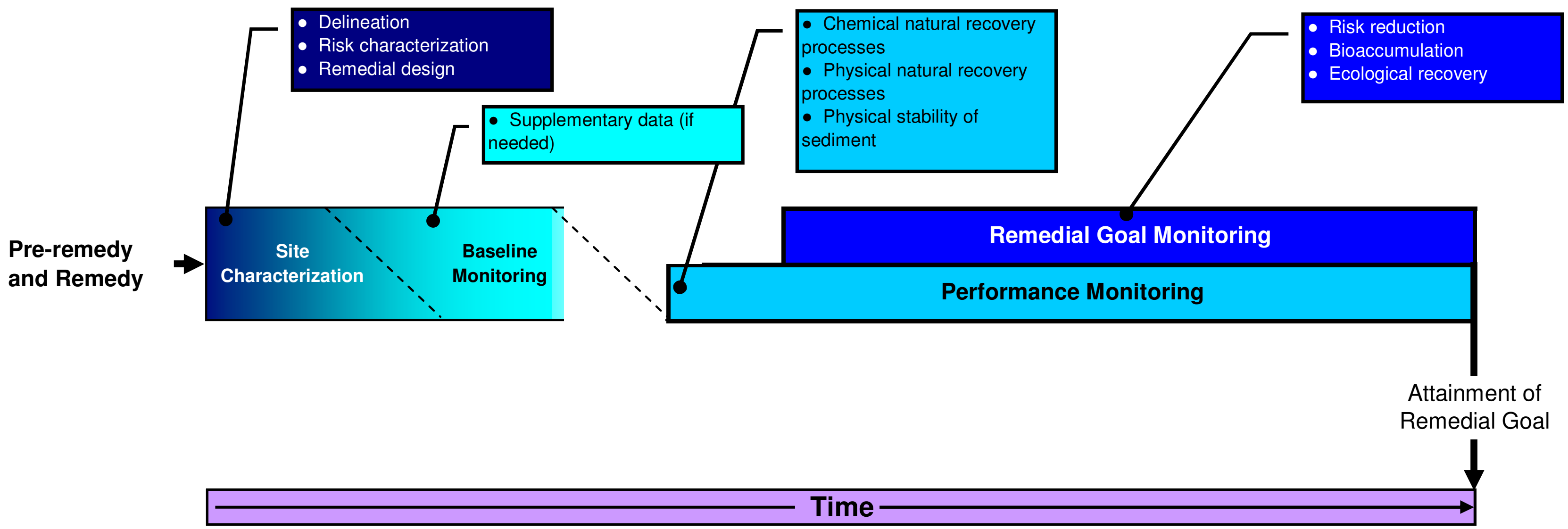

Figure 3.3. Timeline depicting the temporal arrangement of monitoring phases relative to MNR and pre-remedy activities. In contrast to dredging and capping (3.1 and 3.2), MNR monitoring can blend into and overlap with baseline monitoring because there is no specific remedy event (e.g. construction of a cap, completion of dredging, etc.).

The three monitoring categories identified in this document represent a slight modification of categories discussed in other documents, such as state and federal regulatory guidance documents and various site-specific cleanup documents. Monitoring category definitions are often vague, contradictory, and unclear in many documents. There is currently no standardized or regulatory-approved definition of remedial monitoring phases. The monitoring category framework used in this guidance is meant to provide a more straightforward terminology for monitoring phases while maintaining an inclusive conceptual alignment with the monitoring phases identified by other organizations. The alignment of the three monitoring phases discussed in this guidance is compared to monitoring categories identified in USEPA's Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (2005b) and Guidance for Monitoring at Hazardous Waste Sites, Framework for Monitoring Plan Development and Implementation (USEPA, 2004) in Table 3.1.

Table 3.1. Example monitoring questions and objectives, as classified by USEPA (2004, 2005b), compared to the monitoring phases defined in this guidance.

Example Monitoring Questions **Highlight 8-1, Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005b)**	**Monitoring Phase Identified by USEPA (2005b)**	**Monitoring Phase Identified by This Document**
Have the sediment cleanup levels been achieved?	Short-term remedy performance	Remedial Goal Monitoring
Was the cap placed as intended?	Short-term remedy performance	Construction Monitoring
Have the sediment cleanup levels been reached and maintained for at least five years, and thereafter as appropriate?	Long-term remedy performance	Remedial Goal Monitoring
Has the cap withstood significant erosion?	Long-term remedy performance	Performance Monitoring
Do data demonstrate or at least suggest a reduction in fish tissue levels, a decrease in benthic toxicity, or an increase in species diversity or other community indices after five years?	Short-term risk reduction	Remedial Goal Monitoring

Have the remediation goals in fish tissue been reached or has ecological recovery been accomplished?	Long-term risk reduction	Remedial Goal Monitoring

Example Monitoring Objectives **Guidance for Monitoring at Hazardous Waste Sites, Framework for Monitoring Plan Development and Implementation (USEPA, 2004)**	**Monitoring Phase Identified by This Document**
Identification of changes in ambient conditions	Performance Monitoring addresses changes in conditions affecting the cap or natural recovery processes Remedial Goal Monitoring addresses changes in ambient conditions, such as sediment concentrations, if they are directly related to RAOs
Detection of movement of environmental constituents of interest	Performance Monitoring and Remedial Goal Monitoring
Demonstration of compliance with regulatory requirements	All Monitoring Phases
Demonstration of the effectiveness of a particular activity or action	Performance Monitoring examines effectiveness of remedy mechanism Remedial Goal Monitoring examines effectiveness of remedy to reduce risk

3.2 Developing a Monitoring Plan Framework

This section describes the Data Quality Objective process to establish post-remediation monitoring requirements for contaminated sediment sites. By identifying key questions regarding monitoring goals, key monitoring objectives are defined so that the most effective monitoring tools can be selected and implemented. The approach described in this section is based primarily the USEPA's *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (2005b). This framework is also consistent with USEPA's Directive 9355.4-28, *Guidance for Monitoring at Hazardous Waste Sites: Framework for Monitoring Plan Development and Implementation* (2004), as well as the USEPA's 2000b DQO process.

Monitoring data, methods, and endpoints should be related directly to the remediation goals for the site and the performance expectations of the remedy. The following questions should be addressed before developing monitoring plans (USEPA, 2005b):

- What is the purpose of the monitoring?
- Are detection limits adequate to meet the purpose of the monitoring?
- Will other factors, such as local conditions or habitats, influence the monitoring results?
- Are potentially confounding factors well understood?
- How often should monitoring take place and for how long?
- Can the monitoring results be readily placed into electronic databases and shared with others?
- Who is responsible for reviewing the monitoring data?
- What are the methods and triggers for identifying trends in the results?
- What are the most appropriate methods for analyzing the monitoring data (e.g., statistical tests, other quantitative analyses, or qualitative analyses)?
- If statistical analysis is planned, will there be sufficient data to support it?
- Is there agreement on what actions will be taken based on the possible results of the monitoring?
- How will the results be communicated to the public, and who is responsible for this communication?

The ROD typically lists the remediation goals and narrative RAOs that form the basis of the monitoring plan. USEPA (2004) describes a six-step monitoring framework to develop and implement a monitoring plan in a manner consistent with the 2000b USEPA DQO process. These steps are discussed briefly in the following subsections.

3.2.1 Step 1. Identify Monitoring Objectives

A critical first step in developing an effective monitoring plan is to determine specific monitoring objectives by analyzing the remedial action and its intended outcomes. This activity results in the formulation of critical monitoring questions. Identifying and asking the right questions from the start focuses the experimental design and ensures the collection of useful information (USEPA, 2004). Critical monitoring questions will be driven by the specific functions of the remedy. For example, if the function of a cap is to isolate sediments, a critical monitoring question may be "How stable is the cap?" Tables 3.2 to 3.4 at the end of this section identify typical questions related to sediment remedy functions for MNR, capping, and dredging. The tables serve as a guide, and are not necessarily comprehensive of remedy functions or critical monitoring questions, nor are all of these questions necessarily relevant to all sites.

3.2.2 Step 2. Develop Monitoring Plan Hypotheses

Monitoring hypotheses are statements about the relationship between the remedy and its expected outcomes (USEPA, 2004). The monitoring hypothesis may be generally stated as, "Implementing the remedy will achieve the RAOs." A more specific hypothesis depends on the actual remedy design and function. For example, "After five years of MNR, enhanced by a thin-layer cap, PCB levels will achieve RAOs in surface sediments." The monitoring hypothesis also can be stated in the form of a question, such as: "Does implementation of the remedy achieve the RAOs?" or "After five years of MNR, enhanced by a thin-layer cap, do PCB levels achieve RAOs in surface sediments?" Example DQO questions for each monitoring phase for MNR, capping and dredging are shown in Table 3.2, Table 3.3, and Table 3.4, respectively.

3.2.3 Step 3. Formulate Monitoring Decision Rules

Once monitoring hypotheses are stated, the RPM defines decision rules for assessing whether objectives are met. A decision rule is an "if... then..." statement that defines the conditions that would cause the decision maker to continue, stop, or modify the monitoring activity. Decision rules should define the exit strategy. Each decision rule is composed of five elements (USEPA, 2004):

- The parameter of interest
- The expected outcome of the remedial action
- Timeframe for the decision rule
- An action level, upon which a monitoring decision will be based
- Alternative actions and the triggers for the specified actions

3.2.4 Step 4. Design the Monitoring Plan

The fourth step in this process is the design of the monitoring program. Design considerations, guided by the plan hypotheses and decision rules, include:

- Data needs
- Monitoring boundaries (frequency, location, duration)
- Data collection methods
- Data analysis methods

In addition to technical experts and stakeholders, data users (including professionals with statistical and modeling expertise) should be included in this process to ensure adequate monitoring design, including spatial and temporal arrangement of sampling efforts and number of samples or monitoring efforts. Defining the data analysis method during this step is fundamental to a successful monitoring plan design. Guidance on sampling design and statistical analysis can be found in USEPA (2000b, 2000c) and NAVFAC (2003); see Appendix D for more information.

The data produced by monitoring often requires modeling, or geospatial statistics or nonparametric statistics prior to using the results to facilitate decision making (Appendix D). RPMs should be receptive to advanced methods of data analysis; however, it is important to communicate analysis techniques to stakeholders and other data users, and obtain their agreement on proposed methods prior to finalizing the monitoring plan design. The resulting plan should include mechanisms for modifying activities based on new information.

Appendix A provides a brief overview of sediment monitoring tools, methods, and techniques that may be useful to monitoring plan design. Appendix B, available online via the ISRAP, provides a comprehensive list of monitoring tools, their functions, advantages and limitations, and state-of-the-practice with respect to each tool. Case studies providing examples of the usage and validation of the sediment monitoring tools matrices in Appendix B (and the ISRAP) are provided in Appendix C.

3.2.5 Step 5. Monitoring and Data Analysis

The fifth step, guided by the monitoring plan, includes collecting and analyzing data, evaluating analytical results, addressing deviations from DQOs, and communicating findings to stakeholders. Example resources for statistical analysis tools are provided in Appendix D.

3.2.6 Step 6. Establish the Management Decision

In Step 6, monitoring results and uncertainties are evaluated to determine the extent to which RAOs are achieved, and to reach a decision regarding changes in remediation and monitoring. Establishing clearly defined monitoring goals and corresponding exit criteria is central to a well-defined and well-managed monitoring program: RAOs must be translated into success criteria that are able to be evaluated with monitoring data. Success criteria are standards by which to evaluate measurable or otherwise observable aspects of the restored system and thereby indicate the progress of the system toward meeting the project goals (Thom and Wellman, 1997). Success criteria should be as closely linked to the RAOs as possible; the closer the tie, the better the ability to judge progress. From the success criteria, monitoring parameters (i.e., measurement endpoints) can be chosen. Monitoring parameters are the aspects of the system's structure and function that can be measured. These measurement endpoints define the acceptable or optimal range of values for the chosen parameters. Ideally, the parameters are easy to measure and provide direct feedback on performance of a system toward meeting the RAOs.

In many cases, results of remedial goal monitoring can be difficult to interpret in the short-term, and achievement of remedy success only becomes increasingly apparent following a lengthy time period. An **adaptive site management** approach (NRC, 2003; Linkov et al., 2005; USEPA, 2005b) should be used in which effective and time-sensitive decision-making addresses the need to modify the remedial strategy during this time period. Most relevant to MNR and capping remedies, this can include addressing the performance of the remedy itself for the purposes of decision making until remedy goal monitoring is robust.

Taking into account well-defined success criteria in an adaptive site management decision-making framework, the following generic management decisions and contingencies are possible:

1. Remedial goal monitoring data affirm the attainment of RAOs, suggesting that remedy goal monitoring is no longer required. Low-intensity and low-frequency performance monitoring may be required in some cases, such as to verify cap or MNR stability after severe storm events.

2. Performance monitoring data affirm hypotheses regarding effectiveness of the remedy and suggest that success is likely; thus, a continuation of the current monitoring program and remedial strategy is validated.

3. Data are inconclusive and more monitoring or alternate monitoring strategies or tools are required to evaluate remedy goal success or remedy performance.

4. Performance monitoring data affirm hypotheses regarding remedy effectiveness but suggest that success may not be likely; thus, the current monitoring program and remedial strategy may require modification.

5. Remedial goal monitoring data do not affirm the attainment of success (RAOs), suggesting failure of the remedy and that remedial strategy requires modification.

Table 3.2. Example DQO questions to identify monitoring objectives for MNR.

Remedy Function	Monitoring Phase	Example Monitoring Questions
MNR relies on natural aquatic, sedimentary, chemical, and biological processes to contain, destroy, or otherwise reduce the bioavailability of the contaminants in order to protect receptors (NRC, 1997).	Performance Monitoring	Physical conditions of the sediments ▪ Are physical conditions favorable to maintain the physical stability of sediments? ▪ Are sediments stable under normal or high-energy events?
		Conditions associated with biodegradation and/or detoxification ▪ Is there forensic evidence for geochemical, biological, or abiotic chemical transformation or sequestration to less toxic or less bioavailable levels? ▪ Are sediment geochemical conditions favorable to promote or maintain detoxification of chemicals? ▪ Is there evidence of natural recovery based on historical monitoring records? ▪ Is there evidence of natural recovery in surface sediments based on sediment core profiles?
		Rates of biodegradation and/or detoxification ▪ Are chemical concentrations in physical and biological media decreasing at an acceptable rate to achieve RAOs within a reasonable time frame?
	Remedial Goal Monitoring	Ecological recovery ▪ What is the extent of benthic ecological recovery over time? ▪ What is the extent of ecological recovery for higher-trophic species of concern?
		Reduction of risk ▪ Do changes in site conditions increase or diminish risks associated with sediment contaminants? ▪ Is there reduced toxicity or bioaccumulation in organisms? ▪ Are human health risks associated with consumption of fish reduced?

Table 3.3. Example DQO questions to identify monitoring objectives for sediment caps.

Remedy Function	Monitoring Phase	Example Monitoring Questions
Sediment cap functions include: ▪ Isolating contaminated sediments from immediate contact with the aquatic environment ▪ Limiting the potential for vertical chemical dissolved transport ▪ Creating a clean benthic layer; and improving the physical habitat of the sediment surface	Construction Monitoring	Construction risk ▪ Are acute ecological risks (e.g., sediment suspension and transport) during capping placement adequately controlled? ▪ Are acute human health risks (e.g., construction worker safety) adequately controlled?
		Design specifications ▪ Does the cap meet design specifications (e.g., thickness, uniformity, material type/quality)? ▪ Does the cap provide adequate coverage? ▪ Are residual surface sediment concentrations below remedial goals?
	Performance Monitoring	Cap physical integrity ▪ Are there signs of cap erosion and is the extent of erosion within acceptable design parameters? ▪ What is the impact of high-energy events on cap stability?
		Cap chemical integrity ▪ Is the cap adequately preventing chemical migration from the impacted sediments? ▪ Is there the potential for migration to occur? ▪ Are chemical concentrations in surface layers of the cap increasing? If so, can the contaminant source be determined? ▪ Do surface sediment concentrations exceed remedial goals?

Remedy Function	Monitoring Phase	Example Monitoring Questions
		Special performance characteristics ▪ For caps designed with unique physical functions (e.g., a gravel layer to limit or prevent deep benthic burrowing, or an armoring layer), do these functions perform as intended?
	Remedial Goal Monitoring	Ecological recovery ▪ Has the cap surface been colonized by a healthy benthic community? ▪ What is the extent of ecological recovery for higher-trophic species of concern? ▪ What is the extent of benthic ecological recovery over time?
		Reduction of risk ▪ Is there reduced toxicity or bioaccumulation in organisms? ▪ Are human health risks associated with consumption of fish reduced? ▪ Are reductions in risk likely to be compromised due to surface sediment recontamination (background or on-site sources)?

Table 3.4. Example DQO questions to identify monitoring objectives for dredging.

Remedy Function	Monitoring Phase	Example Monitoring Questions
The primary function of dredging is to remove sediment-bound chemicals from the aquatic environment. Additional functions may include: ▪ Improving navigation ▪ Preventing in-place contaminated sediments from acting as a secondary source with potential for off-site transport Dredging also may be combined with capping or MNR to address surface sediment contaminant concentrations and reduce human and ecological risks.	Construction Monitoring	Construction risk ▪ Are acute risks during dredging adequately controlled as regards sediment suspension and off site transport? ▪ Does dredge-induced sediment suspension and release exceed surface water standards established in the ROD? ▪ Are acute construction risks (e.g., worker safety), transportation risks, and human health risks (e.g., construction worker and community exposures) adequately controlled? ▪ Are community heath and safety issues adequately controlled?
		Design specifications ▪ Do dredge cut lines meet design specifications?
		Nuisance issues ▪ Are community nuisance issues adequately controlled?
		Physical impacts ▪ What are the impacts on river hydrodynamics and sediment transport?
		Success in removal of targeted materials ▪ Are dredge residuals a concern? Has dredging adequately achieved surface sediment remedial goals? ▪ Are hot spots adequately addressed? ▪ If applied, does backfilling meet design specifications? If applied, does backfilling adequately achieve remedial goals?

Remedy Function	Monitoring Phase	Example Monitoring Questions
		Reduction of risk ▪ Does dredging followed by MNR, backfilling, or capping achieve meaningful long-term surface sediment contaminant concentration reductions? ▪ Are further reductions in risk facilitated by natural attenuation? ▪ Are reductions in risk likely to be compromised due to surface sediment recontamination (background or on-site sources)? ▪ Is there reduced toxicity or bioaccumulation in organisms? Are human health risks associated with consumption of fish reduced?
		Ecological recovery ▪ Is the sediment surface recolonized with a healthy benthic community after dredging? ▪ What is the extent of benthic ecological recovery over time? ▪ What is the extent of ecological recovery for higher-trophic species? ▪ Are human health risks associated with consumption of fish reduced? ▪ Are contaminant concentrations in benthic or higher trophic organisms reduced and to they meet RAOs?
	Remedial Goal Monitoring	Reduction of risk ▪ Does dredging followed by MNR, backfilling, or capping achieve meaningful long-term surface sediment contaminant concentration reductions? ▪ Are further reductions in risk facilitated by natural attenuation? ▪ Are reductions in risk likely to be compromised due to surface sediment recontamination (background or on-site sources)? ▪ Is there reduced toxicity or bioaccumulation in organisms? ▪ Are human health risks associated with consumption of fish reduced?

Remedy Function	Monitoring Phase	Example Monitoring Questions
	Remedial Goal Monitoring	Ecological recovery ▪ Is the sediment surface recolonized with a healthy benthic community after dredging? ▪ What is the extent of benthic ecological recovery over time? ▪ What is the extent of ecological recovery for higher-trophic species? ▪ Are human health risks associated with consumption of fish reduced? ▪ Are contaminant concentrations in benthic or higher trophic organisms reduced and do they meet RAOs?

4 Remedy-Specific Monitoring Approaches

***Content:** This section discusses the monitoring approaches most applicable to MNR, capping, dredging, and remedial strategies that use more than one remedy. Examples include discussions of performance, construction, and remedial goal monitoring where relevant. Each discussion considers the first four steps of the six-step process defined in Section 3. Appendix C provides example case studies that summarize monitoring approaches for two sites: Bremerton (dredging, capping, and MNR) and Eagle Wyckoff (capping and MNR).*

4.1 Monitored Natural Recovery Monitoring

The primary recovery processes for MNR generally focus on a consistent reduction in surface sediment contaminant concentrations over time, with a commensurate reduction in mobility, exposure, and risk. For MNR to be successful, these reductions must occur within a reasonable time frame that is usually measured in decades from the date of the original releases of contaminants to the water body. Processes most likely to contribute to natural recovery include deposition of clean sediment, with associated burial and isolation of contaminated sediment, dilution of surface sediments due to progressive sediment transport and mixing processes, contaminant transformation and weathering to less toxic forms, reduction in bioavailability and mobility, and dispersion and offsite transport (USEPA 2005b; Magar and Wenning, 2006). Performance monitoring in support of MNR focuses on verifying the presence and rates of natural recovery in the surface sediment (performance of MNR conditions and processes). Remedial goal monitoring generally focuses on successful achievement of RAOs. Example monitoring approaches are provided in Tables 4.1 and 4.2.

Monitoring for natural recovery may involve chemical measurements in sediment, pore water, surface water, and/or biota. Chemical measurement primarily focuses on reduced contaminant bioavailability in surface sediments (e.g., 0-15 cm below the sediment-water interface), and corresponding reductions in biological receptors over time. Contributors to reduced bioavailability include sedimentation and contaminant burial; chemical sorption, precipitation, and sequestration; and chemical or biological transformation/degradation processes. Monitoring to quantify surface sediment deposition and contaminant burial can be achieved by sediment coring to vertically profile chemical concentrations, or monitoring surface sediment grab samples over time. Vertical contaminant profiling often is combined with geochronological age dating using radiological isotopes such as cesium 137 (^{137}Cs) and lead 210 (^{210}Pb). Chemical concentrations in sediment pore water can contribute to better estimates of chemical bioavailability, because concentrations in pore water more accurately reflect bioavailability than whole sediment concentrations (USEPA 2005c; USEPA 2005d). Pore water can be measured using peepers, vacuum samplers, or manipulation of sediment samples (e.g., centrifugation). Chemical weathering, including precipitation, transformation, and partitioning, can be measured using a variety of chemical forensic techniques that provide information about chemical speciation and transformation processes. Biology can be measured by sampling indigenous communities, or by deploying caged organisms and correlating results with changes in ecological or human health risks with time.

Monitoring associated with MNR focuses on trends associated with physical, biological, and chemical characteristics of the natural environment. Depending on the quality of trend data, MNR remedies may require more intensive monitoring early in the recovery period, which may be relaxed once predicted recovery rates are demonstrated.

Table 4.1. Performance monitoring for MNR.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
MONITORED NATURAL RECOVERY: PERFORMANCE MONITORING	The objectives of performance monitoring for MNR include: ▪ Establish baseline conditions. ▪ Determine whether natural processes adequately reduce biological impacts of chemicals in sediments. ▪ Evaluate physical, chemical, and biological processes that contribute to ecological recovery, and evaluate recovery rates associated with those processes. ▪ The focus of MNR is primarily on chemical transport pathways and measuring the extent to which natural processes lead to short- and long-term risk reduction. Natural processes that reduce surface sediment contaminant concentrations include sedimentation and contaminant burial, surface sediment dilution via mixing with clean sediment, chemical transformation, chemical sorption, and sequestration.	Have historical depositional processes led to reduced surface sediment chemical concentrations with time? Have baseline surface sediment chemical concentrations reached acceptable risk-based concentrations? Are surface sediment chemical concentrations expected to reach acceptable risk-based concentrations within a reasonable time frame? Is sediment reasonably stable and expected to withstand normal- and high-energy current velocities? Do chemical or biological conditions reduce chemical mobility or toxicity? Are conditions geochemically stable such that chemicals are not released due to changing or unforeseen conditions? Is the sediment bed sufficiently stable to withstand high energy hydrodynamic events and thus prevent re-exposure of sequestered contaminants?	Decision rules for monitoring performance of MNR are usually site-specific according to site-specific remedial objectives that stipulate MNR feasibility. Decision rules should specify the appropriate conditions conducive to MNR. Conditions not conducive for MNR will likely require more active remediation. Decision rules may include, for example, responses to: ▪ Events that disrupt sediment (e.g., storms or flood stages of a specified recurrence interval or magnitude). ▪ Increasing chemical concentration trends (or trends that decrease at a slower rate than expected) in physical (sediment) or biological media.	Chemical and physical analyses of the sediment, sediment porewater, and water column to assess aqueous chemical exposures. Sediment stability measurements (e.g., in situ or ex situ sediment flumes) to measure sediment cohesiveness and critical shear strength, to predict the probability of sediment erosion. Bathymetric surveys to characterize baseline and long-term sediment and hydrodynamic conditions, particularly following high-energy events (e.g., storms, high winds, or ice scour). Sediment cores to characterize vertical contaminant profiles and changes in surface sediment concentrations with time. Geochronological age dating to quantify sedimentation rates. Chemical forensics to understand risks of exposure and to characterize relevant chemical transformation and sequestration processes. Laboratory biological and chemical experiments to characterize relevant biological and chemical transformation processes.

Table 4.2. Remedial goal monitoring approach for MNR.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
MONITORED NATURAL RECOVERY: REMEDIAL GOAL MONITORING	The key objective of remedial goal monitoring to assess MNR effectiveness is to determine whether natural processes are operating at rates that are expected to: Reduce chemical concentrations in affected media (e.g., sediment or biota) to levels associated with acceptable risk. ▪ Decrease the concentrations of bioavailable/toxic chemical forms within a reasonable time frame. ▪ Provide multiple lines of evidence to address these objectives and reduce uncertainty.	Are surface sediment chemical concentrations decreasing at acceptable and predicted rates? Are RAOs achieved within a reasonable (and predicted) time frame? Are ecological recovery rates likely to lag behind changes in surface sediment concentrations?	A decision rule for MNR may consider appropriate responses if measured long-term recovery rates are inconsistent with predicted recovery rates. Such actions may include additional monitoring and confirmation, and implementation or prolonging of institutional controls. If, following further characterization, measured recover rates do not meet RAOs, additional remediation may be evaluated, such as physical acceleration of MNR recovery (e.g., application of a thin-layer cap), or more aggressive remedial actions (e.g., isolation capping or dredging). Responses should begin with additional monitoring to evaluate trends and short-term ecological exposures and risk, and the extent of chemical releases and exposures associated with the disturbance or measured condition. Additional responses such as a change in remedy implementation would require re-evaluation of the CSM and MNR trends. The monitoring plan should accommodate the relatively rapid turnaround times required to effectively monitor disruptive events.	Surface sediment chemical analyses to assess interim remedial goals related to surface sediment concentrations. Pore water chemical analyses (obtained via peepers, suction samplers, or manipulation (e.g., centrifugation)) to assess chemical bioavailability. In situ biological monitoring or deployment of caged fish or clams followed by monitoring of growth and/or survival and tissue concentrations to assess short- and long-term goals related to human health and ecological risks.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
MONITORED NATURAL RECOVERY: REMEDIAL GOAL MONITORING	The key objective of remedial goal monitoring to assess MNR effectiveness is to determine whether natural processes are operating at rates that are expected to: ▪ Reduce chemical concentrations in affected media (e.g., biota) to levels associated with acceptable risk. ▪ Decrease the concentrations of bioavailable/toxic chemical forms within a reasonable time frame. ▪ Provide multiple lines of evidence to address these objectives and reduce uncertainty.	Are chemical concentrations in biological media decreasing at acceptable and predicted rates?	Example decision rules for effectiveness of MNR are based on expected rates of ecological recovery, reduction of human and ecological risks, or reductions in the bioaccumulation of chemicals in aquatic biota.	Habitat monitoring to assess ecological recovery. Fish and macroinvertebrate community assessment to evaluate ecological recovery. Fish tissue monitoring to evaluate risks to human health. Aquatic organism tissue monitoring to evaluate ecological risk. Monitoring of higher-trophic biological receptors (e.g., avian community structure) to evaluate ecological recovery.

4.2 Cap Monitoring

Capping remedies achieve success through isolation of contaminated sediment and creation of a clean sediment surface, which promotes ecological recovery and reduces the risk of human and ecological exposures to surface sediment contaminants. The primary recovery process for capping is the creation of a clean sediment surface, and the elimination of complete exposure pathways to the underlying contaminated sediment. Example monitoring approaches are provided in Tables 4.3 through 4.5.

Thin-layer capping (e.g., caps less than 12 inches thick) and reactive caps are remedial strategies that partly employ the isolation mechanisms of traditional caps, but rely heavily on natural recovery processes that reduce chemical availability. Because natural recovery is an explicit remedial mechanism in thin-layer and reactive capping, these remedies should be viewed as multi-remedy approaches; thus, monitoring concerns of both MNR (Tables 4.1 and 4.2) and capping (Tables 4.3 through 4.5) should be considered.

The timing and frequency of monitoring is site specific. More extensive monitoring to assess cap performance should be triggered by disruptive events such as storms, ice scour, flood flow stages, and earthquakes in areas where slope failure is a risk. Additional monitoring also may be warranted for frequent, low magnitude physical disruptions, such as tidal and wave pumping or boat propeller wash. Plans should address the fact that seasonal events (e.g., ice formation, closure of navigation structures) can affect the ability to monitor and maintain caps. Monitoring plans should specify actions to be taken if cap functions are not achieved. For example, if monitoring shows that the cap is not as stable as anticipated, eroded material can be replaced with more erosion-resistant cap material. Similarly, if monitoring demonstrates that bottom-dwelling organisms are penetrating the cap and causing unacceptable chemical releases, additional cap material may be called for.

Table 4.3. Construction monitoring approach for capping.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: CONSTRUCTION MONITORING	Key objectives of construction monitoring for capping include: ▪ Determine whether the cap adheres to design specifications (e.g., cap thickness tolerances, material type and aerial extent of placement). ▪ Monitor the extent of chemical releases that may occur during cap placement.	Does the cap material meet design specifications with respect to material type and quality?	Decision rules for capping construction monitoring usually are based on requirements established in detailed design specifications. Decision rules may be required to ensure the application of suitable cap material, such that the cap material meets design specifications. A decision rule would identify an appropriate response if the cap material must be modified, or if the specified material can no longer be obtained.	Tools employed prior to capping to determine the suitability of the cap material for supporting ecological recovery may include: ▪ Chemical analyses of cap material to meet chemical specifications for site use. ▪ Physical analyses of cap material for grain size, porosity, organic carbon content, and pH to assess physical habitat suitability. ▪ Aquatic toxicity or biological testing of cap material to assess toxicological effects associated with cap itself.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: CONSTRUCTION MONITORING	Key objectives of construction monitoring for capping include: ▪ Determining whether the cap adheres to design specifications. ▪ Monitoring the extent of chemical releases that may occur during cap placement.	Does the cap meet design application specifications with respect to cap thickness and uniformity?	Decision rules for capping construction monitoring are usually based on requirements established in detailed design specifications. Decision rules are required under circumstances where cap design specifications are not met. Under these circumstances, decision rules are required to modify construction practices to achieve design specifications. The decision rule would describe the appropriate response if the cap is not constructed properly, or if site-specific conditions establish that the cap cannot meet the design specifications due to physical limitations, such as water depth, slope, or placement technique.	During construction, monitoring can be used to determine whether cap placement meets design specifications or whether design or construction modifications are required to address field constraints. Tools for monitoring whether the cap meets design specifications include: ▪ Mass balance/accounting to compare the amount of cap material introduced to the site to the theoretical amount required to achieve the desired thickness. ▪ Acoustic sub-bottom profiling for detecting extent, thickness, and uniformity of the cap. ▪ Bathymetric surveys (before and after placement) to detect cap extent and thickness. ▪ Sediment profile photography to visualize extent, thickness, and uniformity of cap and to establish baseline biological conditions. ▪ Side-scan sonar to evaluate characteristics of the new sediment bed surface. ▪ Sediment coring to quantify cap thicknesses in different areas and to confirm bathymetric survey comparisons before and after cap placement.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: CONSTRUCTION MONITORING	Key objectives of construction monitoring for capping include: ▪ Determining whether the cap adheres to design specifications. ▪ Monitoring the extent of chemical releases that may occur during cap placement.	Are acute risks due to sediment resuspension during capping adequately controlled or does cap placement result in unacceptable sediment suspension and off site transport? Are acute human health risks (e.g., construction worker safety) adequately controlled?	Decision rules for capping construction monitoring are usually based on requirements established in detailed design specifications. Decision rules are required under circumstances where acute construction risks are elevated and cap placement poses risks to sensitive species or protected receptors. Decision rules are used to modify construction practices to reduce risks, identify and obtain a suitable alternative practices that modify cap construction practices to maintain protection of the environment. Examples may be to modify cap placement rates or methods to reduce turbidity and contaminated sediment suspension during construction. That is, if turbidity exceeds levels determined protective of wildlife, alternative best-management practices may be employed to reduce turbidity during capping. (It should be noted that cap construction should pose little acute risk of contaminated sediment resuspension (Lyons et al 2006); ecological risks can be controlled by capping within fish windows, and by employing best management practices that minimize sediment suspension potential.)	Resuspension and downstream deposition of sediment during capping may be of concern at some sites, though at many sites capping resuspension is of relatively minor concern and does not require monitoring (Lyons et al., 2006). Concerns may include acute exposures to suspended chemicals, water quality impacts, and deposition of impacted sediments at the margins of the cap. Concerns may also include water quality impact associated with the turbidity generated from the cap material. Monitoring tool examples include: ▪ Chemical analysis of sediment collected in sediment traps to assess sediment near- or far-field deposition during capping. ▪ Continuous or discrete suspended sediment monitoring to assess impacts to turbidity. ▪ Analysis of tissue residues in caged organism (bivalves or fish) deployed in situ to assess exposure to chemicals.

Table 4.4. Performance monitoring approach for capping.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: PERFORMANCE MONITORING	The primary objective of performance monitoring for capping includes: ▪ Evaluating the isolation of chemicals in impacted sediments below the cap. ▪ Evaluating cap stability. ▪ Evaluating surface sediment recontamination potential.	Is the cap stable? Is there a reasonable potential for chemical migration through the cap, resulting in unacceptable exposures to benthic and aquatic organisms? Is there evidence for surface recontamination of the sediment cap? If surficial sediment recontamination occurs, is the contamination attributable to on-site or off-site sources? Is additional source control required, or are sources due to releases not controlled by the site?	Decision rules are required for situations where cap integrity is not maintained under normal or high-energy current velocities. Decision rules may include additional monitoring, redefining predicted current velocities, cap repair or modification, or increased armoring. The ability to detect and respond quickly to a loss of cap material and armoring should be considered when evaluating a capping alternative.	Cap performance relies on the isolation of impacted sediments. Cap performance monitoring needs for assessing cap performance may include: ▪ Acoustic sub-bottom profiling to assess cap thickness and stability over time. ▪ Bathymetric surveys to detect changes in cap thickness and stability over time. ▪ Sediment coring to monitor changes in cap depth and topography with time. ▪ Visual observation using divers, photography, or videography to qualitatively monitor cap structure with time. ▪ Side-scan sonar to detect changes in cap thickness and stability over time. ▪ Sediment sampling to assess surface sediment chemistry over time.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: PERFORMANCE MONITORING	The primary objective of performance monitoring for capping includes: ▪ Evaluating the isolation of chemicals in impacted sediments below the cap. ▪ Evaluating the stability of the cap. ▪ Evaluating the potential for surface sediment recontamination (i.e., contamination of the cap surface).	Is there a reasonable potential for chemical migration from impacted sediments due to porewater advection through the cap? Is the cap reasonably stable under normal and high-energy events (e.g., 100-year storm or wind-wave events)? Is the cap surface recontaminated over time?	Decision rules also are required for situations where chemical migration threatens to break through a cap or where external sources threaten to recontaminate a cap. Decision rules may include additional monitoring, redefining cap thicknesses, or augmenting caps with sorbent materials to sequester chemicals within the cap. As much as possible, these considerations should be made during the original cap design rather than in response to long-term monitoring. At most capped sites, decision rules will focus on cap stability and surface sediment recontamination potential. Decision rules are also required to respond to high-energy events that result in adverse cap disturbance (namely, cap scour and redistribution). Decision rules should begin with monitoring to evaluate the extent and impact of the scour event followed by an engineered approach to repair the cap, as appropriate. Decision rules are needed to respond to recontamination of the cap surface, particularly if recontamination suggests inadequate source control. The decision rule would likely begin with additional monitoring, source assessment and identification, and an appropriate engineered response.	Cap performance also relies on the isolation of impacted sediments from ground water (i.e., preventing chemical flux through the cap). Chemical monitoring approaches for assessing cap performance include these example tools: ▪ Chemical analyses of the sediment cap surface and cap pore water. ▪ Surface sediment monitoring to survey surface sediment chemical concentrations. ▪ Evaluating the potential for contaminant migration under advective or diffusive forces, if applicable. ▪ Conductivity (for estuarine sites) or thermal gradient monitoring (for freshwater sites) within the cap for evidence of porewater upwelling into the cap. ▪ Note: porewater analyses are very challenging. Researchers continue to pursue methods to collect and measure recalcitrant contaminants (e.g., metals, hydrophobic chemicals) in sediment porewater.

Table 4.5. Remedial goal monitoring approach for capping.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: REMEDIAL GOAL MONITORING	Key monitoring objectives for remedial goal monitoring to assess capping effectiveness includes: ▪ Assessing chemical risk reductions to wildlife and humans. ▪ Addressing the reduced bioaccumulation potential of chemicals. ▪ Monitoring the ecological recovery of the site.	Is the cap surface recolonized with a healthy benthic community? Is there risk to human consumers of aquatic biota due to bioaccumulation of chemicals, and if so are those risks related to site contaminants? Is the cap surface contaminated with time? What is the extent of ecological recovery for higher-trophic species of concern?	Example decision rules for effectiveness of capping are based on expected rates of ecological recovery, reduction in human and ecological risks, or reductions in the bioaccumulation of chemicals in aquatic biota. Analytical results from chemical monitoring can be compared to remediation goals protective of human health and ecological risks and therefore provide decision rules to address remedial goal monitoring needs. Generally, decision rules are not needed if ecological recovery (e.g., cap colonization) is slower than expected, though in some cases actions may be taken by seeding or planting species to accelerate recovery.	Remedial goal monitoring programs consist of multiple applications of monitoring tools over a period of months-years. Example tools may include: ▪ Surface sediment chemical monitoring after capping to assess long-term attainment of RAOs related to sediment concentrations. ▪ Surface sediment pore water analyses to assess chemical bioavailability and ground water flux, particularly for mobile chemicals (e.g., metals) and sites with groundwater upwelling potential. ▪ In situ biological monitoring of caged deployments or native fish species to assess attainment of RAOs related to human health and ecological risks. ▪ Biological surveys (e.g., grab samples, video surveys, SPI surveys) to assess ecological recovery.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
IN SITU CAPPING: REMEDIAL GOAL MONITORING	Key monitoring objectives for remedial goal monitoring to assess capping effectiveness includes: ▪ Assessing chemical risk reductions to wildlife and humans. ▪ Addressing the reduced bioaccumulation potential of chemicals. ▪ Monitoring the ecological recovery of the site.	Is the cap surface colonized with a healthy benthic community? Is there risk to human consumers of aquatic biota due to bioaccumulation of chemicals, and if so are those risks related to site contaminants? Is the cap surface contaminated with time? What is the extent of ecological recovery for higher-trophic species of concern?	Long-term monitoring decision rules based on less distinct and highly variable endpoints such as ecological recovery create unique challenges. In cases where monitoring results reveal insufficient ecological recovery, additional monitoring is likely required to identify the source of contaminants and ecological stressors. The first task would be to determine whether the limited recovery is due to cap performance or to an external, uncontrolled source. If attributed to cap performance, the cap may require redesign and additional construction.	Remedial goal monitoring programs consist of multiple applications of monitoring tools over a period of months-years. Example tools may include: ▪ Benthic community structure analyses to assess benthic ecological recovery. ▪ Long-term monitoring of higher trophic community structures (e.g., piscivorous avian species) to evaluate ecological recovery. ▪ Long-term fish sampling and community assessment to evaluate ecological recovery and risks to human health.

4.3 Dredge Monitoring

The primary function of environmental dredging is to remove sediment-bound chemicals from the aquatic environment. Additional functions may be to improve navigation and prevent in-place contaminated sediments from acting as a secondary source with potential for off-site transport. Example monitoring approaches are provided in Tables 4.6 through 4.7.

A dredging monitoring plan should include data collection to test the effectiveness of engineering controls such as silt curtains, dredge operation and throughput, and other measures used to control sediment resuspension or sediment or contaminant transport. Generally, sampling may include dissolved and particulate-bound compounds, though it may be appropriate to use a tiered approach that triggers analysis of dissolved compounds if threshold criteria are exceeded for total compounds or suspended solids.

Dredging almost universally must be combined with MNR, backfilling, or capping to achieve surface sediment concentration goals and long-term ecological recovery. Dredging alone is effective at mass removal but typically is ineffective at achieving low-concentration surface sediment concentration goals due to surface sediment mixing, resuspension and deposition, sloughing during dredging, and other physical processes that result in undredged and dredge-generated residuals (NRC 2007; Bridges et al. 2008). While natural deposition can facilitate long-term surface sediment recovery, if rates are too slow, dredging may be followed by backfilling to dilute residual contaminated surface sediments, or capping to isolate sediments and create a clean sediment surface. Monitoring may include components of MNR (Tables 4.1 and 4.2) and capping (Tables 4.3 through 4.5) to monitor post-dredging surface sediment recovery.

Remedial goal monitoring may include sediment toxicity testing, benthic community surveys, and biota sampling and analysis. The sensitivity of biological endpoints to habitat variables necessitates consideration of confounding factors. Monitoring ecological recovery and reduction of risk is a significant long-term commitment, because the rate of the expected response to dredging may be measured in years or decades.

Table 4.6. Construction monitoring approach for dredging.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
DREDGING: CONSTRUCTION MONITORING	The primary function of dredging is mass removal, while the primary function of sediment remediation typically is reduction of surface sediment contaminant concentrations. Key objectives of construction monitoring for dredging includes: ▪ Monitoring dredging performance to determine the extent to which dredge design specifications are met. ▪ Characterizing adverse conditions associated with dredging to minimize short-term ecological and human health impacts. Adverse conditions associated with dredging include impacts to water quality (chemical and physical), offsite transport and deposition of suspended sediment, and atmospheric emission of volatile organic compounds (VOCs). ▪ Evaluating supplemental activities (e.g., backfilling or capping) to ensure they too meet design specifications.	Do dredge cut lines meet design specifications? Do surface sediment concentration goals meet design specifications? ▪ Are dredging residuals a concern? ▪ Do hot spots remain present?	Decision rules are used to achieve target dredge cut elevations or target surface sediment concentrations. For sites where target surface sediment concentrations cannot be achieved via dredging, backfill with clean material may be employed to achieve those concentrations. Typically, repeated dredging is limited to a handful of attempts to achieve low target concentrations, with the understanding that dredging alone may not be able to achieve RAOs. Decision rules are required for conditions if dredge cut elevations are not met or surface sediment concentrations remain above target levels after initial or repeated dredge cuts. Decision rules may include reducing productivity by repeated dredging to achieve target cut lines. Repeated dredging also may be used to achieve surface sediment concentrations, but often is confounded by the difficulty of dredging to low target contaminant concentrations. Hence, a decision rule may include backfilling with a dilution cap or isolation capping if dredging alone cannot achieve surface sediment remedial goals.	Components that support monitoring for compliance with design specifications include: ▪ Dredger Geographic Information Systems (GIS) and geophysical computer tracking results. ▪ Bathymetric surveys to assess attainment of dredge-cut design specifications (multi-beam bathymetry provides much greater accuracy and precision than single-beam). ▪ Ex situ throughput volumes to assess if mass removal meets expectations. ▪ Side-scan sonar of surface characteristics of sediment and bottom profile, in order to assess whether mass removal meets design specifications. ▪ Surface sediment sampling to determine whether dredging meets design specifications for residual surface sediment chemical concentrations.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
DREDGING: CONSTRUCTION MONITORING	The primary function of dredging is mass removal, while the primary function of sediment remediation typically is reduction of surface sediment contaminant concentrations. Key objectives of construction monitoring for dredging includes: ▪ Monitoring dredging performance to determine the extent to which dredge design specifications are met. ▪ Characterizing adverse conditions associated with dredging to minimize short-term ecological and human health impacts. Adverse conditions associated with dredging include impacts to water quality (chemical and physical), offsite transport and deposition of suspended sediment, and atmospheric emission of volatile organic compounds (VOCs). ▪ Evaluating supplemental activities (e.g., backfilling or capping) to ensure they too meet design specifications.	Are acute risks during dredging adequately controlled (i.e., does cap placement result in sediment suspension and off site transport)? Are acute construction risks (e.g., construction worker safety), transportation risks, and human health risks (e.g., construction worker and community exposure to chemicals) adequately controlled?	Decision rules are required for conditions in which sediment resuspension exceeds target levels or construction practices are not adequately protective of workers or the community. Decision rules may include modifying dredging practices or reducing productivity to control sediment suspension during dredging, or halting dredging until a resolution is obtained.	Components associated with monitoring for short-term adverse effects of dredge construction include: ▪ Surface water turbidity or optical back scatter (OBS) surveys to monitor off-site transport. ▪ Surface water sampling and chemical analyses to evaluate downstream contaminant transport. ▪ Caged fish or clam deployments to assess acute effects of dredging. ▪ Sediment settlement traps to evaluate downstream deposition during dredging. ▪ Effluent quality monitoring after sediment dewatering and/or treatment. ▪ Air monitoring at the dredge, transport, on-site disposal, and treatment sites if volatilization potential is significant. ▪ On-site disposal monitoring of dredged sediment or treatment residuals.

Table 4.7. Remedial goal monitoring approach for dredging.

	Step 1: Identify Monitoring Objectives	Step 2: Develop Monitoring Plan Hypotheses (example questions)	Step 3: Formulate Monitoring Decision Rules	Step 4: Design the Monitoring Plan (example monitoring components)
DREDGING: REMEDIAL GOAL MONITORING	Key monitoring objectives for long-term monitoring of dredging effectiveness may include assessment of chemical risks to wildlife and humans, assessment of chemical bioaccumulation potential, and monitoring ecological recovery.	Is the site colonized with a healthy benthic community over time? Is there risk to human consumers of aquatic biota due to biomagnification of chemicals? What is the extent of ecological recovery for higher-trophic species of concern? Are sediments recontaminated due to uncontrolled sources or off-site sources?	Decision rules for long-term dredging effectiveness are based on expected rates of ecological recovery, reduction of human and ecological risks, or reduced chemical bioaccumulation in aquatic biota. Analytical results from chemical monitoring can be compared to remediation goals protective of human health and ecological risks as a basis for decision rules to assess short-term interim monitoring. Decision rules are required to address circumstances in which ecological recovery end points or human health risk reduction is not achieved within acceptable time frames. Under these circumstances, decision rules may require additional monitoring or characterization to understand existing stressors and whether sources persist. Decision rules also may require further remedial action to address residual environmental stressors.	Sediment sample chemical analysis after capping to assess long-term attainment of interim remedial goals related to sediment concentrations. Sediment pore water chemical analysis using peepers, vacuum samplers, or manipulation (e.g., centrifugation) to assess chemical bioavailability. In situ biological monitoring (i.e., deployment of caged fish or clams followed by monitoring of growth and/or survival and tissue concentrations) to assess human health and ecological risks. Long-term monitoring of higher trophic community structures (e.g., piscivorous avian species) to evaluate ecological recovery. Long-term fish tissue monitoring to evaluate risks to human health and ecology. Long-term aquatic organism tissue monitoring to evaluate ecological risk.

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Appendix A: Overview of Sediment Monitoring Tools

Content: *This appendix discusses general monitoring tool for physical, chemical and biological measurements, while Section 4 describes specific tools pertinent to individual remedies. USEPA (2000a, 2001b, 2003b) guidance also offers detailed information on monitoring techniques. The choice of monitoring tools depends on the requirements of the ROD, the monitoring objectives, the monitoring plan hypotheses, and the decision rules established under the monitoring DQO process. The focus of this appendix is on the field monitoring tool used to collect or directly measure a parameter of interest. Monitoring tools must be coupled with appropriate analytical methods to obtain the specific data of interest.*

A.1 Physical Measurements

Physical testing may include measurements of sediment erosion or deposition, ground water advection, surface water flow, and physical characteristics of the sediment (e.g., particle size distribution (PSD), porosity, organic carbon content), and sediment heterogeneity. Most physical endpoints are relatively straightforward to measure and interpret. USEPA (2005b) identifies the following types of physical data and their uses for sediment:

- **Sediment Geochemical Properties**. Used to model fate and transport, evaluate bioavailability, and characterize habitat.
- **Water Column Physical Measurements** (e.g., turbidity, total suspended solids). Used to monitor resuspension of sediment during dredging and cap placement.
- **Bathymetry Data**. Used to evaluate sediment stability over time, navigable depths, bottom surfaces for remedy design, and post-remediation bottom elevations.
- **Side Scan Sonar Data**. Used to monitor the distribution of sediment types and bedforms, commonly used to evaluate presence of debris or bottom formations.
- **Sediment Settlement Plate Data**. Used to monitor cap consolidation and changes in cap thickness over time.
- **Sediment Profile Camera Data**. Used to monitor changes in thin layering within sediment profiles, sediment grain size, bioturbation and oxidation depth, and presence of gas bubbles.
- **Subbottom Profiler Data**. Used to measure density changes in surface and subsurface sediment bedding layers, surface mixing depths, and presence of gas bubbles.
- **Physical Habitat Data**. Used to identify physical structures or measure conditions (depth, salinity, sediment grain size, etc.) related to benthic habitat quality.

A.2 Chemical Measurements

Chemical measurements involve collecting sediment, pore water, surface water, and biota samples and analyzing those samples for chemical concentrations. Chemical measurements also include water quality variables such as organic carbon content, pH, dissolved oxygen, or hardness. USEPA (2005b) identifies the following sampling tools used in support of chemical measurements:

- **Sediment Grab Samples**. Used to collect samples for measurement of surface sediment chemistry. This generally includes COCs, but can also include ancillary analytes related to chemical conditions (organic carbon content, pH, redox conditions, etc.).
- **Sediment Coring** (e.g., vibracore, gravity piston, or drop tube samplers). Used to obtain a vertical sediment profile of sediment chemistry or to detect chemical movement through a cap.
- **Direct Water Column Measurements**. Used to measure water quality parameters such as temperature, pH, dissolved oxygen, salinity, suspended solids, and turbidity in the water column.
- **Surface Water Samplers**. Used to collect and measure dissolved or total chemical concentrations in surface water.
- **Passive Sampling Devices**. Used to measure dissolved chemicals in water; generally used for low-solubility chemicals where accumulation on passive samplers greatly lowers detection levels.
- **Seepage Meters**. Used to measure ground water advection and aqueous chemical flux through sediment and into the water column.

A.3 Biological Measurements

Biological measurements, such as those summarized by USEPA (2005b) and listed below, may be used to evaluate ecological risks, evaluate restoration effectiveness, and determine bioaccumulation:

- **Benthic Community Analysis**. Used to evaluate benthic community structure (e.g., population size, diversity, presence/absence of taxa).
- **Toxicity Testing**. Used to measure acute or chronic effects (e.g., survival, growth, reproduction) of chemicals on biota.
- **Tissue Sampling**. Used to measure bioaccumulation and assess trophic transfer.
- **Caged Fish/Invertebrate Studies**. Used to monitor changes in uptake of chemicals by biota from the sediment or water column.
- **Sediment Profile Camera Studies**. Used to indirectly measure macroinvertebrate recolonization (e.g., population density of polychaetes may be estimated by counting the number of burrow tubes per linear centimeter along the

sediment-water interface).

- **Sediment Surface Camera Studies**. Used to directly and indirectly measure macroinvertebrate recolonization. For example, epifauna can be counted and identified, while infauna can be estimated based on burrow openings and fecal mounds found at the sediment water interface.

Biological measurements integrate the cumulative effects of all stressors to which biota are exposed. This characteristic can complicate data collection and interpretation, but also can provide direct information on remedial effectiveness. To investigate the biological effects of chemicals in sediment or water, biological measurements should control for confounding factors related to nonchemical stressors, such as habitat quality. For example, the results of toxicity tests and benthic community structure surveys often are compared to concentrations of chemicals in sediment and water, but they also should be interpreted in light of physical characteristics of the media (e.g., grain size, organic carbon content, salinity, ammonia, redox conditions, etc.) and presence of other possible stressors (e.g., hydrologic changes due to urbanization of a watershed, siltation due to agriculture).

Toxicity tests must be tailored to the monitoring need. For example, acute toxicity tests may be appropriate for monitoring short-term impacts of remedial construction practices (e.g., placement of cap, dewatering of dredge sediment); whereas long-term (chronic) sublethal toxicity tests are best employed to assess longer-term impacts and changes affected by a remedy. Measurement of chemical concentrations in biota can provide the best integration of site-specific conditions affecting chemical bioavailability and exposure; however, interpretation is complicated by a number of factors, including inter-individual and inter-species variability in home range, lipid content, sex and age, feeding regime, contaminant excretion rates, and other life history parameters. Particularly at low chemical concentrations, these variables can confound the interpretation of relationships between chemical concentrations in sediment and biota, and can complicate the interpretation of data used to evaluate remedy success and the attainment of remedial goals (USEPA, 2005).

Note: A comprehensive list of examples of monitoring tools and needs can be found at ***"www.ISRAP.org"****. The example tools and needs address a wide spectrum of stakeholder concerns and remedial goals that are not all likely to be relevant for all sites. For example, monitoring programs at most sites would not include addressing risks to near shore avian communities, but examples are included to illustrate the ranges of monitoring tools and needs provided in the Monitoring Tool Matrices. Many of the examples are ecologically-focused or risk-focused. In some cases, little or no ecological monitoring is required, and site-specific monitoring needs and tools strictly focus on chemical concentrations in sediment and water.*

Appendix B: Monitoring Tool Matrices

***Content:** This appendix provides a detailed description of the ISRAP matrix organization and an explanation of each field of the monitoring tool matrices **(www.ISRAP.org)**. Hypothetical examples are given to provide a better understanding of sediment monitoring issues beyond identifying the basic monitoring goals and tools discussed in the previous sections. Ultimately, the matrices can be used to develop sediment monitoring tool comparisons (e.g., ISRAP) for tools used for monitoring for dredging, capping, and monitored natural recovery (MNR), to help remedial project managers (RPMs) focus on key issues associated with site-specific monitoring needs and tools, and to facilitate the design of cost effective and meaningful monitoring plans.*

B.1 Matrix Overview

Though several resources identify general monitoring needs associated with sediment remediation (Apitz et al., 2005; USEPA, 2005b), few provide detailed information on monitoring tools available to address these needs. A compendium of detailed information on monitoring tools is available (USEPA, 2003b), but is not presented in a manner that allows RPMs to readily focus on tools applicable to specific monitoring needs. To date, no formal guidance exists to establish a framework that standardizes monitoring approaches and helps RPMs compare monitoring tools when more than one approach can address a monitoring need.

To bridge the gap between detail-oriented descriptions of monitoring tools and general guidelines that identify monitoring needs, sediment monitoring needs and tools are compiled into remedy-specific matrices for this guidance (Appendix B). The matrices provide a decision-making framework with the following objectives:

- Provide a comprehensive list of monitoring needs.
- Identify monitoring tools associated with each monitoring need.
- Enable a screening-level comparison of monitoring tools when several are available for particular a monitoring need.
- Help RPMs focus on key issues associated with site-specific monitoring needs and tools, to facilitate the design of cost effective, and meaningful monitoring plans.

The matrices build on the first four steps of USEPA's *Monitoring Framework Steps* (USEPA, 2004). By using the matrix to identify monitoring needs and investigate monitoring tools associated with those needs, RPMs can more easily identify monitoring plan objectives and appropriate monitoring tools (Step 1). The matrix also identifies uncertainty associated with individual monitoring tools relative to each monitoring need, a crucial consideration in developing monitoring plan hypotheses (Step 2). Attributes of each monitoring need, such as timing, frequency and formal requirements, and special considerations for assessing monitoring needs specific to remedial approaches are tabulated in the matrices and aid the development of monitoring decision rules (Step 3). Specific tools are identified that aid in design of a monitoring plan (Step 4). The primary fields for each of the matrices (monitored natural recovery, capping, and dredging), for all phases of the monitoring process are arranged in the following hierarchy:

REMEDY

→ **Monitoring Phase**

→ **Monitoring Need** (Title, Description, Timing Frequency)

→ **Monitoring Tool** (Title, Description, Type, Commonality of Tool Use, Special Consideration, For More Information)

→ **Monitoring Design** (Spatial Design Experimental Complexity, Temporal Experimental Design Complexity, Monitoring Tool Logistical Complexity, Difficult in Location Tool in Marketplace, Relative Cost, Level of Expertise Required for Data Interpretation, and Uncertainly in Addressing Monitoring Needs)

The matrices do not include all remedy functions or critical monitoring questions. Conversely, the example tools and needs in the matrices address a wide spectrum of stakeholder concerns and remedial goals that are not likely to be relevant for all (or even most) sites. Examples are included to illustrate the ranges of monitoring tools and needs provided in the Monitoring Tool Matrices. In some cases, little or no ecological monitoring is required, and site-specific monitoring needs and tools strictly focus on chemical concentrations in sediment and water. Ideally, remedial needs should be identified from site-specific remedial action objectives (RAOs) or the record of decision (ROD) prior to using the matrices to investigate the details associated with remedial needs and assist in the identification of appropriate monitoring tools.

B.2 Matrix Arrangement and Description of Matrix Fields

The following sections describe each field of the matrix. Field explanations highlight important issues to consider for cases not explicitly described in the matrix.

Although only three matrices have been developed for this guidance (dredging, capping, and MNR), users can browse information in more than one matrix if more than one remedy is applied or if multi-remedy approaches are used. Multi-remedy approaches include remedies such as thin-layer capping, which uses both capping and MNR, or sites that combine MNR, capping, or dredging.

B.2.1 Monitoring Phase

Within each matrix, monitoring tools are arranged by monitoring needs, which have been divided into three monitoring phases:

- **Construction.** The construction monitoring phase includes monitoring needs for the assessment of adverse conditions associated with the remedial activity, attainment of design criteria, and assessment of construction and operations activities. Assessment of the success of the construction activities in meeting design plans and specifications is also relevant to the construction phase.

Examples

Assessing the lateral extent and thickness of the sediment cap or dredge cut lines and bathymetry of the dredged area. Addressing acute environmental impacts associated with remediation, such as sediment suspension and potential off-site transport.

- **Performance**. The performance monitoring phase includes monitoring needs associated with the primary performance of remedy mechanism itself. Performance monitoring is needed for remedies in which contamination is left in place (capping and MNR). The mechanism for capping is isolation of contamination. The mechanism for MNR is usually isolation of contamination, but can also include chemical transformation, reduction in bioavailability and mobility, and dispersion and offsite transport.

Example

For capping, performance monitoring may focus on measuring cap stability and surface sediment chemical concentrations with time. For MNR, performance monitoring may focus on measuring the stability of freshly-deposited surface layers of sediment and surface sediment chemical concentrations with time.

- **Remedial Goal Monitoring.** This monitoring phase provides a definitive assessment of the remedial objectives that are the ultimate goals of sediment management—namely, the reduction of human health and ecological risks (USEPA, 2005b). Feedback provided by remedial goal monitoring is also useful for adaptive management during sediment remediation (NRC, 2003; Linkov et al., 2005), providing cost-effective information to enable more flexible decision-making during and after construction.

Examples

Remedial goal monitoring of remedial effectiveness includes simple chemical assessments, such as the monitoring of post-remediation surface sediment, pore water, and surface water concentrations. Remedial goal monitoring tools to assess ecological recovery may include population surveys of fish, birds, or macroinvertebrates.

B.2.2 Monitoring Need

Monitoring need identifies the purpose of monitoring and whether it is enforced through regulatory requirements or based on site-specific ecological recovery goals.

B.2.2.1 Title

This field provides a name for each monitoring need.

B.2.2.2 Description

This field includes a more detailed description of the monitoring need. The monitoring need expresses the monitoring objective and considers the explicit expressions of the environmental values to be protected or restored, referred to in an ecological risk assessment context as "assessment endpoints" (Suter et al., 2000). In many cases, monitoring needs are only relevant for a limited amount of time, such as until exit criteria are satisfied. Relevancy of the monitoring need may not be readily apparent in all cases. Examples durations are provided in the need description field of the matrix, however, one should consult the RAOs on the DQO decision rules or adaptive management framework to identify when the monitoring need is no longer relevant for a site. All monitoring activities should be clearly linked to management and/or exit strategies.

B.2.2.3 Timing

Timing of the monitoring need refers to the point in time at which the monitoring need is likely to be present.

> **Example**
>
> In the construction monitoring phase, attainment of cap design specifications is assessed immediately after capping is completed.
>
> Ranges are provided for some monitoring needs with less distinct timing. For example, performance monitoring needs associated with assessing cap stability over time are present weeks to years after capping, as well as after severe storms, floods, or other events that could affect the cap.
>
> The timing of long-term monitoring needs is determined according to the site conceptual model and results of ongoing monitoring. In some cases, monitoring needs and monitoring tools require that monitoring proceed prior to remediation in order to develop sufficient pre-remedial site characterization data with which to measure remedial effectiveness.

B.2.2.4 Frequency

Frequency of the monitoring need refers to the schedule of monitoring data collection. Monitoring frequencies provided in the matrices are generic recommendations; more or less frequent monitoring may be required according to site-specific conditions and remedial goals.

B.2.3 Monitoring Tool

Monitoring tools are the methods by which data are generated to enable decision-making concerning a given monitoring need.

In this document, the term also applies to planning and data analysis. At best, information provided by monitoring tools is an estimate of the values to be protected or restored by remedial action, similar to "measurement endpoints" or "measures of effects" in an ecological risk assessment context (Suter et al., 2000). Monitoring tools identified within the matrix often serve multiple monitoring needs and may be repeated accordingly.

B.2.3.1 Title

This field includes a concise monitoring tool name.

B.2.3.2 Description

This field includes a description of the monitoring tool.

B.2.3.3 Type

This field lists the general category of the monitoring tool.

- **Physical**. Physical tools rely on measurements of physical parameters, such as depth, size, velocity, or force.
- **Chemical.** Chemical tools focus on measuring chemical parameters, such as pH, salinity, or the presence of particular chemicals.
- **Biological.** Biological tools focus on biological measurements, such as censuses of onsite organisms, toxicity, or tissue residues.

B.2.3.4 Commonality of Tool Use

This field includes a description of the commonality of the tool use for the selected monitoring need.

- Very common. Tools almost always used to evaluate the specific need.
- Common. Commonly used to evaluate the specific need.
- Rare. Occasionally used to evaluate the specific need, often providing additional or backup information for another more-commonly applied tool.
- Very rare. Tools are not usually used for the specific need, but may be applicable in special cases.

Commonality ratings are given based on historical tool uses. Many innovative tools are ranked as “Rare” or “Very rare” because their novelty has not afforded the opportunity for widespread use. In some cases, “Rare” or “Very rare” may be the best tools for the situation.

B.2.3.5 Special Considerations

This field lists significant restrictions, caveats, and other important information about the monitoring tool, specifically those that may limit or enhance its application.

B.2.3.6 For More Information

This field provides references to additional information sources about the monitoring tools. Where available, this field includes references to EPA Fact Sheets in the EPA sediment monitoring tools compendium (EPA, 2003b) as well as links to other guidance or information available via the internet.

B.2.4 Monitoring Design

This section provides rankings for seven aspects of monitoring design and characterizes the complexity of the various monitoring approaches.

The monitoring design aspects provide information to enable a screening-level comparison of monitoring tools when several are available for a particular monitoring need. Each monitoring design category is ranked low, medium, or high. Except for Relative Cost, rankings are subjective and include brief justifications. The optimal condition for all seven monitoring design characteristics is "low." However, many rankings are variable according to regulatory interpretation, site-specific conditions, and continued development and refinement of monitoring tools. The decision to select one monitoring tool over another should be made only on further investigation of monitoring tools, site-specific conditions, and specific monitoring needs.

B.2.4.1 Spatial Experimental Design Complexity

This field addresses the complexity regarding the location and number of monitoring points required for successful application of the monitoring tool. Also considered is the level of expertise needed to design a spatial monitoring plan and the complexity of tools needed for spatial sampling plan design, such as geographical or statistical software.

This field is ranked low, medium, or high:

- **Low**. Indicates minimal technical requirements to design an explicit spatial monitoring plan.
- **Medium**. Indicates a complex spatial experimental design may be necessary. The design may need to account for site-specific conditions and characteristics of the tool itself, may be complex, or the tool may require background data and/or specialized expertise to ensure that the sampling plan is cost-effective.
- **High**. Indicates that a complex spatial experimental design is likely required. Complex designs are needed to account for complex and heterogeneous site-specific conditions, and for complex characteristics of the monitoring tool itself. A complex spatial experimental design ranking is likely to require substantial background data and expertise with advanced tools (e.g., modeling or geostatistics) to design a cost-effective spatial sampling plan that meets monitoring needs.

B.2.4.2 Temporal Experimental Design Complexity

This field addresses the complexity regarding decisions on the timing and frequency of monitoring tool use. This category considers the Timing and Frequency associated with the monitoring need, but also addresses time constraints imposed by monitoring tools.

This field is ranked low, medium, or high:

- **Low**. Indicates that the temporal design complexity is simple. Monitoring can be scheduled according to the discretion of project personnel. In addition, the proper timing of the monitoring is readily apparent.
- **Medium**. Indicates that the temporal design complexity is moderate. In many cases, monitoring can be scheduled according to the discretion of project personnel. In addition, the proper timing of the monitoring is usually apparent.
- **High**. Indicates that the temporal design complexity is complicated by possibly more than one day of discrete sampling effort or several days of continuous monitoring. The monitoring schedule may not be at the discretion of project personnel, but may be determined by site conditions or other phenomena, such as monitoring storm events, or biological changes over time. In addition, the proper timing of the monitoring may not be readily apparent, requiring multiple attempts over time to obtain adequate data.

B.2.4.3 Monitoring Tool Logistical Complexity

This field addresses the logistical complexity of monitoring tools, with respect to operation of the tool itself.

Examples

Fragile technical apparati, difficult or sensitive monitoring protocols, experimental techniques that may require method development or validation, and methods that require specialized expertise (e.g., taxonomic identifications, scuba diving).

This field is ranked low, medium, or high:

- **Low**. Indicates that the monitoring tool is simple, rugged, and familiar or routinely applied by monitoring professionals. The monitoring tool is not constrained by special conditions and does not require substantial extra efforts (e.g., method development, extensive preparation efforts, etc.) beyond what is required to conduct monitoring at the site. In cases where logistical complexity is low, minimal planning is required to apply the monitoring tool.
- **Medium**. Indicates that the monitoring tool may be moderately more complex, though reasonably familiar to monitoring professionals. The monitoring tool may be constrained by special conditions and may require some non-routine efforts or preparation. In cases where logistical complexity is medium, a greater planning may be required to apply the monitoring tool effectively.
- **High**. Indicates that the monitoring tool is complex, delicate, and may be unfamiliar to monitoring professionals. The monitoring tool is likely to be constrained by special conditions and may require substantial non-routine efforts, significant preparation, or customization. In cases where monitoring tool logistical complexity is high, a significant amount of planning and effort is likely required to apply the monitoring tool effectively, or it may require specialized vendors with appropriate training and experience.

B.2.4.4 Difficulty in Locating Tool in Marketplace

This field addresses the difficulty of locating a commercial monitoring professional to apply a monitoring tool. It is ranked low, medium, or high:

- **Low**. Indicates that the monitoring tool is widely available from traditional commercial sources that supply sediment monitoring services. In most cases, commercial arrangements with monitoring professionals are not complicated by availability or geographic proximity to the site.
- **Medium**. Indicates that the monitoring tool may not be available from traditional commercial sources. In most cases, this category includes more complex tools that may only be available from a limited number of specialized commercial monitoring sources. These tools can be novel, proprietary, or require a high level of technical expertise that is not yet widely available in the monitoring marketplace. Commercial arrangements with monitoring professionals may be complicated by availability or geographic proximity to the site.
- **High**. Indicates that the monitoring tool is likely unavailable from commercial sources. In most cases, this category includes extremely complex or experimental tools. The tool may only be available from non-commercial sources, such as university, non-profit, or government laboratories. In some cases, it may not be possible to obtain access to the monitoring tool.

B.2.4.5 Relative Cost

The cost of sediment monitoring is difficult to estimate and highly variable, depending on the site, the monitoring plan, and other factors. This field ranks costs for tools that fulfill the same monitoring need. The value of the field is dependent on the cost range of a given set of tools. When monitoring needs are associated with only one tool, the relative cost is ranked “medium.” Tools assigned the same ranking for the same monitoring need are roughly equivalent in cost.

Note: Because rankings are relative, this field cannot be used to compare costs across different monitoring needs.

Example

Multiple short-term and long-term monitoring tools are potentially appropriate for investigating human health risks associated with consumption of fish, including simple chemical methods, laboratory or highly-controlled biological investigations, and field surveys of native fish. Of these approaches, the least expensive are ranked "low." The most expensive are ranked "high."

B.2.4.6 Level of Expertise Required for Data Interpretation

This field addresses the level of expertise required to interpret data and to use the interpreted data to address the monitoring need within a decision framework. This field is ranked low, medium, or high:

- **Low**. Indicates that little specialized expertise is required to interpret and apply monitoring data for decision making. In many cases, data produced are readily applied to decision making and interpretation.
- **Medium**. Indicates that experience may be required to interpret and apply monitoring data for decision making. In some cases, data may not be in a readily usable form for decision making and may require interpretation relative to other studies, modeling, or outside expertise.
- **High**. Indicates that significant specialized expertise is required to interpret and apply monitoring data for decision making. Data may not exist in a readily-usable form for decision making. Interpretation may require comparison with other studies, modeling, or the assistance of specialized expertise. May require specialized vendors.

B.2.4.7 Uncertainty in Addressing Monitoring Need

This field addresses the level of uncertainty associated with using data to satisfy the monitoring need. This aspect of monitoring design is critical to a successful monitoring program.

Uncertainty associated with monitoring can originate from multiple sources. Uncertainty tends to be lower for long-term monitoring than for short-term monitoring due to differences in the temporal representativeness and predictive abilities of long-term monitoring designs. In some cases, monitoring uncertainty is a function of the relationship between the type of data provided by the tool and the information required to definitively assess the monitoring need. Data provided by basic monitoring tools may require extrapolation to link the monitoring results to complex monitoring needs. When applied to simple monitoring needs, the same monitoring tools produce results with greater certainty. In cases where basic and advanced tools are both available, there is a tradeoff between levels of effort and certainty. In some cases, information required for the monitoring need may be unquantifiable.

This field is ranked low, medium, or high:

- **Low**. Indicates high confidence in the ability of the monitoring tool to satisfy monitoring needs. Data produced using the monitoring tool are directly relevant to assessment endpoints associated with the monitoring need and are directly applicable in the decision-making process.

- **Medium**. Indicates moderate confidence in the ability of the monitoring tool to satisfy monitoring needs. Data produced using the monitoring tool are relevant to assessment endpoints associated with the monitoring need, but may require extrapolation or may not be sufficient to address more complex monitoring needs if the monitoring tool is used as a single line of evidence.

- **High**. Indicates low confidence in the ability of the monitoring tool to provide useful information to satisfy monitoring needs. Data produced using the monitoring tool are only partially relevant to assessment endpoints associated with the monitoring need, and may require significant extrapolation for use in decision-making. The monitoring data are likely insufficient to address more complex monitoring needs when the monitoring tool information is used as a single line of evidence. In many cases, monitoring tools with high uncertainty serve as screening tools for refining the monitoring program using more complex monitoring tools with greater certainty.

Appendix C: Case Studies

***Content:** This appendix details two case studies that compare actual sediment remedy monitoring at Bremerton Naval Complex and Wyckoff/Eagle Harbor to the guidance and information provided by the matrices. The case studies were conducted not only to validate and refine the matrices, but also to illustrate the use and interpretation of the matrices using real-world sediment remedy monitoring examples at the two case study sites.*

C.1. Validation and Refinement of the Matrices

Overall, the information and structure of the matrices corresponded well to the real-world monitoring plans reviewed in the case studies. The case studies provided a validation of the matrices, and in some instances, prompted minor refinements to detailed information. Key conclusions of the validation and refinement process include:

- **The matrices provide a comprehensive and accurate overview of possible sediment remedy monitoring needs and tools.** Greater than 90% of the monitoring needs and monitoring tools present or considered at these sites were presented and discussed in the matrices. Based on the case studies, the matrices present users with most of the monitoring needs likely to be encountered during monitoring and provide most of the monitoring tools available for addressing monitoring needs.

- **The organization and design of the matrices facilitate the retrieval of information on sediment monitoring planning.** All monitoring needs and tools of the case study monitoring plans could be organized and categorized according to organizational hierarchy of the matrices (classification according to remedy, then remedy need, etc.). This suggests that the organization of the matrices was able to place the wide variety of monitoring needs and tools into logical groups and categories. The organizational ability of the matrices is important because a good organizational hierarchy facilitates a user's understanding of sediment remedy monitoring and enables them to efficiently navigate the matrices in order to identify the most relevant need and tool information.

- **Monitoring tool information in the matrices provides relevant information to identify potential monitoring tools.** As highlighted in the case studies, many of the most important monitoring tool considerations noted by case study project managers are listed in the matrices. This confirms that monitoring tool information provided in the matrices is relevant and accurate compared to information routinely considered during sediment remedy monitoring. Accurate and relevant information enables matrices users to efficiently identify potential monitoring tools.

- **The matrices were refined based on case studies.** Based on new information collected during the case studies, such as new monitoring tool information or important details to consider for particular monitoring needs, approximately 5% of the fields contained in the matrix were modified. Approximately 3-4 new monitoring tools were added to the matrices.

Although the case studies represented a crucial internal validation and refinement step for this project, presenting an overview of each of the case studies in this section further illustrates how the matrices should be used. The case studies provide examples of how information in the matrices relates to "real world" remedial monitoring plans. In addition to many examples of how monitoring needs and tools were identified at the sites covered in these case studies, and how information in the matrices could be used to reach similar conclusions, a key message throughout the case studies is that readers should consider site-specific conditions during review of information provided by the matrices.

C.2 Bremerton, Washington (Puget Sound Naval Shipyard)

C.2.1 Site Description

Puget Sound Naval Shipyard (PSNS) is currently a 1,350 acre site that serves as a home port for Navy vessels, including aircraft carriers. The site has six major piers, six large dry docks, and more than 400 buildings supporting industrial operations throughout the complex. The site is contained in the marine environment of operable unit (OU) B which includes the nearshore portion of Sinclair Inlet that extend east and west along the shorelines of the Bremerton Naval Complex in Puget Sound, Washington.

C.2.2 Problem

The primary contaminants of concern are PCBs and mercury. The remedial investigation concluded that concentrations of these contaminants in fish tissue, assumed to be present due to elevated concentrations in site sediment, were associated with unacceptable levels of human health risk. Ecological risk was found to be insignificant.

C.2.3 Description of Selected Remedies

Remedies included dredging, capping, and monitored natural attenuation (Figure C.1).

C.2.3.1 Dredging

Approximately 200,000 cubic yards of sediment containing PCBs was dredged in an area of 32 acres and disposed of in excavated confined aquatic disposal (CAD) cells. CAD cells were located on Navy owned submerged land. Sediments with PCB concentrations greater than the remedial action level of 12 mg/kg organic carbon (OC) were removed by dredging. Sediments that were also dredged where mercury concentrations exceed 3 mg/kg and PCB concentrations exceed 6 mg/kg OC. An accumulation of sediments above the acceptable level at the mouth of Drydock 1 were also dredged. While PCBs in this area were below 6 mg/kg OC, mercury had been found above 3 mg/kg nearby.

The remedial design required that areas targeted for dredging be dredged to a minimum depth of 2 feet. With an allowance for overdredge depth and side slopes, the volume of impacted sediments dredged for environmental remediation is estimated at 200,000 in-place cubic yards. Dredging was accomplished mechanically with a clamshell bucket.

C.2.3.2 Capping

Capping remedies were applied to isolate impacted sediments in a 13-acre area and in the CAD cells on Navy-owned submerged land, occupying approximately 10 acres. For intact sediments, both thick and thin layer caps were used. Thin layer caps used at the site were a nominal thickness of at least 20 cm. This layer was not intended to provide a complete "seal" over the bottom, but to provide a layer of clean sediment to mix with underlying sediments, thereby facilitating natural recovery. In some areas, a 3-ft thick cap was constructed as needed to isolate sediment, withstand erosional forces, and provide a clean surface for improved ecological habitat. CAD cells were capped with a nominal 4-6 ft thick layer of clean import material.

C.2.3.3 Monitored Natural Recovery

MNR was used to remediate sediments offshore of the southwestern portion of the Bremerton Naval Complex and in areas not specifically remediated by dredging or capping. Natural recovery was also assumed to be a key remedial strategy in thin-layer capping. The key process associated with natural recovery was chemical transformation (mineralization) of PCBs rather than physical isolation of impacted sediments through natural sedimentation.

C.2.4 Retrospective Application of the Matrices to Bremerton Remedial Monitoring

C.2.4.1 Introduction

The following section provides a comparison of the monitoring needs and tools identified for the site remedies by the matrices to the actual monitoring conducted on the site. This section illustrates how information in the matrices relates to "real world" remedial monitoring plans and how site-specific conditions must be considered when reviewing information provided by the matrices.

For each monitoring phase relevant to the site (e.g., dredging performance monitoring, capping construction monitoring, etc.), tables are provided that contain the following information:

- **Potential monitoring needs and tools:** Possible monitoring needs identified by the matrices and the list of tools provided in the matrices that are associated with each monitoring need.
- **Site:** Whether the monitoring need was relevant to the site or a particular monitoring tool was used at the site.
- **Critical considerations identified in the matrices:**
    - For all monitoring needs, this field contains a brief description of the need, as presented in the matrices.
    - For monitoring tools used at the site, this field contains a sample of the information from the matrices that is particularly relevant to the site monitoring program. Information was obtained directly from matrices monitoring tool fields (e.g., "Special Considerations", "Uncertainty in

Addressing Monitoring Need", "Difficulty in Locating Tool in Marketplace", etc.).

- **Notes on actual site-specific monitoring program:** Information on actual monitoring needs identified or monitoring tools used at the Site.

Tables are provided at the end of this case study (all five possible monitoring phases are represented in this case study due to the application of MNR, capping, and dredging at Bremerton):

- Table C.1: Dredging Construction Monitoring
- Table C.2: Capping Construction Monitoring
- Table C.3: Capping Performance Monitoring
- Table C.4: MNR Performance Monitoring
- Table C.5: Remedial Goal Monitoring

C.2.4.2 Key Considerations for Using the Matrices: Highlights from Bremerton Remedial Monitoring

This section highlights how information presented in the matrices should be evaluated in the context of site-specific considerations, using the Bremerton remedial monitoring program as an example.

- **All monitoring needs listed in the matrices may not be relevant to the site**. For example, the "Ecotoxicological risks" monitoring need was not relevant to Bremerton, because ecological risk assessment conducted as part of the remedial investigation concluded that ecological risk was insignificant (Table C.5).

- **Information for monitoring tools may not always be relevant to the site**. For example, sediment profile photography was chosen as one of the tools to assess ecological recovery at Bremerton (Table C.5). Information provided for this monitoring tool in the "Monitoring Tool Logistical Complexity" field of the matrices is not an important consideration for selecting this tool because it notes that the tool is "Limited to use in soft-bottom sediments". As all sediment at Bremerton were relatively soft (slits and sands), this information would likely be of minor importance when considering this tool for use at a site like Bremerton.

- **Several monitoring tools are often selected to address a single monitoring need**. For example, four of the six monitoring tools identified in the matrices for addressing capping design specifications during the construction monitoring phase for capping were used at Bremerton (Table C.2). Several tools were selected because each tool offered its own advantages and disadvantages relative to site-specific monitoring conditions. Some of the information provided in the matrices highlights these advantages and disadvantages, and a sample of this information is presented in the "Critical considerations identified in matrices" column of Table C.2. For example, the matrices note that information provided by bathymetric survey is easily interpreted and widely available tool for assessing coverage of caps, although it lacks resolution and accuracy of the more advanced acoustic sub-bottom profiling monitoring tool (Table C.2). A disadvantage of acoustic sub-bottom profiling noted in the matrices was relevant to areas of Bremerton where the texture and composition of cap materials were similar to the underlying sediment, making interpretation of acoustic sub-bottom profiling data to assess cap presence and thickness difficult. To supplement this information, sediment coring and sediment surface photography was used to provide easily-interpreted visual information regarding cap thickness and/or coverage; however, these tools provided information only at a few discreet points rather than the continuous, site-wide coverage provided by bathymetric survey and acoustic sub-bottom profiling.

- **Monitoring tools can be used to address more than one monitoring need**. For example, sediment sample chemical analysis is one of the tools selected for addressing downstream deposition and ecotoxicological risks during dredging and capping construction monitoring (Tables C.1 and C.2), chemical flux through cap during capping construction monitoring (Table C.3), chemical natural recovery processes during MNR performance monitoring, and bioaccumulation and human health risks during remedial goal monitoring (Table C.5). In most cases at Bremerton, data obtained using this tool could be used to provide information for all of these needs. For example, samples collected during cap placement or during dredging could be potentially useful for addressing rates of chemical natural recovery processes, especially when these locations were resampled during the years following remediation. During evaluation of monitoring tools for different needs at sites like Bremerton, dual uses of data produced by monitoring tools addressing different monitoring needs should be taken into consideration when evaluating potential monitoring tools.

- **Among the information and references provided by the matrices, a single piece of information may be the key to identifying monitoring tools**. Sediment coring was one of the monitoring tools selected to address capping design specification during the construction monitoring phase for capping at Bremerton (Table C.2). The matrices note that this monitoring tool may damage the cap ("Special Considerations" field). This information would be critical to RPMs at a site like Bremerton, where both thin (0.5-ft) and thick (3-ft) caps were applied. As coring would likely damage thin caps, RPMs did not utilize this monitoring tool in all areas at Bremerton. Coring was restricted to assessing the performance of thick caps, although shallow (non-penetrating) coring techniques were used to avoid damage or release of underlying contaminated sediment.

- **Selection of monitoring tools should consider prior monitoring tools used at the site**. Analysis of edible biota tissues was selected as a monitoring tool to assess the reduction of human health risks in the remedial goal monitoring phase (Table C.5). For this monitoring need, the matrices note that this tool yields data with low uncertainty, and is often the best tool for evaluating human health risks associated with the consumption of site-related biota. In addition, information produced by this monitoring tool (e.g., PCB concentration in fish fillets) was directly compared to data collected during the Bremerton remedial investigation, providing an effective before-and-after comparison of remedial effectiveness. In addition, data were directly linked to the site-specific human health risk assessment performed during the remedial investigation and could be interpreted in a decision-making framework that specified benchmark concentrations of PCBs in tissue associated with unacceptable human health risk. Along with benchmark concentrations in sediment that were associated with unacceptable levels of human health risk, benchmark concentrations in fish served as guidelines by which to evaluate the attainment of remedial goals and enable decisions regarding the termination or continuation of remedial goal monitoring.

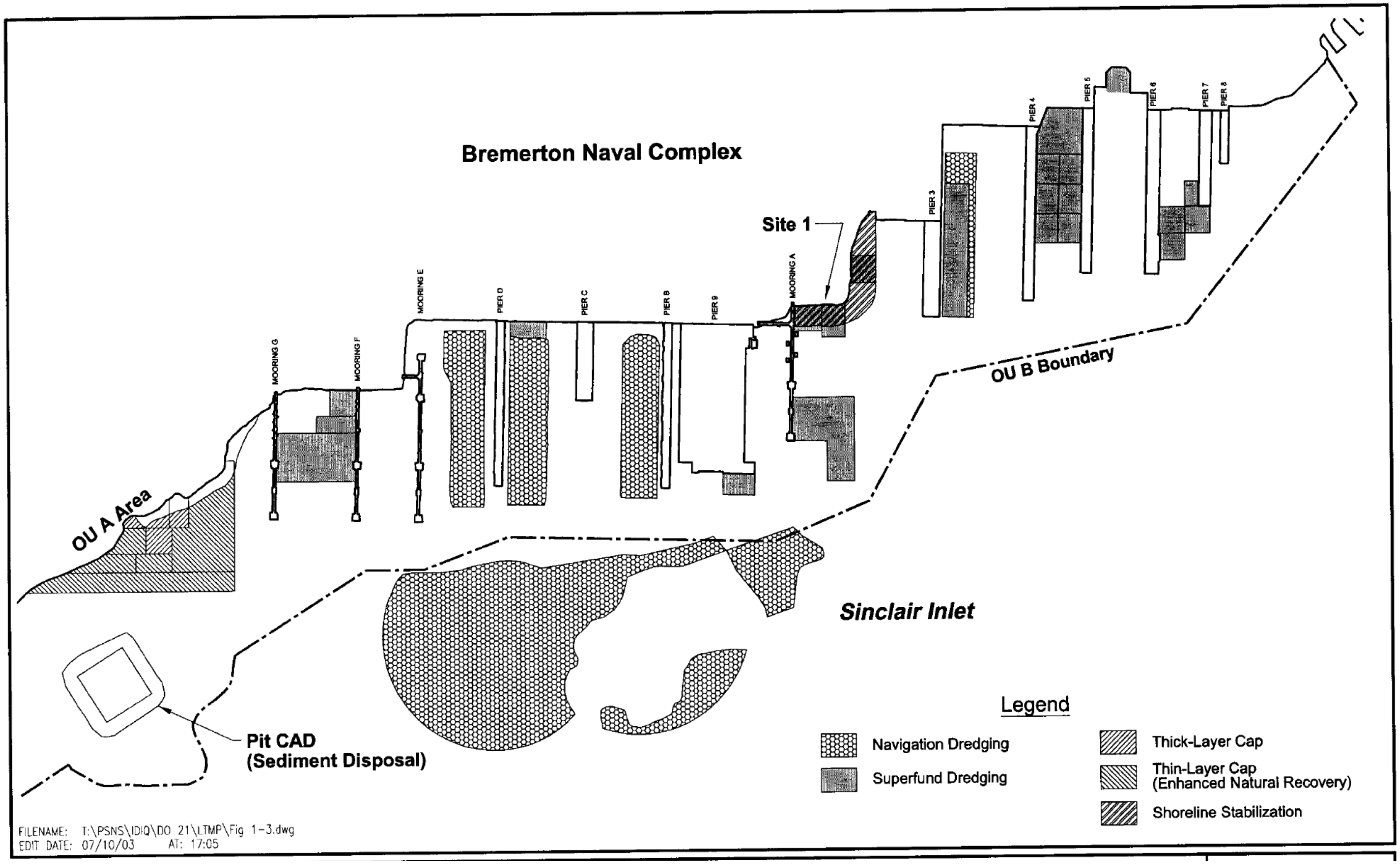

Figure C.1. Remedial actions at Bremerton Naval Complex.

Table C.1. Monitoring needs and tools identified by the matrices for dredging construction monitoring compared to the Bremerton monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	**Need Description**	**Tools**			
Acute dewatering effects	Assess acute effects or short-term changes due to discharge of dewatering effluent	Toxicity testing	Not used		Dredged sediments were not dewatered, as they were placed in a CDF cell.
		Caged organisms	Not used		
Bioaccumulation	Assessment of bioaccumulation potential to pelagic and possibly benthic species due to chemicals released due to sediment resuspension during remedial activity	Bioaccumulation testing	Unknown		Unknown if this need was monitored during dredging.
		Caged organisms	Unknown		
		Passive sampling devices	Unknown		
		Sediment sample chemical analysis (bioavailability extraction)	Unknown		
		Sediment and water sample chemical analysis	Unknown		
Downstream deposition	Assessment of downstream deposition to surface sediment	Sediment sample chemical analysis	Likely used	Rugged, simple tool. May be difficult to separate contamination associated with remedial activity from background contamination and requires collection of pre-remedy samples from downgradient locations prior to remedial activity.	No site-specific details were available regarding this monitoring need, although downstream deposition was likely monitored. Sediment samples were likely analyzed for physical parameters and COCs. Data likely compared to samples collected before dredging. Site managers recommended that surface and deep samples be collected.
		Sediment traps	Not used		
		Sediment profile photography	Not used		
		Current velocity measurement	Not used		
Dredging design specifications	Assess if mass removal meets design specifications (cut lines, topography, etc.)	Bathymetric survey	Likely used	Other acoustic survey methods (e.g., side scan sonar, acoustic sub-bottom profiling) may be more accurate. Widely available and easily interpreted.	No site-specific details were available regarding this monitoring need, although design specifications were likely assessed. Site managers recommended that pre-remedial and post-remedial bathymetry be conducted using the same methods and equipment.
		Ex situ dredge measurement	Not used		
		Side scan sonar	Not used		

Table C.1, dredging construction monitoring, *continued*

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	**Need Description**	**Tools**			
Excavation operations	Assess excavation operations including dredging, transport, dewatering, treatment, transport and disposal	Dredging observation	Used	Observational data easily interpreted.	Monitored during dredging.
Sediment resuspension	Assess physical water quality impairment due to sediment resuspension during remedial activity	Continuous suspended sediment monitoring	Used	Can provide continuous, real-time information on suspended sediments.	Water column monitoring conducted to ensure water quality criteria were not exceeded outside the designated dilution zones and dredged sediment was not resuspended in water column. Monitoring conducted using continuous monitoring probes in water column to measure endpoints (e.g., turbidity) associated with suspended sediment.
		Discrete suspended sediment monitoring	Not used		
		Real-time biomonitoring	Not used		
Ecotoxicological risks	Assessment of toxicity to pelagic and possibly benthic species due to chemicals released from sediment resuspension during remedial activity	Toxicity testing	Recommended later	Routine monitoring tool. Monitoring data may be affected by conditions independent of remedial activity or contamination.	Water column monitoring conducted to ensure that water quality criteria were not exceeded outside the designated dilution zones. In retrospect, site managers recommended that toxicity testing would have been useful in evaluating ecotoxicity in sediment potentially affected by downstream deposition during dredging. Only water column chemistry was monitored. Dissolved oxygen and standard water quality parameters monitored continuously with the use of probes. Discreet samples were obtained for COCs and compared to water quality guidelines.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Real-time biomonitoring	Not used		
		Sediment and water sample chemical analysis	Used	Inexpensive and simple. Can be compared to established criteria; however, simple chemical analysis usually overestimates toxicological risks.	
Volatile compounds in air	Air monitoring of volatile compounds at the dredge, transport, and disposal sites	Volatile organic compound monitoring	Not used		Volatile compounds were unlikely to be present in dredged sediment at this site.
Backfilling requirements	Assess need for backfilling following dredging.	Sediment sample chemical analysis	Unknown		Unknown if this need was monitored during or after dredging.
Presence of hot spots	Assess presence of hot spots following dredging.	Sediment sample chemical analysis	Unknown		Unknown if this need was monitored during or after dredging.

Table C.1, dredging construction monitoring, *continued*

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Presence of residual mass	Assess presence of residual mass following dredging.	Sediment sample chemical analysis	Unknown		Unknown if this need was monitored during or after dredging.
Impacts on hydrodynamics and sediment transport	Assessment of the physical impacts of dredging on hydrodynamics and sediment transport.	Hydrodynamic analysis	Unknown		Unknown if this need was monitored during or after dredging.

Table C.2. Monitoring needs and tools identified by the matrices for capping construction monitoring compared to the Bremerton monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	**Need Description**	**Tools**			
Bioaccumulation	Assessment of bioaccumulation potential to pelagic and possibly benthic species due to chemicals released from sediment resuspension during remedial activity.	Bioaccumulation testing	Not used		The minimal amount of capping was assumed to result in no significant displacement of impacted sediments and would not lead to bioaccumulation of PCBs in biota in surrounding areas.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Sediment and water sample chemical analysis	Not used		
Capping design specifications	Assess lateral extent, thickness, and/or uniformity of cap.	Acoustic sub-bottom profiling	Used	Used primarily to detect detecting extent, thickness, and uniformity of cap. One of the tools with highest levels of certainty in addressing monitoring need.	Several tools were used to confirm the ROD requirement that the cap meets the minimum specifications of a 3-foot thickness and to verify complete coverage of target areas. Sub-bottom profiling was conducted during and after placement of the cap to map surface features of the cap and estimate thickness of the cap. Sampling followed same sampling pattern as earlier bathymetric surveys. Bathymetric survey conducted before, during, and after placement of the cap to understand site and map surface features of the cap and estimate thickness of the cap. Site managers recommended that both pre-remedial and post-remedial bathymetry be conducted using the same methods and equipment. Four shallow (non-penetrating) cores collected and inspected visually to confirm presence and thickness of cap. Surface photography (underwater video) was conducted to supplement acoustic sub-bottom profiling and bathymetry. Conducted before and after construction to understand site and map surface features of the cap.
		Bathymetric survey	Used	Other acoustic survey methods (e.g., side scan sonar, acoustic sub-bottom profiling) may be more accurate; widely available, inexpensive, and easily interpreted.	
		Sediment coring	Used	May serve best as validation tool for continuous methods such as acoustic sub-bottom profiling. Coring may damage cap.	
		Sediment profile photography	Not used		
		Sediment surface photography	Used	Limited to sediment surface and limited by site conditions (turbidity). Easily interpreted visual method.	

Table C.2, capping construction monitoring, *continued*

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Downstream deposition	Assessment of downstream deposition to surface sediment.	Sediment sample chemical analysis	Used	Rugged, simple tool; May be difficult to separate contamination associated with remedial activity from background contamination and requires collection of pre-remedy samples from downgradient locations prior to remedial activity.	Downstream deposition of cap material and chemically-impacted sediment was hypothesized to occur near the fringe (0-20 ft) of the cap. Monitoring results demonstrated deposition up to 600 ft from fringe of the cap. Chemical analysis of sediment samples collected near margins (0-20 ft) of some caps following cap placement. Samples were analyzed for physical parameters and COCs. Data were compared to samples collected before cap placement. Site managers recommended that surface and deep samples be collected. Sediment traps were used to indicate sediment deposition as far as 1000 ft from the fringe of the cap.
		Sediment profile photography	Used	Data are point based; Allows visual inspection; May be difficult to visually distinguish freshly deposited layers or identify cap material or contaminated sediments visually.	
		Sediment traps	Not used		
		Current velocity measurement	Not used		
Ecological suitability of cap material	Assessment of cap material for use as a clean substrate capable of supporting ecological recovery.	Toxicity testing	Not used		Sediment used for cap was characterized prior to use to ensure suitability for ecological recovery. Chemical analysis was likely used to address the suitability of cap sediment, with results compared to ecological screening criteria to ensure that chemicals in cap material were not high.
		Bioaccumulation testing	Not used		
		Cap sample chemical analysis	Likely used	Simple tool, although simple chemical analysis may overestimate toxicological and bioaccumulation risks.	
		Cap sample physical analysis			
		Macroinvertebrate community census			
Physical suitability of cap material	Assessment of cap material for engineering purposes.	Cap sample physical analysis	Used	Highly relevant tool for assessing physical characteristics of capping material.	Sediment used for cap was characterized prior to use to ensure engineering purposes. Among standard analyses to evaluate long-term physical stability of cap material as surface sediment, physical analyses were conducted to evaluate the potential for cap material to liquefaction during seismic events, as the site is located in an area that has a relatively high incidence of earthquakes.

Table C.2, capping construction monitoring, *continued*

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	**Need Description**	**Tools**			
Sediment resuspension	Assess physical water quality impairment due to sediment resuspension during remedial activity	Continuous suspended sediment monitoring	Used	Can provide continuous, real-time information on suspended sediments.	Water column monitoring conducted to ensure that water quality criteria were not exceeded outside the designated dilution zones and that a turbidity wave did not form, indicating suspension of cap material or chemically-impacted sediments. Continuous monitoring probes were deployed in water column to measure endpoints (e.g., turbidity) associated with suspended sediment.
		Discrete suspended sediment monitoring	Not used		
		Real-time biomonitoring	Not used		
Ecotoxicological risks	Assessment of toxicity to pelagic and possibly benthic species due to chemicals released due to sediment resuspension during remedial activity.	Toxicity testing	Recommended later	Routine monitoring tool; Monitoring data may be affected by conditions independent of remedial activity or contamination.	Site managers recommended assessing ecotoxicity in the water column and sediments potentially affected by downstream deposition during cap placement due to the potential to disturb contaminated sediment during remedial activity. Assessment focused on the water column, although in retrospect, site managers recommended sediment ecotoxicity monitoring. In retrospect, site managers recommended that this monitoring tool would have been useful in evaluating ecotoxicity in sediments potentially affected by downstream deposition during cap placement. Monitoring sediments in the buffer zone around the cap both before and after cap placement may have been useful.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Real-time biomonitoring	Not used		
		Sediment and water sample chemical analysis	Used	Inexpensive and simple; Can be compared to established criteria; however, simple chemical analysis usually overestimates toxicological risks.	Only water column was monitored; Dissolved oxygen and standard water quality parameters monitored continuously with the use of probes. Discreet samples were obtained for COCs and compared to water quality guidelines.

Table C.3. Monitoring needs and tools identified by the matrices for capping performance monitoring compared to the Bremerton monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	**Need Description**	**Tools**			
Cap stability	Assess settlement and stability of cap over time.	Acoustic sub-bottom profiling	Likely used	Used primarily to detect detecting extent, thickness, and uniformity of cap. One of the tools with highest levels of certainty in addressing monitoring need.	Monitoring conducted to identify erosion of the cap, sediment movement, or mixing of cap with underlying sediment. For all tools, Site managers recommended that the same equipment and methods used to assess cap design (construction) be used for this monitoring need. Acoustic sub-bottom profiling was used to very capping design specifications during and immediately after placement of the cap; however, it was unclear if it was used to assess cap performance years after cap construction. Bathymetric survey was conducted along same sampling points as prior surveys. Thickness of the cap (3+ ft) not a limiting factor in the use of bathymetry for measuring the stability of this cap. Shallow (non-penetrating) cores collected and inspected visually to confirm presence and thickness of cap. Sediment profile photography was used to visually inspect cap profile.
		Bathymetric survey	Used	Other acoustic survey methods (e.g., side scan sonar, acoustic sub-bottom profiling) may be more accurate. Widely available and easily interpreted.	
		Sediment coring	Used	Subsurface profile easily interpreted from sediment core to yield information regarding cap thickness, although coring may damage cap.	
		Sediment profile photography	Used	Data are point based. Allows visual inspection. May be difficult to visually distinguish freshly deposited layers or identify cap material or contaminated sediments visually.	
		Sediment surface photography	Not used		
		Settlement plate	Not used		
		Side scan sonar	Not used		
		Cap sample physical analysis	Used	Relevant tool for assessing physical characteristics of cap useful for predicting susceptibility to erosion.	
Chemical flux through cap	Assessment of chemical flux through the cap.	Passive sampling devices	Not used		Monitoring focused on the transport of PCBs from underlying sediment. Samples of cap analyzed chemically for PCBs. Cap samples collected via shallow coring to avoid penetrating cap, and vertical profile of PCBs in core used to assess vertical migration of PCBs towards cap surface.
		Sediment sample chemical analysis	Used	Chemistry of subsurface profile easily interpreted to address contaminant migration through cap, although potential to damage cap.	
		Seepage meter/Flux sampler	Not used		
		Trident Probe	Not used		
		Surface sediment pore water	Not used		
Impacts on hydrodynamics and sediment transport	Impacts on hydrodynamics and sediment transport.	Hydrodynamic analysis	Not used		Local hydrodynamics were not assumed to be affected by the size and thickness of the cap relevant to size and depth of the basin.

Table C.4. Monitoring needs and tools identified by the matrices for MNR performance monitoring compared to the Bremerton monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Chemical flux from sediment	Assessment of chemical flux from sediment surface to water column.	Passive sampling devices	Not used		Not specifically addressed due to the stability of most areas of the site.
		Seepage meter/Flux sampler	Not used		
		Trident Probe	Not used		
		Surface sediment pore water	Not used		
Chemical natural recovery processes	Assess the progress of or potential for degradation, detoxification, or chemical sequestration of chemicals.	Sediment sample chemical analysis	Used	High confidence in method to describe contaminant degradation and transformation; No ability to provide information on chemical sequestration of contaminants.	The natural attenuation of chemicals in sediment (primarily PCBs) was assumed to be the primary remedial strategy for most of the site. Addressing this need simultaneously addressed overall remedial goals addressing the reduction of bioaccumulation risks and human health risks over time. PCB concentrations in sediment were measured over time, with natural recovery modeling to address chemical natural recovery rates. This tool would not be able to identify reductions in PCB bioavailability (chemical sequestration) that may occur as a result of natural attenuation.
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Surface sediment pore water	Not used		
		Laboratory biodegradation experiments	Not used		
		Sediment redox potential	Not used		
		Sediment profile photography	Not used		
Physical natural recovery processes	Assess stability of sediment during recovery and/or isolation of impacted sediment over time.	Acoustic sub-bottom profiling	Not used		Not addressed, as it was assumed that primary means of attenuation would be via chemical transformation of PCBs rather than natural physical isolation of sediment.
		Bathymetric survey	Not used		
		Sediment surface photography	Not used		
		Side scan sonar	Not used		
		Sediment coring	Not used		
		Sediment traps	Not used		
		Sediment sample physical analysis	Not used		
		Isotope analysis	Not used		

Table C.5. Monitoring needs and tools identified by the matrices for remedial goal monitoring compared to the Bremerton monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Bioaccumulation	Assessment of bioaccumulation potential to benthic and/or pelagic species.	Bioaccumulation testing	Not used		Baseline/Site Characterization monitoring revealed bioaccumulative chemicals (primarily PCBs and mercury) present in bottom-dwelling fish. Comparisons of monitoring data (PCB concentrations in sediment) were made to concentrations in sediment expected to result in PCB bioaccumulation in aquatic biota (likely via a PCB bioaccumulation model). Analysis of PCBs and mercury in bottom-dwelling fish and sea cucumbers was also conducted. Selection of this tool allows comparison of data collected during Baseline/Site Characterization monitoring. This tool requires less modeling/extrapolation, but is more-resource intensive.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment and water sample chemical analysis	Used	Standard monitoring tool. Simple chemical analysis usually overestimates bioaccumulation potential. Selection of this tool allows comparison of data collected during Baseline/Site Characterization monitoring.	
		Surface sediment pore water	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Avian chemical analysis	Not used		
		Chemical analysis of biota tissue	Used	Tissue residues in organisms easily interpreted to assess bioaccumulation potential.	
Human health risks	Assessment of exposure of bioavailable chemicals to humans via consumption of aquatic organisms.	Bioaccumulation testing	Not used		Human health risks identified in remedial investigation (primary risk associated with consumption of PCBs bioaccumulated by fish). Monitoring of PCBs in sediment, with comparison of data to site-specific, human health risk-based sediment criteria for PCBs expected to result in minimal bioaccumulation in aquatic biota. Selection of this tool allows comparison of data collected during Baseline/Site Characterization monitoring. Monitoring of PCBs in edible fish and sea
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment and water sample chemical analysis	Used	Standard monitoring tool. Simple chemical analysis usually overestimates bioaccumulation and subsequent human health risks.	
		Surface sediment pore water	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Avian chemical analysis	Not used		

Table C.5, remedial goal monitoring, *continued*.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
		Chemical analysis of edible biota tissue	Used	Best tool for estimating health risks posed by bioavailable chemicals in edible tissue of aquatic organisms are consumed by humans.	cucumbers and comparison to site-specific, human health risk-based criteria was also conducted. Selection of this tool allows comparison of data collected during Baseline/Site Characterization monitoring. This tool requires less modeling/extrapolation, but is more-resource intensive.
Physical benthic habitat quality	Assessment of benthic physical habitat.	Acoustic sub-bottom profiling	Not used		Need to ensure cap material meets design specifications for shoreline restoration of physical habitat quality following dredging and capping. Site managers focused on engineering suitability of cap material (no comparison to needs of biota was conducted).
		Bathymetric survey	Not used		
		Sediment sample physical analysis	Used	Provides simple assessment of physical habitat, but does not predict physical habitat suitability for all species.	
		Laser Line Scan Imaging	Not used		
		Remote sensing	Not used		
		Sediment profile photography	Not used		
		Sediment surface photography	Not used		
		Side scan sonar	Not used		
Ecotoxicological risks	Assessment of toxicity to benthic and/or pelagic species.	Toxicity testing	Not used		Ecological risks were not identified as significant in remedial investigation.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Real-time biomonitoring	Not used		
		Sediment and water sample chemical analysis	Not used		
		Rapid Sediment Characterization Tools	Not used		
		Surface sediment pore water	Not used		
		Avian chemical analysis	Not used		
		Chemical analysis of biota tissue	Not used		
Ecological recovery	Assessment of benthic and/or pelagic ecological recovery over time.	Artificial substrate samplers	Not used		Capping activities were hypothesized to disrupt ecological habitat; therefore, ecological recovery was investigated in capped areas only. Recovery was not assessed for other areas, as ecological effects of chemical contamination were found to be minor. In retrospect, site managers recommended that all monitoring efforts should have included monitoring a buffer zone around the cap. Sediment profile photography was applied within
		Avian community or productivity census	Not used		
		Drift net sampling	Not used		
		Fish community census	Not used		
		Macroinvertebrate community census	Recommended later	Highly relevant tool for assessing ecological recovery.	
		Vegetation survey	Recommended later	Highly relevant tool for assessing ecological recovery for sites with vegetation or the potential to support vegetation.	
		Sediment profile photography	Used	Provides qualitative indicator of macrobenthic habitat recovery. Suitable tool for use in soft sediments.	

Table C.5, remedial goal monitoring, *continued*.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
		Side scan sonar	Not used		the boundary of caps to assess ability of ambient macroinvertebrate fauna to recolonize capped areas. In retrospect, site managers recommended that macroinvertebrate community census and vegetation surveys would have been useful in evaluating ecological recovery.

C.3 Wyckoff/Eagle Harbor, Washington

C.3.1 Site Description

The 3,780 acre Wyckoff/Eagle Harbor site (Figure C.2) is located in central Puget Sound on the eastern border of Bainbridge Island, Washington. The source of sediment contamination originated from the shipyard and a former wood-treating plant. The site currently consists of the four Operable Units (OUs): OU 1, Wyckoff Facility; OU 2, East Harbor; OU 3, West Harbor; and OU 4, Wyckoff Groundwater. The West Harbor, OU 3, includes contaminated intertidal and subtidal sediments in the western portions of Eagle Harbor, as well as upland sources of contamination to the West Harbor.

C.3.2 Problem

The shipyard released metals and organic contaminants, and the wood treating operations involved pressure treatment with creosote and pentachlorophenol. Preservative chemicals delivered to the facility by barge and ship and were stored in tanks nearby. The primary contaminants of concern are organics, including PAHs, and metals, including arsenic, chromium, and lead. Remedial goals focused on the reduction of human health risks, and were evaluated using cleanup goals for PAHs and mercury in sediment and fish. On the basis of their widespread prevalence above apparent effects thresholds (AETs), mercury and the sixteen PAH were selected as indicator contaminants to define areas for remediation.

C.3.3 Description of Selected Remedy

The selected remedial actions for OU1 in the East Harbor are: (a) capping of the sediment in areas of high concern with a 1-meter layer of clean sediment and placing a thin layer of clean sediment in subtidal areas of low to moderate concern to enhance natural sediment recovery; (b) institutional source control; (c) natural recovery; and (d) long-term environmental monitoring.

- Phase I (1993-1994): Contaminated subtidal harbor sediments were covered by a 3-ft cap consisting of clean river sediment (approximately 275,000 cy). The objective was to reduce immediate risk until upland source control was achieved via the installation of a sheet pile wall. After Phase I cap placement, chemical migration appeared to be under control, although pools of creosote were observed at cap edges. Creosote pools likely migrated from the Phase II/III area, which was not contained at the time; divers extracted the pools regularly.

- Phase II (2000-2001): Contaminated nearshore sediments at depths of up to 45 ft were capped by a 3-ft cap consisting of upland fill (clean sand) (approximately 120,000 cy). The objective was to extend the Phase I cap from to the northern shoreline of the Wyckoff facility.

- Phase III (2001-2002): Additional material (upland fill, approximately 80,000 cy) was placed on the Phase II area (slightly smaller footprint). Capping material used was upland fill (80,000 cy). The objective was to construct an intertidal area connecting the Phase II area to the north shoal and to add more confinement material to the cap. A NOAA study documented rapid and substantial increase in quality of habitat

C.3.4 Retrospective Application of the Matrices to Wyckoff/Eagle Harbor Remedial Monitoring

C.3.4.1 Introduction

The following section provides a comparison of the monitoring needs and tools identified for the site remedies by the matrices to the actual monitoring conducted on the site. This section illustrates how information in the matrices relates to "real world" remedial monitoring plans and how site-specific conditions must be considered when reviewing information provided by the matrices.

For each monitoring phase relevant to the site (e.g., dredging performance monitoring, capping construction monitoring, etc.), tables are provided that contain the following information:

- **Potential monitoring needs and tools:** Possible monitoring needs identified by the matrices and the list of tools provided in the matrices that are associated with each monitoring need.
- **Site:** Whether the monitoring need was relevant to the site or a particular monitoring tool was used at the site.
- **Critical considerations identified in the matrices:**
    - For all monitoring needs, this field contains a brief description of the need, as presented in the matrices.
    - For monitoring tools used at the site, this field contains a sample of the information from the matrices that is particularly relevant to the site monitoring program. Information was obtained directly from matrices monitoring tool fields (e.g., "Special Considerations", "Uncertainty in Addressing Monitoring Need", "Difficulty in Locating Tool in Marketplace", etc.).
- **Notes on actual site-specific monitoring program:** Information on actual monitoring needs identified or monitoring tools used at the Site.

Tables are provided at the end of this case study (all four possible monitoring phases are represented in this case study due to the application of capping and MNR at Eagle Harbor):

- Table C.6. Monitoring needs and tools identified by the matrices for capping construction monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.
- Table C.7. Monitoring needs and tools identified by the matrices for capping performance monitoring compared to the Wyckoff/Eagle Harbor monitoring plan
- Table C.8. Monitoring needs and tools identified by the matrices for MNR

performance monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.

- Table C.9. Monitoring needs and tools identified by the matrices for remedial goal monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.

C.3.4.2 Key Considerations for Using the ISRAPs: Highlights from Wyckoff/Eagle Harbor Remedial Monitoring

This section highlights how information presented in the ISRAP should be evaluated in the context of site-specific considerations, using the Wyckoff/Eagle Harbor remedial monitoring program as an example.

- **All monitoring needs listed in the ISRAP may not be relevant to the site**. For example, ground water was not addressed by cleanup actions in the East Harbor and therefore is not identified as a medium of concern. Monitoring needs or tools in the matrix that are focused on addressing ground water interactions with sediment are not relevant.

- **Information for monitoring tools may not always be relevant to the site.** For example, sediment profile photography was chosen as one of the tools to assess ecological recovery at Wyckoff/Eagle Harbor (Table C.9). Information provided for this monitoring tool in the "Monitoring Tool Logistical Complexity" field of the matrices is not an important consideration for selecting this tool because it notes that the tool is "Limited to use in soft-bottom sediments". As all sediment at Eagle Harbor were relatively soft (slits and sands), this information would likely be of minor importance when considering this tool for use at a site like Eagle Harbor.

- **Several monitoring tools are often selected to address a single monitoring need**. For example, four of the six monitoring tools identified in the matrices for addressing capping design specifications during the construction monitoring phase for capping were used at Eagle Harbor (Table C.7). Several tools were selected because each tool offered its own advantages and disadvantages relative to site-specific monitoring conditions. Some of the information provided in the matrices highlights these advantages and disadvantages, and a sample of this information is presented in the "Critical considerations identified in matrices" column of Table C.7. For example, the matrices note that information provided by bathymetric survey is easily interpreted and widely available tool for assessing coverage of caps, although it lacks resolution and accuracy of the more advanced acoustic sub-bottom profiling monitoring tool (Table C.7). A disadvantage of acoustic sub-bottom profiling noted in the matrices was relevant to areas of Eagle Harbor where the texture and composition of cap materials were similar to the underlying sediment, making interpretation of acoustic sub-bottom profiling data to assess cap presence and thickness difficult. To supplement this information, sediment coring and sediment surface photography was used to provide easily-interpreted visual information regarding cap thickness and/or coverage; however, these tools provided information only at a few discreet points rather than the continuous, site-wide coverages provided by bathymetric survey and acoustic sub-bottom profiling.

- **Monitoring tools can be used to address more than one monitoring need**. For example, at Eagle Harbor, bioaccumulation in organisms was used to address remedial goals associated with human health risks, but could be used to address potential ecological concerns.

- **Among the information and references provided by the ISRAP, a single piece of information may be the key to identifying monitoring tools**. Sediment coring was one of the monitoring tools selected to address capping design specification during the construction monitoring phase of capping at Wyckoff/Eagle Harbor (Table C.8). The matrices note that this monitoring tool may damage the cap ("Special Considerations" field). As coring would likely damage thin caps, RPMs did not utilize this monitoring tool in all areas at Wyckoff. Coring was restricted to assessing the performance of thick caps (3-ft) and shallow (non-penetrating) coring techniques were used to avoid damage or release of underlying contaminated sediment.

- **Selection of monitoring tools should consider prior monitoring tools used at the site**. At Eagle Harbor, bioaccumulation in organisms was used for both the ecological and human health risk assessments conducted during the remedial investigation. To enable pre-remedial comparisons, analysis of edible biota tissues was selected as a monitoring tool to assess the reduction of human health risks in the remedial goal monitoring phase (Table C.9). These data were directly compared with risk-based cleanup levels and human health criteria identified in the remedial investigation and feasibility study, facilitating the interpretation of remedial goal attainment that enabled decisions regarding the termination or continuation of remedial goal monitoring

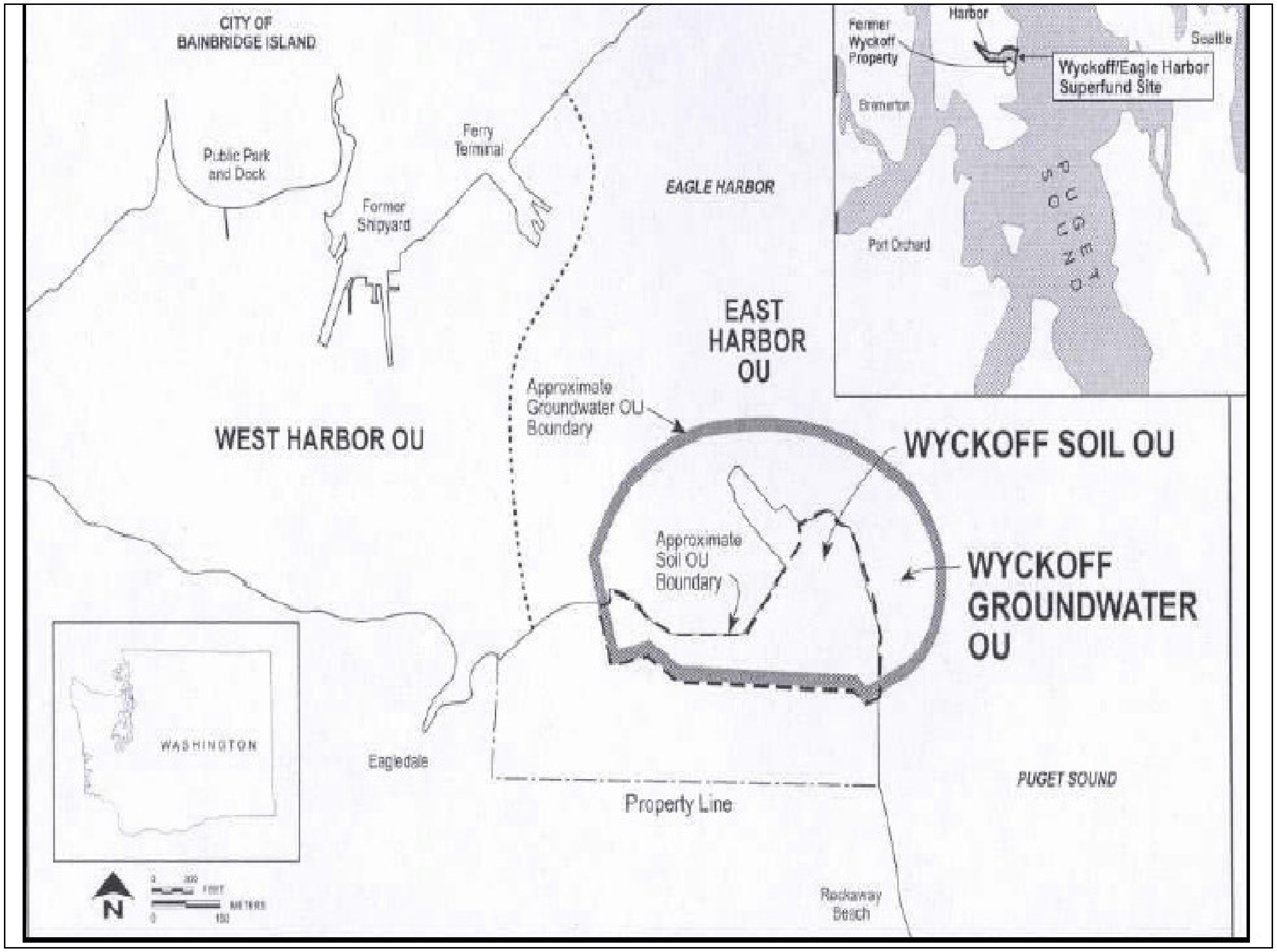

Figure C.2. Wyckoff/Eagle Harbor Site.

Table C.6. Monitoring needs and tools identified by the matrices for capping construction monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Bioaccumulation	Assessment of bioaccumulation potential to pelagic and possibly benthic species due to chemicals released due to sediment resuspension during remedial activity.	Bioaccumulation testing	Not used		Bioaccumulation was not investigated at in the context of re-suspended sediment.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Sediment and water sample chemical analysis	Not used		
Capping design specifications	Assess lateral extent, thickness, and/or uniformity of cap.	Acoustic sub-bottom profiling	Used	Used primarily to detect detecting extent, thickness, and uniformity of cap. One of the tools with highest levels of certainty in addressing monitoring need.	Acoustic sub-bottom profiling was conducted under an interagency agreement with the EPA. Bathymetric surveys were conducted to measure seafloor elevation. Sediment coring was done in order to establish a baseline for the cap by collecting undisturbed, representative samples (0-10 cm down). Underwater video was taken to analyze the presence, type, and density of epifauna.
		Bathymetric survey	Used	Other acoustic survey methods (e.g., side scan sonar, acoustic sub-bottom profiling) may be more accurate; Widely available, inexpensive, and easily interpreted.	
		Sediment coring	Used	May serve well as validation tool for continuous methods such as acoustic sub-bottom profiling. Coring may damage cap.	
		Sediment profile photography	Not used		
		Sediment surface photography	Used	Limited to sediment surface and limited by site conditions (turbidity). Easily interpreted visual method.	
Downstream deposition	Assessment of downstream deposition to surface sediment.	Sediment sample chemical analysis	Used	Although a routine method, analysis may not be able to separate recently deposited chemical residues from background sources of contamination.	Chemical analysis of off-site deposition of suspended material generated during cap construction was conducted using sediment traps. Sediment trap data was augmented by analysis of the upper 2 cm of off-cap sediments.
		Sediment profile photography	Not used		
		Sediment traps	Used	Accurate measure of sediment deposition with the lowest uncertainty of the potential tools used to investigation downstream or off-site deposition during construction.	
		Current velocity measurement	Not used		
Ecological suitability of cap material	Assessment of cap material for use as a clean substrate capable of supporting ecological recovery.	Toxicity testing	Unknown		Sediment for cap was characterized prior to use to ensure suitability for ecological recovery and if it would meet the State of Washington Sediment Management Standards.
		Bioaccumulation testing	Unknown		
		Cap sample chemical analysis	Likely used	Simple tool, although simple chemical analysis may overestimate toxicological and bioaccumulation risks.	
		Cap sample physical analysis	Unknown		

Table C.6, capping construction monitoring, *continued*

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
		Macroinvertebrate community census	Unknown		
Physical suitability of cap material	Assessment of cap material for engineering purposes.	Cap sample physical analysis	Used	Highly relevant tool for assessing physical characteristics of capping material.	Sediment used for cap was characterized prior to use to ensure engineering purposes.
Sediment resuspension	Assess physical water quality impairment due to sediment resuspension during remedial activity	Continuous suspended sediment monitoring	Not used		
		Discrete suspended sediment monitoring	Not used		
		Real-time biomonitoring	Not used		
Ecotoxicological risks	Assessment of toxicity to pelagic and possibly benthic species due to chemicals released due to sediment resuspension during remedial activity.	Toxicity testing	Not used		
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Real-time biomonitoring	Not used		
		Sediment and water sample chemical analysis	Not used		

Table C.7. Monitoring needs and tools identified by the matrices for capping performance monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Cap stability	Assess settlement and stability of cap over time.	Acoustic sub-bottom profiling	Used	Used primarily to detect detecting extent, thickness, and uniformity of cap. One of the tools with highest levels of certainty in addressing monitoring need.	Monitoring conducted to identify erosion of the cap, sediment movement, or mixing of cap with underlying sediment. For all tools, Site managers recommended that the same equipment and methods be used to assess cap design (construction) be used for this monitoring need. Acoustic sub-bottom profiling was conducted by the USGS under an interagency agreement with the EPA. Bathymetric survey was done to measure seafloor elevation. Sediment coring was done in order to test for contamination of the sediment cap. Sediment profile photography was used to visually inspect the cap profile and look for seeps.
		Bathymetric survey	Used	Other acoustic survey methods (e.g., side scan sonar, acoustic sub-bottom profiling) may be more accurate. Widely available and easily interpreted.	
		Sediment coring	Used	Subsurface profile easily interpreted from sediment core to yield information regarding cap thickness, although coring may damage cap.	
		Sediment profile photography	Used	Data are point based. Allows visual inspection. May be difficult to visually distinguish freshly deposited layers or identify cap material or contaminated sediments visually.	
		Sediment surface photography	Used	Benthic photography and videography of cap and sediment surface to detect damage to cap and changes in cap stability over time; does not assess changes in thickness and may only be useful for detecting severe damage.	
		Settlement plate	Not used		
		Side scan sonar	Not used		
		Cap sample physical analysis	Used	Relevant tool for assessing physical characteristics of cap useful for predicting susceptibility to erosion.	
Chemical flux through cap	Assessment of chemical flux through the cap.	Passive sampling devices	Not used		Monitoring focused on the transport of PAHs from underlying sediment.
		Sediment sample chemical analysis	Used	Chemistry of subsurface profile easily interpreted to address contaminant migration through cap, although potential to damage cap.	
		Seepage meter/Flux sampler	Not used		
		Trident Probe	Not used		
		Surface sediment pore water	Not used		
Impacts on hydrodynamics and sediment transport	Impacts on hydrodynamics and sediment transport.	Hydrodynamic analysis	Not used		Local hydrodynamics was assumed to be unaffected by the size and thickness of the cap relevant to size and depth of the basin.

Table C.8. Monitoring needs and tools identified by the matrices for MNR performance monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Chemical flux from sediment	Assessment of chemical flux from sediment surface to water column.	Passive sampling devices	Not used		Not specifically addressed due to the stability of most areas of the site.
		Seepage meter/Flux sampler	Not used		
		Trident Probe	Not used		
		Surface sediment pore water	Not used		
Chemical natural recovery processes	Assess the progress of or potential for degradation, detoxification, or chemical sequestration of chemicals.	Sediment sample chemical analysis	Used	High confidence in method to describe contaminant degradation and transformation; No ability to provide information on chemical sequestration of contaminants.	East beach sediments were analyzed and results were compared to minimum cleanup levels and human health criteria. Concentrations in the top 10 cm of sediment were measured over time to investigate natural attenuation of PAHs.
		Passive sampling devices	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Surface sediment pore water	Not used		
		Laboratory biodegradation experiments	Not used		
		Sediment redox potential	Not used		
		Sediment profile photography	Not used		
Physical natural recovery processes	Assess stability of sediment during recovery and/or isolation of impacted sediment over time.	Acoustic sub-bottom profiling	Not used		Intertidal cap, habitat mitigation beach and North & East beach intertidal sediments were assessed to see if they were providing functioning habitat. Bathymetric survey was instigated to measure seafloor elevation and to detect changes in thickness of sediment profile over time due to sediment erosion and sedimentation. Core samples from the 10 cm for contaminants of concern to track the physical stability of surface sediments. Physical analysis of core samples was also conducted to determine the susceptibility for erosion. Sediment traps were deployed to estimate sediment accumulation rates affecting the physical isolation of sediments. Topological surveys to look for changes in grain size and beach elevation were done to identify additional engineering needs (for example: material added due to erosion).
		Bathymetric survey	Used	Routine monitoring tool that is widely available.	
		Sediment surface photography	Not used		
		Side scan sonar	Not used		
		Sediment coring	Used	Routine monitoring tool that is widely available, but usually must be coupled with chemical or physical analysis to draw conclusions regarding physical stability of sediment.	
		Sediment traps	Used	Accurate measure of sediment deposition, but limited ability to provide information regarding erosion.	
		Sediment sample physical analysis	Used	Relevant tool for assessing physical characteristics of sediment useful for predicting susceptibility to erosion, but does not provide information on deposition rates.	
		Isotope analysis	Not used		

Table C.9. Monitoring needs and tools identified by the matrices for remedial goal monitoring compared to the Wyckoff/Eagle Harbor monitoring plan.

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	Need Description	Tools			
Bioaccumulation	Assessment of bioaccumulation potential to benthic and/or pelagic species.	Bioaccumulation testing	Not used		Chemical analysis of clam tissue was interpreted in a human health risk assessment and to measure the effectiveness of remedy effectiveness. Sediment chemical analysis was also conducted, with comparison of results to sediment criteria based on site-specific risk assessment (bioaccumulation and human health risks).
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment and water sample chemical analysis	Used	Requires interpretation and background data to predict bioaccumulation potential (risk assessment model), but simple and widely-applied tool.	
		Surface sediment pore water	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Avian chemical analysis	Not used		
		Chemical analysis of biota tissue	Used	Tissue residues in organisms easily interpreted to assess bioaccumulation potential.	
Human health risks	Assessment of exposure of bioavailable chemicals to humans via consumption of aquatic organisms.	Bioaccumulation testing	Not used		Human health risks for Eagle Harbor were primarily associated with the consumption of contaminated shellfish. Risk analysis was not required, but clam tissue data was collected in case further analysis of risk became warranted in the future. Clam tissue analyses focused on PAH body burden of clams (native littlenecks, geoduck clams & horse clams) on East Beach. Sediment chemical analysis was also conducted, with comparison of results to sediment criteria based on site-specific risk assessment (bioaccumulation and human health risks).
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Sediment and water sample chemical analysis	Used	Requires interpretation and background data to predict bioaccumulation potential (risk assessment model), but simple and widely-applied tool.	
		Surface sediment pore water	Not used		
		Sediment sample chemical analysis (bioavailability extraction)	Not used		
		Avian chemical analysis	Not used		
		Chemical analysis of edible biota tissue	Used	Best tool for estimating health risks posed by bioavailable chemicals in edible tissue of aquatic organisms consumed by humans.	
Physical benthic habitat quality	Assessment of benthic physical habitat.	Acoustic sub-bottom profiling	Not used		Cap material assessed for design specifications for shoreline restoration of physical habitat quality following dredging and capping. Bathymetric survey conducted to measure seafloor elevation.
		Bathymetric survey	Used	Widely available, routine monitoring tool, although data are point-based.	
		Sediment sample physical analysis	Used	Provides simple assessment of physical habitat, but does not predict physical habitat suitability for all species.	
		Laser Line Scan Imaging	Not used		
		Remote sensing	Not used		
		Sediment profile photography	Not used		
		Sediment surface photography	Not used		
		Side scan sonar	Not used		
Ecotoxicological risks	Assessment of toxicity to benthic and/or pelagic species.	Toxicity testing	Not used		Ecological risks were not identified as significant in remedial investigation.
		Caged organisms	Not used		
		Passive sampling devices	Not used		
		Real-time biomonitoring	Not used		

Table C.9. Remedial goal monitoring, *continued.*

Monitoring Matrices Output			Site Monitoring Plan	Critical Issues Identified in Matrices	Site Monitoring Program Notes
Potential Needs	**Need Description**	**Tools**			
		Sediment and water sample chemical analysis	Not used		
		Rapid Sediment Characterization Tools	Not used		
		Surface sediment pore water	Not used		
		Avian chemical analysis	Not used		
		Chemical analysis of biota tissue	Not used		
Ecological recovery	Assessment of benthic and/or pelagic ecological recovery over time.	Artificial substrate samplers	Not used		Visual surveys of bird, mammal and fish usages of the habitats were conducted.
		Avian community or productivity census	Used	Highly relevant tool for assessing ecological recovery.	
		Drift net sampling	Not used		
		Fish community census	Used	Highly relevant tool for assessing ecological recovery.	
		Macroinvertebrate community census	Used	Highly relevant tool for assessing ecological recovery.	
		Vegetation survey	Used	Highly relevant tool for assessing ecological recovery for sites with vegetation or the potential to support vegetation.	
		Sediment profile photography	Not used		
		Side scan sonar	Not used		

Appendix D: Example Statistical Resources for Experimental Design and Data Interpretation

Content: *This section presents an annotated bibliography of example resources for using statistics for data interpretation and monitoring program experimental design.*

D.1 Annotated Bibliography

An annotated bibliography of resources of statistical guidance's and tools are presented in Table D.1. The bibliography is not all-inclusive. Provided is a small sample of publicly-available resources of statistical guidance's and tools specifically designed for environmental sampling or sediment investigations.

Table D.1. Annotated bibliography of sediment- and water-quality specific statistical and experimental design guidances potentially useful for sediment remedial monitoring.

Resource	Description	Reference	URL
Guidances and Compendiums			
Guidance for Environmental Background Analysis	Analytical methods and statistical procedures that can be used to identify background chemicals in sediment (whether from anthropogenic or natural sources), and estimate the chemical concentration ranges that represent site-specific background conditions.	Naval Facilities Engineering Command (NAVFAC). 2003. Guidance for Environmental Background Analysis, Volume II: Sediment.	http://web.ead.anl.gov/ecorisk/related/documents/Final_BG_Sediment_Guidance.pdf
Derivation of Sample Size for Comparison to an Action Level	Statistical method for deriving necessary sample size in a sampling plan to enable comparison to an environmental action level.	USEPA. 2006. Derivation of Sample Size Formula for Testing Mean of Normal Distribution Versus an Action Level. Appendix A of Guidance for the Data Quality Objectives Process. EPA QA/G-4. EPA/240/B-06/001.	http://www.epa.gov/quality1/qs-docs/g4-final.pdf
Derivation of Sample Size	Provides guidance and statistical method for deriving necessary sample sizes for various experimental designs, including designs for comparing sample data to an environmental action level and comparing different locations at a site.	USEPA. 2001. Statistical Considerations in Determining the Appropriate Number of Replicate Samples Needed at Each Sampling Station. Appendix C of Methods for Collection, Storage and Manipulation of Sediments for Chemical and Toxicological Analyses: Technical Manual. EPA-823-B-01-002.	http://www.epa.gov/waterscience/cs/toc.pdf
Experimental Design for Sediment Investigations	Provides general overview of spatial, temporal, and statistical considerations for the experimental design of sediment monitoring programs and investigations.	USEPA. 2001. Methods for Collection, Storage and Manipulation of Sediments for Chemical and Toxicological Analyses: Technical Manual. EPA-823-B-01-002.	http://www.epa.gov/waterscience/cs/toc.pdf