CHAPTER 14

MONITORING REMEDIAL EFFECTIVENESS

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14.1 INTRODUCTION

Contaminated sediment remediation is a long-term, often decadal, process from initial characterization to achieving remedial action objectives (RAOs). Monitoring remedial effectiveness is critically important in contaminated sediment management. It seeks to answer the fundamental question of "Were we successful?" As a result, it is also a topic of great sensitivity. From a pragmatic point of view, there are many disincentives to conducting remedy effectiveness monitoring. What happens if the remedy is not "successful" and hundreds of millions of private and public dollars have been spent over many years of cleanup, after years of investigation and negotiation? Do we start over again? Determine it cannot be done? While this concern is very real, it does not outweigh the statutory requirements, cost accountability, human and ecological risk implications, and the standards of good governance and environmental stewardship that mandate remedy effectiveness be tracked and verified.

It is our belief that a rigorous monitoring program will improve the effectiveness of sediment remediation, or, at a minimum, uncover its limits, thereby modifying our expectations. Monitoring, if done well, will tighten the relationships between contaminated water and sediment and the adverse human and ecological effects targeted for remediation. At the same time, robust monitoring tightens the cause-effect associations between remedial actions and environmental improvements. Without such monitoring, decisions on cleanup areas and techniques have far less basis and chance for success (e.g., NRC, 2007).

This chapter focuses on remedial goal (or remedy effectiveness) monitoring and we differentiate that activity from performance and construction monitoring. Remedial goal monitoring assesses whether risk reduction objectives were achieved. Construction and performance monitoring assess whether the remedy was constructed as designed and whether the specific remedial technology is performing as expected (e.g., whether monitored natural recovery [MNR] is occurring at the anticipated rate; caps maintain contaminant isolation, and dredging achieved contaminant cleanup levels in the dredge area). This chapter presents the elements necessary to monitor remedial effectiveness and provides guidelines for the design of monitoring plans. Lines of evidence to support remedial effectiveness evaluations are presented along with technologies and techniques used to develop those lines of evidence. Finally, Case Study examples are provided to describe how technologies are used to develop lines of evidence and how that information supports decision making.

Ultimately, we hope this chapter helps to clarify how to (1) develop a strong remedial goal monitoring plan using a project's RAOs and conceptual site model (CSM) and (2) develop and test hypotheses that serve to answer if, and why or why not, the remedy was effective.

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14.2 MONITORING PHASES AND TIMEFRAMES

U.S. Environmental Protection Agency's (USEPA's) *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* states that a successful sediment remedy is one where selected sediment chemical or biological cleanup levels have been met and maintained over time and risks are reduced to acceptable levels (USEPA, 2005, p. 8–1). That document highlights four key metrics for remedy effectiveness:

- Short- and long-term remedy performance (reduction and maintenance of sediment contaminant levels) and
- Short- and long-term risk reduction (e.g., decreases in fish tissue levels or benthic toxicity).

This is the essence of remedy effectiveness: *Has the remedy reduced exposures and risk in the short- and long-term?*

14.2.1 Monitoring Phases

Monitoring at contaminated sediment sites is conducted during different phases of the remedial action for different purposes. USEPA (2005) describes the purposes of monitoring before and during remedial action as "(1) assess compliance with design and performance standards; (2) assess short-term remedy performance and effectiveness in meeting sediment cleanup levels; and/or (3) evaluate long-term remedy effectiveness in achieving RAOs and in reducing human health and/or environmental risk."

A similar distinction is provided in the U.S. Navy's Guidance for long-term monitoring and implementation (Navy, 2010, p. 14) where four monitoring phases are described: baseline monitoring, construction monitoring, performance monitoring, and remedial goal monitoring. This partitioning is useful because the different phases have different purposes and parameters. Briefly,

1. *Baseline monitoring* establishes a pre-remediation basis for comparison during subsequent performance or remedial goal monitoring.
2. *Construction monitoring* evaluates parameters directly related to the construction. For example, whether dredge depth or cap thickness was achieved. Construction monitoring data are used to answer the question: Is the remedy constructed as designed?
3. *Performance monitoring* evaluates specifically whether the remedial technology is performing as designed; for example, did the cap effectively isolate contaminated sediments; are sediment contaminant concentrations addressed under MNR declining at an appropriate rate? Performance monitoring data are used to answer the question: Is the remedy mechanism performing as designed?
4. *Remedial goal monitoring* (remedial effectiveness monitoring) evaluates whether contaminant exposures and corresponding risk are reduced (the purpose of the remedy) to acceptable levels. Remedial goal monitoring data are used to answer the question: Is the remedy achieving anticipated risk reduction?

The phases are distinguished by the purpose, logistics, and the monitoring parameters. While the purposes are distinct, there can be overlap of parameters; for example, sediment chemistry will be monitored during baseline, performance, and remedial goal monitoring.

It is particularly important to note the distinction between performance and remedial goal monitoring. Performance monitoring evaluates whether the remedy itself is performing as designed (e.g., the cap continues to isolate contaminated sediment), remedial goal monitoring evaluates if the overall goal of the remedy is being achieved (e.g., fish tissue contaminant concentrations have been achieved). Again, in this chapter, we focus on remedial goal monitoring, supported by baseline monitoring. The emphasis is on the biological receptors commonly intended to be protected by remediation (e.g., benthos, fish, or consumers of aquatic organisms, including humans) and the contaminant exposures driving risk to those receptors.

14.2.2 Timeframes

USEPA's sediment management "Principles" (USEPA, 2002a) and Sediment Guidance (USEPA, 2005) recommend monitoring "*during and after* remedial action" (italics added for emphasis). The 2005 Guidance clarifies that "Baseline data needed for interpretation of the monitoring data should be collected. . ."

To appropriately assess remedy effectiveness, data from four timeframes are needed:

1. *Baseline, pre-remediation*: Establish pre-remedy conditions and trends for comparison to post-remediation conditions.
2. *During remediation*: Monitor exposures and risks to receptors during remedy implementation, particularly for remedies that may require years or decades to complete. Increases in exposure – transient or otherwise – are important to understanding the level of protection afforded by the remedy as well as trends in the post-remedy timeframe.
3. *Immediately following remediation*: Establish post-remedy conditions soon after remedy implementation so that long-term monitoring data points have appropriate context and can inform on mechanisms influencing remedy effectiveness, such as recontamination. Navy Guidance (Navy, 2010) includes this timepoint as "baseline monitoring" because it serves as a subsequent reference point; regardless of terminology, this "time = 0" timepoint is critical for understanding post-remediation trends and remedy effectiveness.
4. *Long-term*: Monitor in the post-remediation timeframe to establish whether performance standards and RAOs are achieved.

14.3 EFFECTIVE COMPARED TO WHAT?

Any statement regarding remedy effectiveness inherently contains a comparison: Has a performance standard been achieved? Do trends (e.g., a rate of decline in contaminant concentrations) indicate that a remedial goal can be achieved at a future timepoint? Are conditions better than they were? Are conditions now similar to an unimpacted reference area? To assess the effectiveness of a remedial action, there are three requirements. First, the objective of the remediation needs to be stated in terms that are measurable. Second, a pre-remediation baseline needs to be established for comparison to the post-remediation condition. Finally, the monitoring plan design needs to be capable of answering whether the objectives were achieved.

14.3.1 State Your Objective

The first step in monitoring for remedial effectiveness is to have clear RAOs linked to measurable performance standards. Typically, RAOs are narrative statements intended to provide a general description of what the cleanup is expected to accomplish (USEPA, 2005, pp. 2–15).

Cleanup levels[1,2] establish the contaminant concentrations in various environmental media to be achieved by the remediation. To best support remedy effectiveness monitoring, the RAOs should be supported by quantitative statements including cleanup levels that describe expectations of the remedy. Those statements should document the "what, where, and when" of the conditions that are to be altered by the remedy.[3] For example, the remedy is expected to reduce adult largemouth bass contaminant concentrations to 20 micrograms per kilogram (μg/kg) wet weight in [a specified area] within 10 years following implementation, or, post-cleanup, surface sediment samples (top 10 centimeters [cm]) within [a specified area] will achieve a surface-weighted average concentration of 50 μg/kg dry weight. The need for quantitative statements describing expectations of a remedy is expressed in the National Contingency Plan (NCP), the implementing regulations of the Superfund Program, where the Agency is directed to

> *Establish remedial action objectives specifying contaminants and media of concern, potential exposure pathways, and remediation goals…Remediation goals shall establish acceptable exposure levels that are protective of human health and the environment and shall be developed…40 CFR 300.430(e)(2)(i)*

Such quantitative statements provide a basis for evaluation and form the hypothesis that is tested via a structured monitoring program. The cleanup level may be risk-based; for instance, fish tissue contaminant levels derived from risk assessment procedures. Or, cleanup levels may be set at "background"contaminant concentrations. For sites where risk-based concentrations are achievable only in the long-term, then interim objectives may be appropriate. For example, the Hudson River Record of Decision (USEPA, 2002b) selected a risk-based concentration in fish tissue of 0.05 milligram per kilogram (mg/kg), but also included 0.4 and 0.2 mg/kg polychlorinated biphenyls (PCBs) as target concentrations with the intention that, if achieved, such levels could trigger relaxing of the fish tissue consumption advisory.

14.3.2 Establish a Baseline

An adequate pre-remediation baseline needs to be established to provide the basis for comparison to the post-remediation condition (USEPA, 2005). Once remediation begins, the capped or dredged areas cannot represent conditions in the absence of remediation. Baseline

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[1] In practice, there is great variety in the terminology (and nuance in meaning) associated with the contaminant concentrations that are to be achieved in various media by the remediation. Such terms include cleanup levels, cleanup goals, chemical and biological standards, remedial goals, cleanup criteria, target concentrations, performance goals, performance metrics, and performance standards. Federal Guidance (2005) does not precisely define the terms and their usage; that issue is still in flux (Ells, 2011).

[2] The term "cleanup level" is used here and is defined simply as the contaminant concentration (in whatever media is specified) that will achieve the risk reduction targeted by the remediation. The term "remedial goal" was not used because it typically specifies a "protective" concentration (see NCP quote in text), which may not be the target of a specific remedial action (e.g., if background or an interim concentration is to be achieved).

[3] The application of "cleanup levels" can vary: at some sites, a cleanup level may be expected immediately post-remediation; another may have one cleanup level to be achieved immediately post-remediation and another to be achieved 10 years post-remediation. Some large sites with a patchwork of contamination may have higher cleanup levels set for certain areas that, when integrated across the entire site, achieve a lower site-wide cleanup level. Those variations are site-specific, and not central to the main point: cleanup levels need to be specified that clearly define the concentration, area, and time of anticipated attainment.

monitoring informs what would have happened absent remedial activities. Baseline conditions are used to develop the "no action" scenario, which is used when comparing the expected performance of remedial options in a feasibility study. Two options exist for establishing baseline: (1) pre-remediation trends in sediment and organism contaminant levels are monitored in the targeted remediation area, assuming that pre-remedy trends would continue in the absence of remediation and/or (2) an unremediated area with similar environmental and chemical characteristics is monitored. The latter option is rarely used, and emphasizes the importance of monitoring sufficient time points prior to remediation to establish trends. Establishing trends – in contrast to a single monitoring point – is necessary to capture any ongoing changes occurring in the absence of remediation (NRC, 2007; Bridges et al., 2010). Static conditions cannot be assumed. Still, a single year of baseline characterization to establish pre-remediation conditions is preferable to none for evaluating remedy effectiveness. Box 14.1 uses two Case Studies to emphasize the value of baseline in interpreting site monitoring data.

BOX 14.1 Long-Term Monitoring With and Without Baseline

Baseline data provide a critical context for assessing remedy effectiveness. Baseline is fundamental to evaluating whether the remediation has improved the condition (in contrast to whether a numerical objective has been achieved). Two site examples are provided here to highlight the importance and use of a robust baseline data set.

Tabbs Creek. Tabbs Creek (Figure 14.1) collected robust sample sizes of mummichogs annually for 7 years following remediation. The data set is quite useful for showing post-remediation concentration trends over time. However, a baseline remediation data set is not provided (Tetra Tech EC, 2009). The site's record of decision (USEPA, 1998a, Appendix A) does present a data point for "fish" at sampling stations, but no species or year are provided for context.

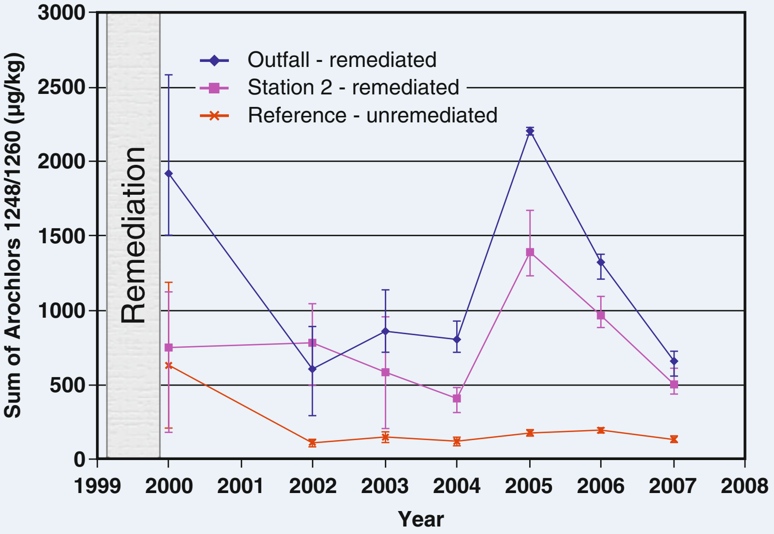

Figure 14.1. Post-remediation mummichog PCB concentrations at Tabbs Creek, Virginia. In 1999 and 2000, 12,371 t of sediment were dredged from the site and the dredged area was backfilled. The goal was to remove all sediments greater than 5 ppm of total PCBs and PCTs (polychlorinated terphenyls). Mummichog sampling consisted of three replicate, composite, whole body samples (20 individuals per composite) taken for 7 years post-remediation (data from Tetra Tech, 2009).

(continued)

BOX 14.1 (continued)

Without pre-remediation data, the effect of the remediation is unclear. Post-remediation monitoring data have no context for evaluating the effectiveness of the remedial operation. While the fish tissue contaminant levels could be compared to numeric cleanup levels (though none existed), the impact of the remediation cannot be ascertained.

Bryant Mill Pond. In contrast, the state of Michigan has monitored fish tissue contaminant concentrations in Portage Creek at the location of the (former) Bryant Mill Pond, which was remediated in 1999 (see Figure 14.2). Baseline fish tissue concentrations were collected at several time points prior to remediation and trend analysis was conducted to depict the expected trend in those concentrations into the future. That information was used to compare to post-remediation fish tissue contaminant concentrations. The analysis concluded that the removal action accelerated the rate of recovery in fish contaminant levels (CDM, 2009). Overall, the baseline data provide an appropriate context to evaluate the extent to which the remediation improved the primary indicator of health risk at the site.

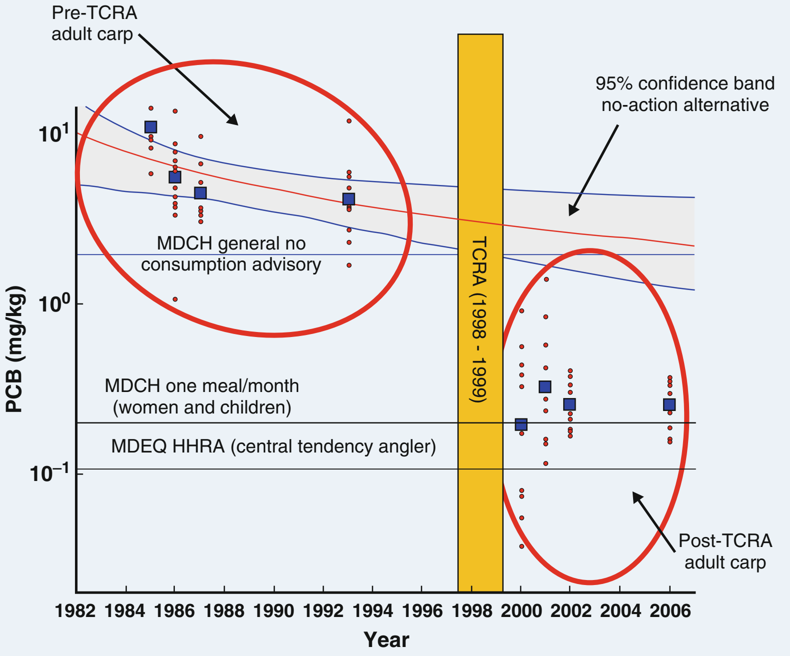

Figure 14.2. Baseline and post-remediation adult carp PCB concentrations in Bryant Mill Pond on Portage Creek, Michigan. In 1998 and 1999, Portage Creek was diverted and the pond area was dry excavated, removing 146,000 cubic yards to 1 ppm (cleanup level). Individual data for adult carp fillets analyzed for Aroclors are presented (CDM, 2009).

14.3.3 Develop a Plan

A monitoring plan needs to be structured to answer whether the RAOs and their related cleanup levels were achieved. Prior to remediation, monitoring endpoints and cleanup levels need to be established to determine whether the remedy was effective. Data collection has to be of sufficient spatial and temporal resolution to establish trends and rates of change, discern differences between sampling points, and confidently depict the levels that are being sought.

Consistency in sampling methods and parameters (e.g. season, locations and techniques) over time is critical; if these change, the ability to assess temporal differences (hence, remedial effectiveness) may be lost.

These concepts will be further addressed in the section on monitoring plan design and data quality objectives (DQOs), but their importance to remedy effectiveness monitoring warrants early, central emphasis. Monitoring plan elements should be developed as early in the process as possible – well before the remedy is implemented – and as early as it is understood which receptors are to be protected to what level. Implementation should also begin on a timely basis, prior to remedial action, in order to establish a baseline.

14.4 MONITORING TOOLS AND APPROACHES

There are a number of comprehensive resources that compile and describe technologies available for monitoring remedial effectiveness at sediment sites (Table 14.1). The choice of approaches or technologies for monitoring remedy effectiveness should be derived from RAOs and the CSM. The RAOs define the receptors of concern. The CSM represents the site's contaminant sources, transport pathways, exposure pathways, and receptors (USEPA, 2005) and guides the selection of the most important parameters to incorporate in the monitoring plan (See additional discussion in Section 14.5). This chapter does not seek to document all available approaches; rather it emphasizes those that have proven useful at sites.

Because contaminant exposures occur through various media and pathways to impact various receptors, monitoring plans frequently evaluate multiple parameters. Information derived from analyses or sampling technologies are commonly referred to as lines of evidence.[4] Rarely would a single endpoint or data source be sufficient to fully depict the risk to receptors at a site and the effect that remediation has had on the system. So, multiple lines of evidence are collected to depict contaminant exposures and effects. Table 14.2 presents commonly used lines of evidence, along with technologies for collecting those lines of evidence and their purpose in supporting remedy effectiveness evaluations. Section 14.8 provides Case Study examples of the uses of these lines of evidence to support site decision making.

Table 14.1. Technical Resources on Sediment Sampling Tools and Approaches

Document	References
A compendium of chemical, physical and biological methods for assessing and monitoring the remediation of contaminated sediment sites.	Battelle, 2003
A guidance manual to support the assessment of contaminated sediments in freshwater ecosystems. Volumes I–III.	MacDonald and Ingersoll, 2002
Long-term monitoring strategies for contaminated sediment management. Final guidance document.	Navy, 2010
Methods for collection, storage and manipulation of sediments for chemical and toxicological analyses: technical manual.	USEPA, 2001

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[4] See Magar et al. (2009) for a useful discussion on lines of evidence and their use to support decision making.

Table 14.2. Lines of Evidence for Supporting Remedy Effectiveness Evaluations

Line of Evidence	Example Technology or Technique	Purpose
Exposure pathways		
Sediment contaminant chemistry	Cores and grab samples	Document contaminant levels in sediments
Water column contaminant chemistry	Grab samples, composite samplers	Document contaminant levels in water column
Porewater contaminant chemistry	Grab samples, *in situ* or *ex situ* passive samplers	Document contaminant levels in porewater
Effects on receptors		
Benthic toxicity	Laboratory or *in situ* based organism toxicity tests (e.g., 28-day evaluations of mortality in the sediment-dwelling oligochaete *Lumbriculus variegatus*)	Document toxic effects of sediments to sediment-dwelling organisms
Contaminant bioaccumulation analyses	Laboratory or *in situ* monitoring of contaminant accumulation in benthic organisms accumulation (e.g., 28-day evaluations of contaminant accumulation in the sediment-dwelling *L. variegatus*)	Document uptake of contaminants into organisms from sediments
Contaminant concentrations in resident organisms	Monitoring of contaminants in electroshocked or trapped fish from the area of concern	Establish contaminant levels in organisms resident to the area of concern. The line of evidence serves as a proxy for potential effects to humans via consumption or directly to assess adverse effects to the organism (when toxicity data exist for comparison)
Benthic community indices	Monitoring benthic community diversity and/or pollution tolerance	Document health of benthic community structure and quantity

14.5 SELECTING RELEVANT INDICATORS OF EFFECTIVENESS

There are no requirements or guidance documents that direct the use of particular endpoints or technologies for documenting remedy effectiveness. USEPA's (2005) sediment remediation guidance states simply that:

> *Selection of endpoints depends on the requirements in the decision and/or enforcement documents, as well as more general considerations related to the cleanup methods selected and the phase of the operation...*

So, can direction be provided beyond "monitoring endpoints and approaches are site-specific"? Overall, monitoring is conducted to demonstrate that the objectives of the remediation are met; this entails directly monitoring the biologic receptors that are the Focus of the RAO[5] and the contaminant exposures driving risk to those receptors (i.e., it is not sufficient to simply monitor effects to the receptor to establish remedial effectiveness). See Box 14.2 for further discussion.

BOX 14.2 Monitoring Requirements: Regulatory and Scientific Perspective

At contaminated sediment sites, the question arises, "What do I need to monitor?" At least at the federal level, there are no specific requirements that define endpoints or media to be monitored. Indeed, a review of site experiences indicates wide variation in monitoring programs at remedial sites. Whereas some sites have used several inter-related lines of evidence capable of evaluating remedial effectiveness, others have collected only construction monitoring data (NRC, 2007).

Starting with the assumption that you need to monitor the target of your RAOs (e.g., fish contaminant levels or benthic toxicity), then what else is necessary? That is, if fish contaminant levels and/or benthic toxicity are being measured, is it necessary to also measure contaminant levels in water and sediments? These exposure data serve to verify the CSM; for example, if the biological monitoring data (e.g., fish tissue concentrations) are not improving, they can assist in evaluating why improvements did not occur. The reasons to not sample the environmental matrices presumed responsible for the adverse effects warranting remediation are expediency, cost, or avoidance of complications arising from the collected information. However, there is not a technical basis to eschew that sampling.

From a management or accountability viewpoint, contaminated sediment remediation is conducted (at substantial public and private cost) to eliminate or lessen contaminant exposures to receptors of concern from sediments. The effect of the remediation on targeted exposures needs to be evaluated to appropriately ascertain the effectiveness of the remediation.

RAOs document the purpose of the remedy and condition (or receptors) to be improved, and they "should reflect objectives that are achievable from the site cleanup" (USEPA, 2005). Presumably this means the RAOs and associated cleanup levels should be attainable; in turn, that attainment should be measurable. The CSM delineates the media and processes that drive risk to the relevant receptors. For example, RAOs at contaminated sediment sites commonly seek to protect benthic communities from exposure to harmful sediment contaminant concentrations or humans from exposure during consumption of fish (or shellfish) with elevated contaminant concentrations. In these instances, remedial goal monitoring would evaluate benthic toxicity and fish tissue contaminant levels, respectively. RAOs are the basis of endpoint selection and monitoring plan development. The CSM is used to identify monitoring parameters that document contaminant exposures that drive the unacceptable risk to receptors of concern. At sediment sites, these exposures will include sediment contaminants (as monitored by bulk sediment or sediment porewater chemistry), but may include other pathways such as soluble

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[5] In some instances, biologic receptors may not be specified, as the objective of the sediment remediation may be to reduce flux of contaminants from the remediated area. In this case, contaminant flux would be the primary determinant of remedial effectiveness.

contaminants in the water column. Monitoring contaminant exposure pathways (Table 14.2) serves overlapping roles. For performance monitoring, it verifies that the remediation had its intended operational effect. For remedial goal monitoring, it assesses whether the remedy reduced exposures as anticipated. The concordance of exposure and effects (or tissue residue) data is also used to verify (or modify) the CSM and assess whether remedy modifications are needed. For example, if, following successful remediation of sediment contaminant exposures, fish tissue contaminant levels do not decline, the CSM was not correct and further refinement is required.

Endpoints appropriate for remedial goal monitoring will also be influenced by the environmental setting. For example, at geographically large sites or sites that represent the primary source of contaminants to a water body, the remediation may be expected to decrease contaminant concentrations in site-wide populations of upper-trophic-level fish that are often targeted for consumption by humans. At smaller sites that lie within a water body impacted by a range of sources and areas, remedial goal monitoring may focus solely on local conditions by evaluating contaminant levels in benthos or fish with home ranges limited to the geographic areas of the site (in this instance, it would not be reasonable to anticipate decreases in tissue contaminant concentrations of wide-ranging fish). Alternatively, remediation at such a site may only be expected to reduce contaminant loading to the water body or food web (ostensibly, a source control effort). Here, contaminant flux from the area, sediment bioaccumulation or bioavailability assessments would be the primary endpoints to assess remedial effectiveness.

Ultimately, site managers are responsible for establishing the endpoints influenced by the remediation and the extent to which those endpoints are expected to be improved, and hence, risks reduced. These are the hypotheses the monitoring plan evaluates. The selected monitoring endpoints – whether they are wide-ranging upper-trophic-level fish or stationary benthos – are site-specific. Risk managers need to ensure they can be linked to the remediation and that they appropriately represent the RAOs of the project (NRC, 2007; Gustavson et al., 2008).

14.6 DEVELOPING A MONITORING PLAN: DATA QUALITY AND DATA MANAGEMENT

A monitoring plan establishes the monitoring objectives, and the monitoring parameters, locations, and frequency to meet the monitoring objectives. The monitoring plan should include documentation that ensures data quality and data management such that it complies with the Data Quality Act of 2001 (PL 106–554, Section 515). This legislation was passed by the U.S. Congress to ensure the "quality, objectivity, utility, and integrity of information, including statistical information" that may be used to support any federal agency's position, decision, regulation, guidance, or dissemination of information.

Within the context of a monitoring plan, the RAOs should be specifically addressed through the development of monitoring DQOs. The DQO process helps to ensure that the proposed data collection and analysis is capable of answering the questions for which they were proposed. In the context of remedial effectiveness, this is whether the RAOs and associated cleanup levels have been achieved.

The USEPA's Quality Program Procedures[6] contain numerous guidance documents including the use of DQOs, quality assurance project plans (QAPPs), and sampling designs – all of which are useful to ensuring the conduct of a technically- and legally-defensible

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[6] http://www.epa.gov/quality/qa_docs.html. Accessed July 31, 2012.

monitoring program. Additionally, more specific guidance on QAPPs for efforts that include geospatial data and modeling – which are common at sediment sites – are also provided. Database management is also important to establish early in the monitoring program, particularly because the monitoring program itself may last from years to decades whereas the parties and software may change over time.

14.7 ADAPTIVE MONITORING AND DECISION CRITERIA

The monitoring program for a site should be set up to be adaptive. Much has been written about the general practice and utilization of adaptive management (NRC, 2003, 2004), and this chapter will not reiterate those points. What adaptive monitoring means here is that as the data are collected and evaluated, changes or refinements to the monitoring plan (e.g., increase/decrease in sampling periodicity or sample sizes) can be made for many reasons. Technical examples informing such changes include: (1) a cleanup level, or RAO, or interim target or benchmark has been met; (2) a significant trend, expected trajectory, or percentage change in a line of evidence or monitoring endpoint has been (or not been) demonstrated by the data (e.g., slope of decline or percentage reduction of contaminant concentration in fish tissue); (3) the data have shown that the DQO for a monitoring endpoint cannot be adequately evaluated under the current sampling design; or (4) recovery of an ecological monitoring endpoint has been demonstrated (e.g., benthic community established and stable, reduction in toxicity). Cost considerations are also an important factor when establishing a monitoring plan, and they should be revisited throughout the program to additionally inform decisions on changes, additions, or refinements to the monitoring. The monitoring plan should be cost-effective and implementable.

The decision criteria that will be used as the basis for changes to the monitoring program should be developed prior to its onset, or as early as practicable. This is important given that for most contaminated sediment sites – especially those where the cleanup decisions were based on persistent organic contaminants like PCBs – the ultimate benefits of the remedy are not expected to be realized until decades into the future. This long-term expectation for achieving the RAOs poses challenges to the site technical team such that the monitoring program needs to be capable of: (1) demonstrating that a remedy is moving toward the RAOs in the short term (months to years), and (2) establishing a database that is adequate for evaluating whether the RAOs have been achieved over the long-term.

On a site-specific basis, it is possible that more intense monitoring is needed in the short term (5–10 years) following implementation of a remedy. Once the immediate post-remedial conditions, including failure, are understood and/or the temporal and spatial trends of key lines of evidence (i.e., fish tissue, sediment concentrations) are established, the frequency and/or sample sizes of the monitoring can be reduced while ensuring that the expected trajectory of recovery is still accurate. Decision criteria for the shorter term evaluations of post-remedial conditions and trends should define a goal (e.g., an acceptable concentration or rate of decline in fish tissue concentrations), and then define the statistical tests that will be used to ascertain whether that goal was achieved. Those decision criteria should function to demonstrate the status of the remedy (i.e., approaching or achieving RAOs/targets/goals or failing to do so) and inform decisions on whether the monitoring plan needs to be changed, or whether another aspect of the remedy (e.g., scope of remedial action, project objectives) needs to be revised under adaptive site management. The application of statistical power analysis and determination of minimum significant differences that are achievable under various sampling design options is helpful to ensure that adequate sample sizes are collected (USEPA, 2008). Finally, the decision criteria should also be used for ending the monitoring program (i.e., exit criteria) when there is confidence that the cleanup levels and RAOs have been achieved. Those analyses would use the same technical and statistical bases as described above, but be specific to the RAOs.

14.8 CASE STUDIES: LINES OF EVIDENCE IN REMEDY EFFECTIVENESS MONITORING

In this section, Case Studies are outlined to provide a practical perspective on the implementation and use of the lines of evidence outlined in Table 14.2. Examples are not comprehensive reviews of site activities or sampling efforts, but are intended to present how a specific line of evidence was developed and used. Details are provided on the site, remediation, sampling, and use of the data to support decision-making for several Case Studies (Table 14.3). The reader is referred to site references for further detail.

14.8.1 Sediment Contaminant Chemistry, New Bedford Harbor, Massachusetts

Background. New Bedford Harbor was listed on the National Priorities List (NPL) in 1984 due to sediment contamination with PCBs and metals from historical industrial discharges (USEPA, 1998b). Several projects, including dredging, shoreline excavations, and a pilot-scale sediment cap, have occurred at the site since the early 1990s to address the contamination. The "North of Wood Street" area is the upstream area of the harbor, where the Acushnet River enters the harbor. In 2002–2003, earthen berms were constructed above and below the area, the river flow was diverted, and contaminated sediments between the berms were excavated in the dry. Shoreline areas were excavated and replaced with clean fill (Tetra Tech FW, 2005).

Sampling Description. Samples were collected following remediation to determine whether cleanup goals had been achieved; 61 samples were taken throughout the 3.8 acre sediment bed remediation area. The data showed an average concentration of 7.0 parts per million (ppm) in the remediation area (Tetra Tech FW, 2005), which was below the 10 ppm "cleanup criteria" for sub-tidal sediments. Post-remediation, monitoring of PCBs in the top 6 inches (in.) of sediments was conducted to assess recontamination of the excavation area and was planned to include 20% of the original sample locations (Tetra Tech FW, 2005). Post-remediation sampling has been conducted multiple times since 2004; several locations have been consistently sampled over that period. Figure 14.3 (from Battelle, 2009) shows data from the repeat sampling locations between 2003 and 2008.

Table 14.3. Case Study Examples of Lines of Evidence Used in Decision Making at Contaminated Sediment Sites

Line of Evidence	Site
Sediment contaminant chemistry	New Bedford Harbor North of Wood Street Remediation, Massachusetts
Water column contaminant chemistry	Hudson River Implementation Monitoring, New York
Porewater contaminant chemistry	Grasse River Activated Carbon Pilot, New York
Benthic toxicity	Ward Cove, Ketchikan, Alaska
Contaminant bioaccumulation analyses	Grasse River Activated Carbon Pilot, New York
Contaminant concentrations in resident organisms	Cumberland Bay, Lake Champlain, New York

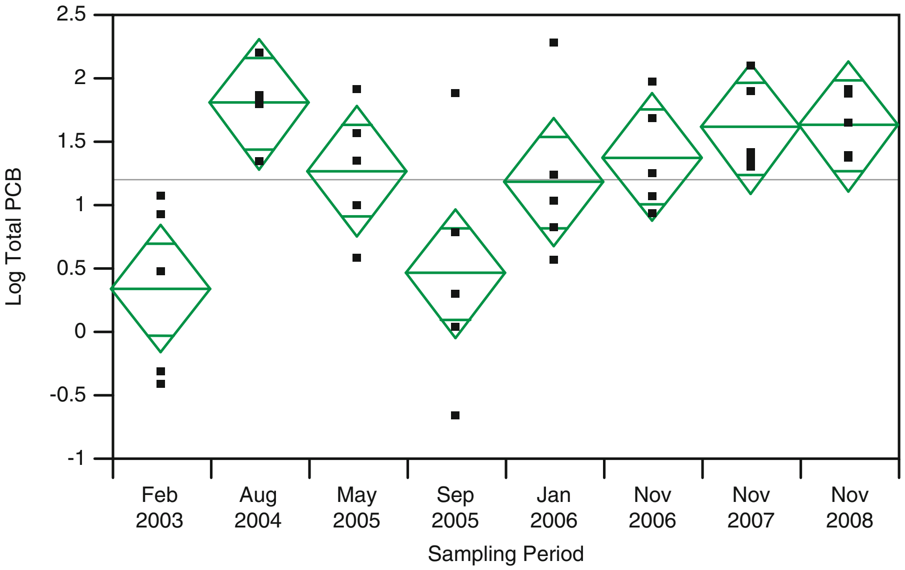


Figure 14.3. Temporal trends in total PCB (log scale) in river sediment at sampling stations North of Wood Street (2003–2008). *Squares* represent individual points; *top* and *bottom* of the *diamonds* are the 95% confidence interval of the mean (excerpted from Battelle, 2009).

Use of Data. The objective of the post-remediation sediment contaminant monitoring was to assess the effectiveness of prior remediation and potential recontamination of this area due to sediment transport from unremediated areas of the Harbor (Battelle, 2009). The lowest sediment PCB concentrations were seen just after remediation. A post-remediation increase was observed in 2004 and recent years remain elevated compared to 2003 (Figure 14.1). These data provide empirical evidence on sediment movement and recontamination. Annual sediment monitoring is slated to continue at the North of Wood Street area to assess recontamination from adjacent unremediated harbor areas (Battelle, 2009).

14.8.2 Water Column Contaminant Concentrations, Hudson River, New York

Background. Sediments in the Hudson River, New York, are contaminated by PCBs associated with manufacturing processes and waste discharges to the river. Following an interim No Action decision in 1984, the 2002 Record of Decision called for dredging of areas within a 40-mile stretch of the river between Hudson Falls, New York, and the Federal Dam at Troy, New York (USEPA, 2002b). Phase 1 dredging began in 2009, using a number of barge-mounted mechanical excavators with sediments transported by scow to a shore-based off-loading facility. During dredging activities, the water column was sampled to assess releases of PCBs to the water column (Louis Berger Group, 2010).

Sampling Description. As part of the site's Engineering Performance Standards, sampling for PCBs in the water column was conducted at several locations downstream of active dredging operations (Malcolm Pirnie Inc. and TAMS Consultants, 2004). Thompson Island Dam, the closest downstream sampling station, was located approximately 2–5 miles downstream from where dredging occurred. Sampling was taken daily from fixed sampling inlets as a 24-hour composite at transects across the river. Unfiltered (whole) samples were analyzed for "tri + PCBs" (PCB congeners with three or greater chlorine atoms) (Anchor QEA, 2009).

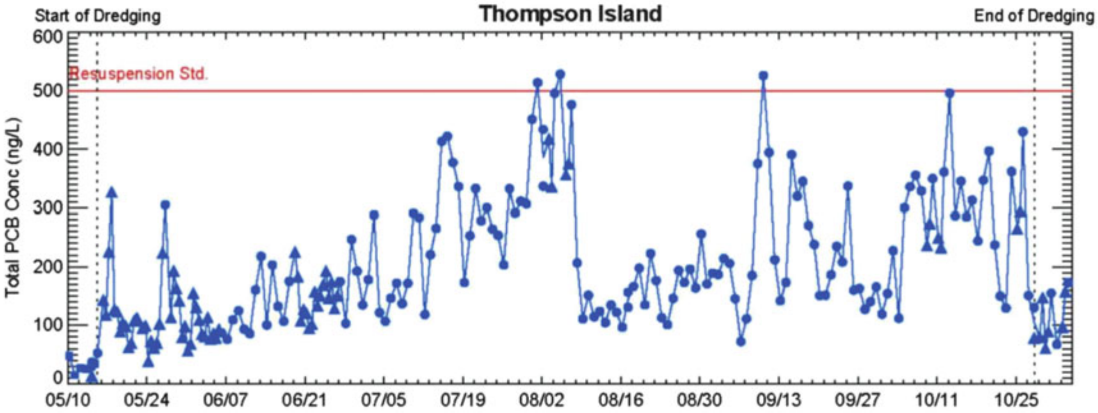


Figure 14.4. Tri+total PCB concentrations in Hudson River whole water samples taken at Thompson Island, downstream of 2009 dredging activities (excerpted from Anchor QEA, 2009).

Use of Data. The primary objectives of the water column monitoring were to evaluate conformance with USEPA's Safe Drinking Water Act Maximum Contaminant Level (MCL) (500 nanograms per liter [ng/L] parts per trillion [ppt]) and to minimize the release of PCBs to downstream areas (Louis Berger Group, 2010). Data indicate that Phase 1 dredging activities increased water column concentrations of PCBs that were available for downstream transport, including three exceedances of the MCL (Figure 14.4). These data were used directly to trigger shutdown of the Phase 1 dredging operations when the MCL was exceeded. In addition, the data have been used to: (1) estimate the amount of contaminants released and transported by dredging activities; (2) provide insight on aqueous exposure concentrations to fish in the study area; and (3) inform improvements to the project design and operation to minimize such increases in water column PCBs during Phase 2 dredging that began in 2011.

14.8.3 Contaminant Concentrations in Porewater, Grasse River, New York, Activated Carbon Pilot

Background. Sediments at the Grasse River site near Massena, New York, are contaminated with PCBs released during historical waste discharges. To support the development of remedial alternatives within the feasibility study for the site, several pilot studies have been conducted to evaluate capping, dredging, addition of activated carbon, and MNR as remedial options for PCB-contaminated sediment (Alcoa, 2010). The Activated Carbon Pilot Study (ACPS) was initiated in 2006 to evaluate whether granular activated carbon placed in sediments reduces the bioavailability of PCBs in sediments. The ACPS evaluated different placement and mixing techniques in a 0.5-acre test area of the river bed; results were compared to an untreated background area within the site. To date, post-remediation monitoring was conducted over three consecutive years (2007–2009).

Sampling Description. Amongst other parameters, porewater contaminant chemistry has been monitored to evaluate changes in PCB bioavailability since the addition of carbon to the sediments. Two methods have been used: (1) laboratory batch equilibrium testing and (2) *in situ* passive sampling with polyoxymethylene (POM). Passive samplers, such as POM, accumulate only the freely-dissolved contaminants, which can be quantified and used to estimate the freely-dissolved concentration in the porewater. Three to six replicate sediment samples were taken for the batch testing in the treatment and reference areas (Alcoa, 2010). Batch equilibrium testing involves equilibrating sediment samples with overlying water during mixing and analyzing the aqueous phase for contaminant concentrations after suspended particulates are

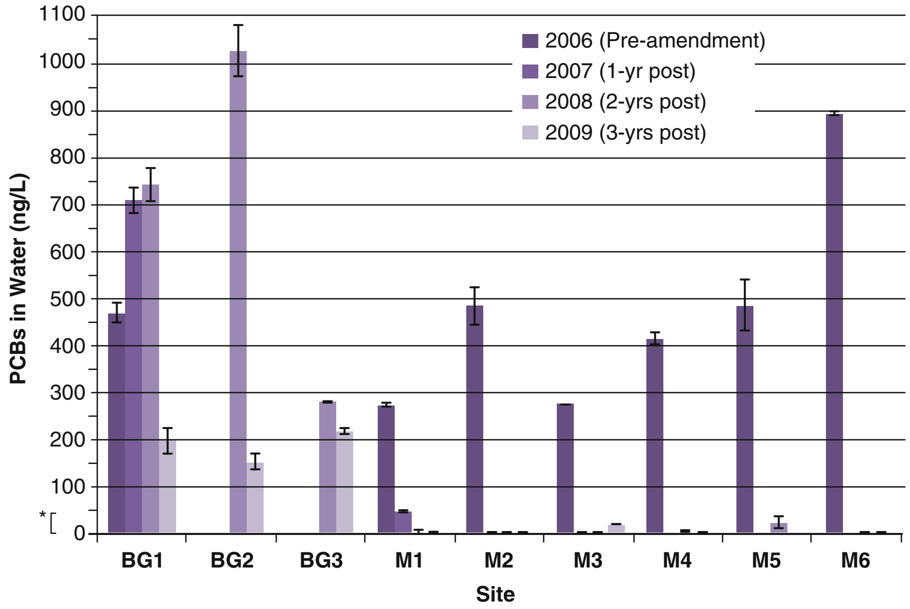


Figure 14.5. Aqueous equilibrium PCB concentrations in sediment porewater for background and activated carbon treatment area based on batch equilibrium measurements. BG – background; M 1–6 are locations within the treatment area (excerpted from Alcoa, 2010).

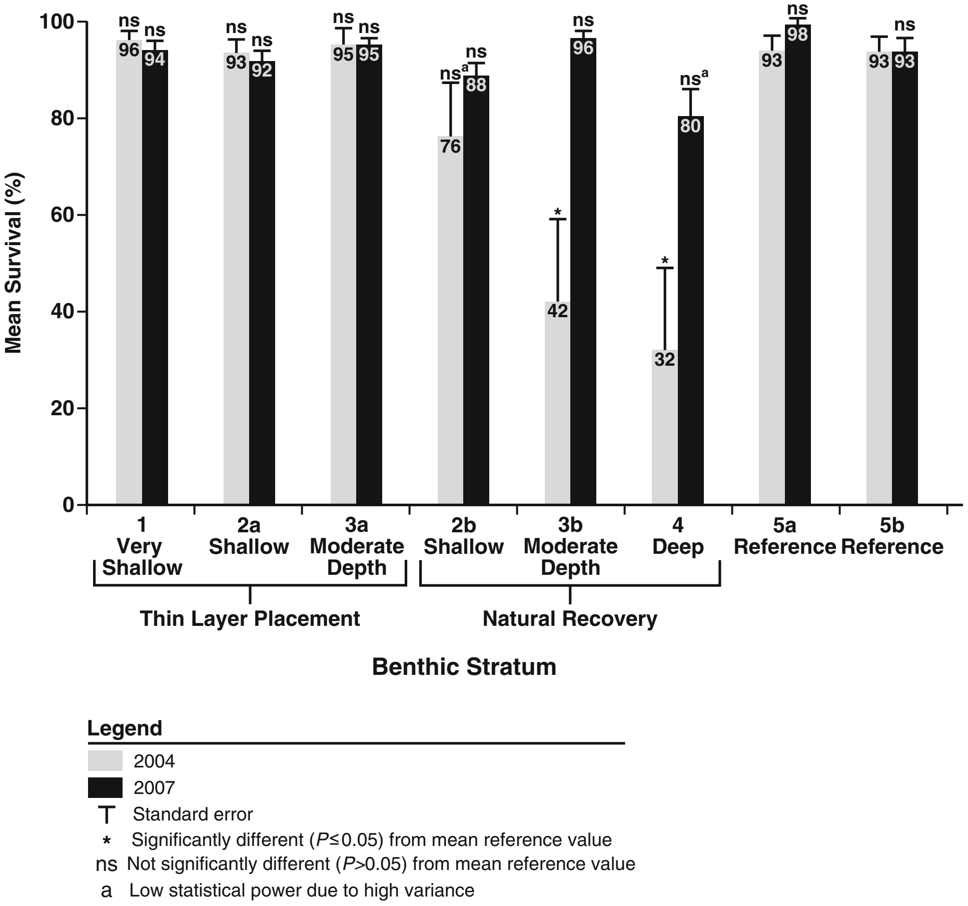
removed by flocculating with alum (Alcoa, 2006). *In situ* POM exposures were tested initially on a trial basis in 2006 and 2007, with more sites added in 2008 and 2009. Porewater results indicating the effectiveness of the carbon amendment for reducing porewater PCB concentrations are shown in Figure 14.5.

Use of Data. These data indicate that the treatment with activated carbon substantially decreased concentrations of PCBs in interstitial porewater, which indicates reduced bioavailability of the contaminants (Alcoa, 2010). This information indicates the potential for integrating activated carbon placement into the site remedy during the remedial design phase.

14.8.4 Benthic Toxicity, Ward Cove, Ketchikan, Alaska

Background. Sediments in Ward Cove, Ketchikan, Alaska, were contaminated from historical releases of large quantities of organic material as byproducts from wood pulping. Cleanup targeted ecological risks associated with the benthic toxicity of three contaminants of concern (ammonia, 4-methlyphenol, and sulfide) in sediments (USEPA, 2000). Remediation took place from 2000 to 2001, over 80 acres. The selected remedy included areas of MNR, placement of 6–12 in. of sand ("thin layer placement"), or dredging (USEPA, 2010). The RAOs at the site were to reduce toxicity of surface sediments and enhance recolonization of surface sediments to support healthy marine benthic macroinvertebrate communities (USEPA, 2000).

Sampling Description. Sediment sampling was specified to occur in July every third year after completion of the remedial activities (e.g., 2004 and 2007) until RAOs were achieved (Integral, 2009). Toxicity testing was one line of evidence used to evaluate attainment of the RAOs. Toxicity of the surface sediments was tested using the 10-day amphipod acute toxicity test based on *Eohaustorius estuarius*. Two reference areas were also designated within the cove, based on water depth and distance from known sources of chemical contamination. Comparisons were made by statistically comparing the mean conditions in each area of concern with conditions in the corresponding reference area.



Note: Value of mean amphipod survival is noted at top of each bar

Figure 14.6. Amphipod acute toxicity results at various stations (based on depth and remedial activity) in Ward Cove during 2004 and 2007 (excerpted from Integral, 2009).

Use of data. The RAO for the reduction of surface sediment toxicity was considered achieved when organism survival exceeded 75%. In 2009, all locations exceeded that criterion, indicating that the RAO based on sediment toxicity has been achieved throughout the area of concern (Integral Consulting, 2009) (Figure 14.6). Based on toxicity and other lines of evidence (e.g., benthic community metrics), USEPA determined that the RAOs for the Marine Operable Unit have been achieved and that no further sediment monitoring would be performed (USEPA, 2010).

14.8.5 Contaminant Bioaccumulation Analyses, Grasse River, New York, Activated Carbon Pilot

Background. As described above, several pilot studies were conducted in Grasse River, New York, to evaluate remedial options for PCB contaminated sediments, including evaluating the effect of activated carbon additions on PCB bioavailability (Alcoa, 2010). The effect of the carbon treatment on PCB bioaccumulation in the sediment-dwelling oligochaete *Lumbriculus variegatus* was the key biological line of evidence used to evaluate whether carbon treatment reduced the bioavailability and organism uptake of PCBs.

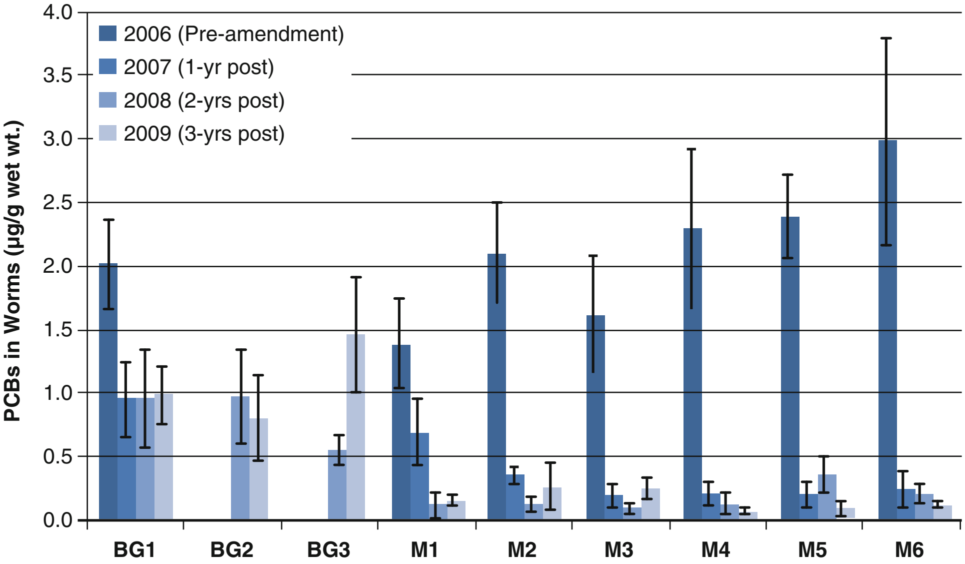


Figure 14.7. Average total PCB concentration in *Lumbriculus variegatus* from before and for 3 years after activated carbon treatment of sediments. Bioaccumulation tests were conducted *in situ* at background and activated carbon treatment sites. BG – background; M 1–6 are locations within the treatment area (excerpted from Alcoa, 2010).

Sampling Description. *L. variegatus* were exposed *in situ* and *ex situ* to Grasse River sediments. *In situ* sampling was accomplished by placing organisms in cages on the sediment bed (Alcoa, 2006; methods adapted from Burton et al., 2005). Briefly, site sediments were placed in replicate exposure chambers along with *L. variegatus*. These chambers were placed on a rack, lowered to the sediment surface, and left in the river for 14 days. *Ex situ*, or laboratory, exposures were conducted by collecting river sediments and shipping them for testing. At the Grasse River, *L. variegatus* were exposed in 150 milliliters (mL) of sediment for 14 days. In both cases, PCB concentrations in *L. variegatus* were measured by congener analysis. Further details on the sampling and monitoring results are available in Beckingham and Ghosh (2010, 2011).

Use of Data. PCB uptake by sediment-dwelling organisms is a direct measure of the bioavailability of contaminants in sediments. *L. variegatus* assays are widely used as standardized measures of bioaccumulation of contaminants from sediments. One advantage is that in contrast to, for example, resident fish, the exposure history of the organisms is fully understood. Contaminant uptake only stems from the collected sample so uncertainty exists as to whether results are representative of the entire site (an issue addressed through collection of multiple locations and replicates at individual locations). The reduction in PCB bioaccumulation following activated carbon treatment was apparent over 3 years in both *in situ* and *ex situ* evaluations (Figure 14.7 [*in situ*]). The reduction in tissue concentrations mirrors the reduction in porewater concentrations shown in Figure 14.5.

14.8.6 Contaminant Concentrations in Resident Organisms, Cumberland Bay, Lake Champlain, New York

Background. Cumberland Bay, located on Lake Champlain at Plattsburgh, New York, was contaminated with PCBs from industrial discharges, including from paper recycling activities. Sediment PCB contamination in the bay was greatest within a sludge bed of wood and paper pulp, wood debris, and waste paper that encompassed approximately 50 acres (NYSDEC, 2001).

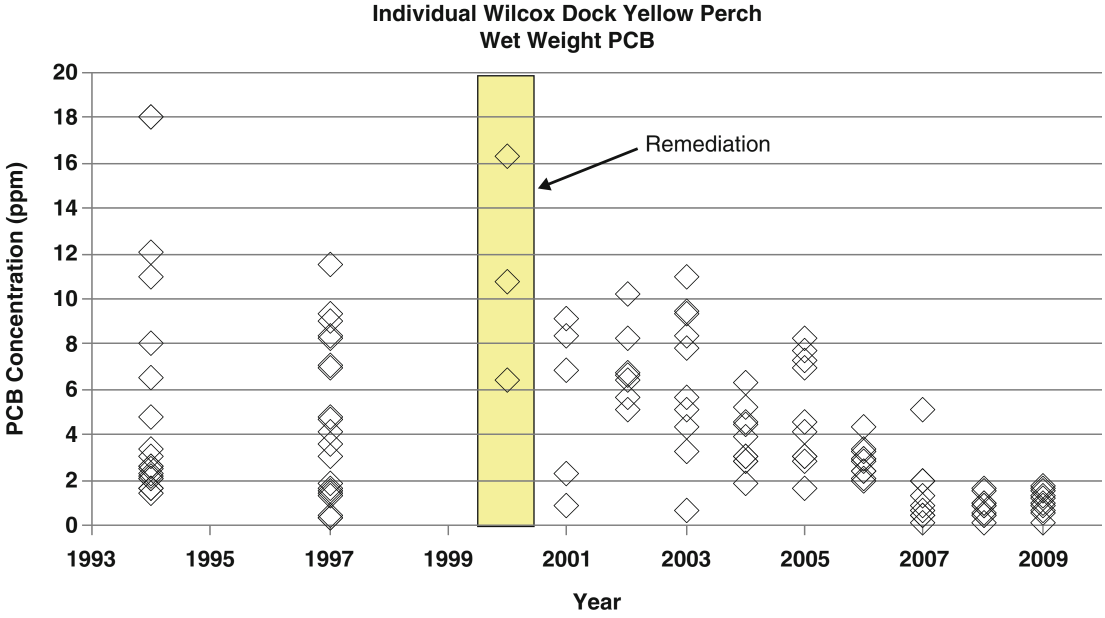


Figure 14.8. Fish tissue PCB concentrations (total PCB as Aroclors) over time in yellow perch sampled in the fall in Lake Champlain, New York, at Cumberland Bay (Wilcox Dock) (adapted from figure provided by Michael Kane, New York State Department of Environmental Conservation, April 2010).

Dredging occurred at the site between 1999 and 2000, with the objective of removing the entirety of the contaminated sludge bed. Residual contamination remained following dredging, owing to challenges presented by debris and heterogeneity of bottom conditions (NYSDEC, 2001; NRC, 2007).

Sampling Description. Fish tissue monitoring at the site includes a variety of species, such as rock bass, perch, and American eel. These have been collected by the state of New York since the 1980s and have been used to support fish consumption advisories, which are in place for Cumberland Bay for American eel, brown bullhead, and yellow perch (NYSDOH, 2010). The site is notable for the relatively long time since remediation and the consistent collection of resident fish for contaminant monitoring during that timeframe. Fish sampling had previously occurred during the spring and fall, but has shifted to the fall timeframe when levels of PCBs are higher and believed to be more representative of resident fish (Myers, 2007). The long-term data set for yellow perch collected during the fall at Wilcox Dock (within the cleanup area) has 12 time points, typically consisting of ten perch from each period (a notable exception: the "during dredging time frame, in 2000 only has three fish").

Use of Data. The primary purpose of these data is to evaluate whether fish consumption advisories are warranted for Cumberland Bay on Lake Champlain. However because of their consistent collection before, during, and after remediation, they also can be used to evaluate the influence of the remedial dredging on fish tissue contaminant concentrations. The data demonstrate substantial inter-individual variability in contaminant concentrations with some animals above 10 ppm prior to and immediately after remediation (Figure 14.8). Since then, average concentrations have declined and the variability has lessened; however, fish are currently still at levels that necessitate fish consumption advisories (NYSDOH, 2010).

14.9 SUMMARY

Contaminant cleanup at sediment sites is a long-term process from initial characterization to achieving RAOs. Along with statutory requirements, the human and ecological risk implications of the cleanups, the large private and public expenditures associated with operations, and the generally public ownership of remediated waterways mandates that remedy effectiveness is tracked and verified. Planning is needed as early in the process as possible to set the stage for monitoring the progress toward and attainment of RAOs. Active remediation at sites is a complex undertaking with monitoring occurring to establish risk, verify “as-built” conditions, satisfy permit (or their substantive) requirements, and monitor whether risk reduction objectives were met. Thus, a framework of remediation phases and timeframes has been presented to place site activities and their associated monitoring into context.

Remedy effectiveness monitoring includes a number of fundamental components. First, clear objectives of the remediation need to be stated in terms of the media or receptors to be improved, contaminant levels to be achieved, and the associated timeframe. An adequate database of baseline conditions is required so that environmental improvement and remedy effectiveness can be quantitatively evaluated. Finally, a monitoring plan needs to be developed that includes indicators and analyses capable of establishing whether remediation has achieved the RAOs of the project. A range of chemical and biological lines of evidence can be used to document that contaminant exposures have been lessened and that resulting risk to (or from) biological receptors has been reduced to acceptable levels. Lines of evidence supporting remedy effectiveness evaluations are drawn from the RAOs that define the receptors of concern and the CSM that defines the environmental media driving risk to those receptors. The usefulness in decision-making of several of these lines of evidence has been borne out in applications at contaminated sediment sites.

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