NATURAL RECOVERY: MONITORING DECLINES IN SEDIMENT CHEMICAL CONCENTRATIONS AND BIOLOGICAL ENDPOINTS

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ABSTRACT: Monitored Natural Recovery (MNR) of sediments is a risk management alternative that relies upon natural environmental processes to reduce risk to the environment. Reduction of human health and environmental risks from naturally occurring sedimentation, degradation, and other processes has been demonstrated at a number of sites through focused long-term monitoring programs. Long-term MNR programs implemented to date at such sites have included: 1) attention to quality control of long-term chemical and biological monitoring records; 2) characterization of source loadings and key contaminant transport and sediment stability processes; 3) development of acceptable and defensible predictive tools; 4) implementation of statistically-based sediment chemistry monitoring programs, including focused surface sampling and/or subsurface coring; and 5) implementation of statistically-based biological monitoring programs focused on key exposure and risk endpoints. This paper reviews example case histories from two representative sediment contamination sites within Washington State, USA. Natural recovery processes occurring at these sites have effectively reduced over a period of years to tens of years the concentration, bioavailability, and toxicity of contaminants in sediment. Bioaccumulation and histopathology endpoints were not explicitly evaluated in the two example case studies discussed in this paper, though the evaluation framework described herein has been applied elsewhere in Washington State an elsewhere to address such relatively more complex site conditions. The evaluation framework presented in this and supporting papers is intended to contribute to the development of science-based assessments of MNR in the remedy evaluation processes for other contaminated sediment sites.

This working draft paper outlines a "weight-of-evidence" approach for evaluating the use of monitored natural recovery (MNR) for the remediation of contaminated sediments. This paper is one in a series of five papers proposing a framework, based on site-specific information, of five interrelated elements to assess the use and effectiveness of MNR. Developed by individual members of the Sediments Remediation Action Team under the Remediation Technologies Development Forum (RTDF), the papers are meant to serve as a resource to interested parties, but are not intended to be comprehensive or provide detailed information.

The five working draft papers represent the views of the authors and have not been subjected to EPA peer review. Therefore, it does not necessarily reflect the views of the EPA, and no official endorsement should be inferred. The working draft papers are not a regulation, and therefore, they do not impose legally binding requirements on EPA, States, or the regulated community, and may not apply to a particular situation based upon the circumstances. Interested parties are free to raise questions and objections regarding the "weight-of-evidence" approach provided in the papers. The RTDF Sediments Remediation Action Team is seeking and welcomes public comments on the papers. The papers are working drafts and may be revised periodically without public notice. Use or mention of trade names does not constitute endorsement or recommendation for use.

INTRODUCTION

For many contaminated sediment sites, implementing a focused program of source control and/or "hotspot" remediation has provided environmental benefits within the receiving water environment. Sediment monitored natural recovery (MNR), which relies upon natural environmental processes (chemical/biological or physical) to reduce risk, may be particularly effective at sites where processes are sufficient to reduce risks within a time frame comparable to that required for more active risk reduction strategies.

As discussed in Davis et al. (2004), evaluations of MNR are best performed using multiple lines of information. To promote proper technical evaluation, and increase the certainty associated with implementation of this remedial option in appropriate situations, the Remediation Technologies Development Forum (RTDF) Sediment workgroup has developed a framework for performing an appropriate MNR evaluation. The framework relies on a weight-of-evidence approach to evaluate and document risk reduction resulting from a combination of source controls and naturally occurring processes. Typically, the assessment of MNR is conducted as a component of a broader assessment of risk management alternatives for a given site.

This paper examines those lines of evidence that address the historical record of contaminant concentrations in sediments, as well as corroboration of MNR based on key biological endpoints. To the extent such historical monitoring information are available, the reliability of the overall MNR evaluation can be substantially improved, also reducing uncertainties in forecasts of the future effectiveness of MNR to achieve human health and environmental risk reductions. Monitoring data available for representative contaminated sediment sites are summarized in this paper, and in a manner consistent with the RTDF-Sediment workgroup framework. These data provide important case history examples of the effectiveness of MNR following implementation of source controls, including focused "hotspot" remediation at selected sites. Such monitoring data suggest that in appropriate settings, over a period of years to tens of years, natural recovery processes can effectively reduce the concentration, bioavailability, and toxicity of contaminants in sediment.

EVALUATION FRAMEWORK

A critical component in the evaluation of any sediment management option, including MNR, is an accurate characterization of historic and current contaminant loading to the sediment site (e.g., from watershed and point sources). In the not-uncommon situation where ongoing sources of chemicals to a site are sufficient to contaminate (and potentially re-contaminate) sediments within at least portions of a site, additional steps may be needed to further identify current sources and support focused source control actions. At many sites, it may also be critical to characterize the importance of internal resuspension sources, including "hotspots", since these internal sources can act as a potential reservoir of chemicals that are available for recirculation through the aquatic system, including biota. As discussed in Davis et al. (2004), the site characterization should elucidate the mechanisms, rates, and spatial variation for these and other key processes to provide an adequate understanding for use in the MNR evaluation.

Another key element of the weight-of-evidence MNR evaluation framework developed by the RTDF is the retrospective evaluation of historical chemistry and biological data to document and corroborate risk reduction resulting from source controls and naturally occurring processes. By reviewing data assembled from past sampling events, the historical record for contaminated sediments can be established. These historical trends can be used to assess whether significant reductions in chemical concentrations have previously occurred in surface sediments, and can also be used to project future rates of recovery. However, it is important when evaluating these trends to assess the quality (e.g. QA/QC) of the data, including comparisons of field and analytical techniques used during different sampling events.

Sediment coring data is often used to corroborate long-term chemical monitoring data and can be used to further establish the historical record of sediment deposition, sediment mixing, as well as weathering patterns. Reconstruction of the history of chemical loadings and natural recovery processes at a site may be obtained through characterization of vertical sediment profiles. Sediment cores, collected in depositional areas, are vertically segmented, with the contaminant concentrations determined in representative segments to establish a vertical contaminant profile. Coupling the vertical contaminant profile with radioisotope dating (e.g., ^{7}Be, ^{210}Pb and/or ^{137}Cs) can be used to help reconstruct the pattern of historical chemical releases to the site, also providing basic information on sedimentation and mixing (bioturbation) rates. Vertical contaminant concentration profiles are often a valuable tool to corroborate historical trends of surface sediment concentrations.

At some sediment sites, biological endpoints may serve as the primary line of evidence for assessing human health and/or ecological protection. Depending on the specific site conditions, monitoring of key biological endpoints can provide a direct measure to corroborate whether or not MNR has occurred. It is particularly important in such cases to consider whether there are adequate, comparable historical biological endpoint data available to support an evaluation of temporal trends, including evaluations of the comparability of techniques used during different sampling events, along with consideration of the nature of the biological processes being measured. Statistically valid methods for testing the significance of identified biological trends can often be employed, controlling for potentially confounding factors such as organism age and other variables.

In consideration of these issues, successful long-term MNR programs implemented to date have often included:

- Attention to quality control to ensure the comparability, representativeness, and accuracy of long-term chemical and biological monitoring records;
- Characterization of source loadings and key contaminant fate/transport and sediment stability processes;
- Development of acceptable and defensible predictive tools;
- Implementation of statistically-based sediment chemistry monitoring programs, including both surface sediment samples and subsurface sediment cores collected at regular spatial and temporal intervals, along with supporting radioisotope tracer data; and
- Implementation of statistically-based biological monitoring programs focused on key exposure and risk endpoints, including one or more of the following:
    - Tissue chemical and/or histopathology analyses of target species;

- Whole sediment acute and chronic bioassay analyses; and
- Community analyses of benthic infauna and/or fisheries.

Representative long-term MNR case histories from two sediment contamination sites in Washington State are presented in the following sections to further describe the evaluation framework.

Bellingham Bay, Washington, USA: Bellingham Bay is a relatively large (> 100 km^2), shallow (10 to 15 m water depth) estuary located in northwest Washington State. Beginning in 1965, wastewaters containing mercury were discharged into the inner (western) portion of the bay from a newly constructed chlor/alkali facility. Starting in 1971, mercury discharges from the facility were controlled through a series of process changes and wastewater treatment improvements. Monitoring data collected under the facility's state wastewater discharge permit, supplemented with additional research data, provide an accurate reconstruction of annual mercury loadings to the bay from this source, relative to area background inputs (Figure 1; Bothner et al., 1980; Officer and Lynch, 1989; Anchor, 2000). These data document that significant reduction in mercury loadings to the bay were achieved at the site by the early 1970s.

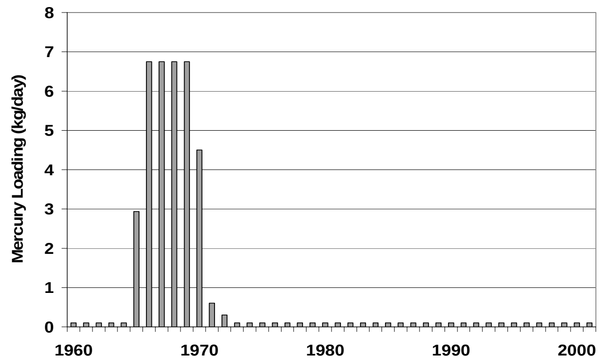

FIGURE 1. Historical Mercury Loadings to Bellingham Bay

Key sediment and mercury fate and transport processes were characterized in Bellingham Bay as part of a sediment cleanup remedial investigation/feasibility study (RI/FS) of the site (Anchor, 2000). Following initial screening-level monitoring and modeling assessments suggesting the effectiveness of natural recovery at this site (Bothner et al., 1980; Officer and Lynch, 1989), the RI/FS provided more definitive characterization of the more important processes such as sedimentation, erosion/resuspension, and biological and physical mixing in the bed. Sediment stability assessments were performed to project the integrity of the bed under future extreme events, such as episodic storm surges. Based on these evaluations, a region of stable sediments exposed to current velocities below 40 cm/sec was identified in an area of the bay proximal to the point of historical mercury release from the chlor/alkali facility (Figure 2).

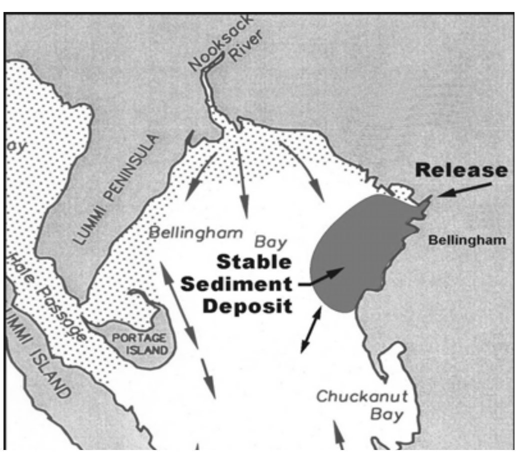

FIGURE 2. Location of Stable Sediment Deposits in Bellingham Bay

As a result of a variety of academic research studies, regional monitoring programs, and the RI/FS (Anchor, 2000), a considerable amount of surface and subsurface sediment chemistry data have been collected over time in Bellingham Bay.

Sediment total mercury sampling data collected with proper quality control procedures are available for the site beginning in the early 1970s, and provide a basis to assess historical changes in sediment quality over more than a 30-year monitoring period. These data reveal that surface sediment mercury concentrations in inner Bellingham Bay declined between 10- and 100-fold following the implementation (in the early 1970s) of increasingly effective source controls (Figure 3). The rate of recovery was greatest at locations closest to the point of historical release. By the year 2002, surface sediments throughout much of Bellingham Bay had recovered to below Washington State Sediment Management Standards (SMS; Anchor, 2003).

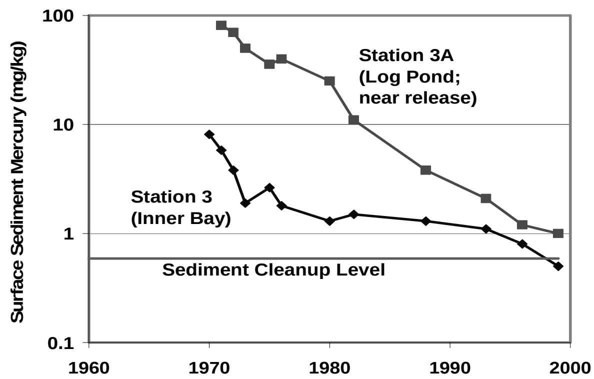

FIGURE 3. Recovery of Bellingham Bay Surface Sediment Mercury Concentrations

In addition to the surface sediment data presented above, subsurface sediment sampling data with supporting radioisotope tracer data are also available for the Bellingham Bay site, with comparable coring data collected at several time intervals following source control (Figure 4). These data corroborate both the magnitude and rate of recovery observed in the separate surface sediment sampling monitoring record, and also further elucidate the mechanism by which the observed recovery occurred. Recovery in this case (e.g., at inner bay Station 3) is consistent with the measured net sedimentation rate (based on radioisotope dating) of approximately 1.6 cm/yr, and with bioturbation of the surface 16 cm of sediments at an average measured rate of 34 cm^2/yr (Bothner et al., 1980; Officer and Lynch, 1989; Anchor, 2000). Sediment trap data confirmed that relatively low sediment input concentrations were being deposited onto the site, providing a direct measure of the effectiveness of prior source control measures.

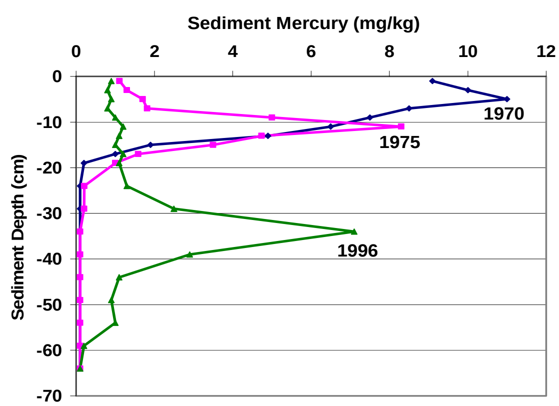

FIGURE 4. Historical Changes in Sediment Core Profiles: Inner Bellingham Bay

Although the chemical monitoring data presented above revealed that nearly all of Bellingham Bay had recovered to below sediment cleanup standards by 2000, a localized sediment "hotspot" nevertheless remained at the site near the original source area (near Station 3A; Figure 3), that had the potential to act as an internal source of mercury to the adjoining waterway through sediment resuspension processes. Accordingly, in late 2000/early 2001, this area of the site was remediated through a combined sediment capping/habitat restoration action (Anchor, 2001). The action controlled "hotspot" releases of mercury to the site, and accelerated the recovery of the adjacent waterway by further reducing sediment input/depositional concentrations. Post-construction monitoring confirmed the effectiveness/protectiveness of the integrated cleanup and habitat restoration action, and also verified that the action accelerated recovery of adjacent waterway areas (Anchor, 2002, 2003).

Bioaccumulation of mercury in fish and shellfish populations within inner Bellingham Bay was evaluated through direct sampling of target fish/shellfish tissues conducted during the RI/FS (Anchor, 2000). While tissue mercury (primarily methylmercury) concentrations within the site area were approximately 2-fold higher than regional background levels for certain species such as Dungeness crab, even the maximum tissue concentration detected during the RI/FS was below the current U.S. Environmental Protection Agency (EPA, 2002) risk-based tissue residue screening criterion of 0.3 mg/kg wet wt. Even under conservative assessment assumptions (e.g., 90^{th} percentile combined upper-bound consumption rates and upper-bound measured tissue concentrations), no human health risk was identified for tribal fishers or other consumers within the site area. Similarly, the maximum tissue mercury concentrations were also below benchmark levels that are protective of sensitive fish-eating wildlife.

Although the RI/FS did not identify bioaccumulation-related risks in Bellingham Bay, whole sediment acute and chronic bioassays performed on surface sediment samples (0 to 15 cm) collected from the site nevertheless indicated that certain areas of the site posed ecological risks to benthos, particularly during the early stages of the recovery period (PTI, 1989). Whole sediment bioassays at this site were performed following SMS protocols, and included amphipod acute toxicity bioassays, larval toxicity/abnormality bioassays, and juvenile polychaete growth tests. Consistent with the chemical monitoring record, by 1996 the areal extent of sediment toxicity in Bellingham Bay had been reduced by nearly 10-fold (Figure 5), and by 2002 had nearly fully recovered to below SMS risk-based criteria (Anchor, 2000, 2003). Thus, the biological endpoint monitoring record available for inner Bellingham Bay provided important corroborating evidence that environmental exposure at this site had recovered to below risk targets. Semi-quantitative community analyses of benthic infauna and fisheries provided further evidence of biological recovery at this site (Broad et al., 1984; Behr, 1998).

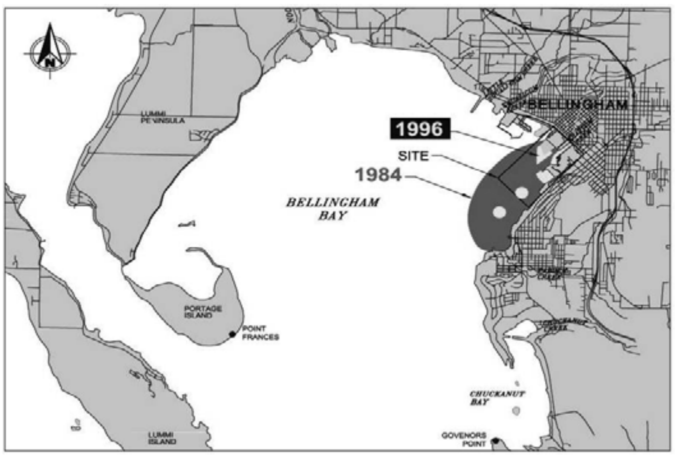

FIGURE 5. Surface Sediment Toxicity Recovery in Bellingham Bay

All information considered, the Bellingham Bay case history provides a compelling example of an integrated program consisting of effective and early implementation of source controls, focused hotspot cleanup to accelerate recovery, and monitoring over time to document recovery of chemical and biological conditions. To the extent that conditions in inner Bellingham Bay are similar to those of other sites, the observed rates of MNR may also be expected in other locations. The current site status can be found at: http://www.ecy.wa.gov/programs/tcp/sites/blhm_bay/sites/.htm.

Sitcum Waterway, Commencement Bay, Washington, USA: The Sitcum Waterway, part of the Commencement Bay estuary, is located within a similar environmental setting as the Bellingham Bay site discussed above. As such, these embayments share many similarities in terms of water depth (10 to 20 m), sediment stability, net accumulation rates (1.5 cm/yr), and bioturbation processes. However, largely because of the considerable navigation use of the main channel of the Sitcum Waterway, and the associated potential for future dredging and/or propeller wash-induced sediment resuspension, the EPA-approved cleanup remedy for this site consisted of hydraulic dredging of the navigation channel, associated berth areas, and waterway side slopes (both underpier and exposed slopes), with disposal in a nearby nearshore confined disposal facility (Port of Tacoma, 1992). The dredging project, implemented in 1993/1994, successfully removed contaminated sediments containing a range of metals, PAHs, and PCBs from the open water channel areas of the waterway and most of the side slope areas, achieving risk-based cleanup standards on the post-dredge surface. However, a portion of the side slope areas under Terminal 7, while successfully dredged as part of the cleanup action, still had remaining sediments that exceeded EPA's established sediment quality objectives. This was not unexpected, and this scenario was provided for as part of the approved cleanup plans. Based on the post-dredging conditions of the waterway, it was determined that the sediments under Terminal 7 would be appropriate for MNR.

The natural recovery determination was made as part of an established evaluation process that had commenced during pre-remedial design and continued through the remedial action phase. The effectiveness of natural recovery processes at the Sitcum Waterway site had initially been indicated through a focused RI/FS and pre-design evaluation program. Then, following collection and review of the post-dredging sediment quality data, the natural recovery processes were again evaluated based on current waterway conditions. The site investigation process conducted prior to the remedial action included deployment of sediment traps to characterize the status of source controls and sediment inputs, sediment core profiling and associated radioisotope analyses to characterize key fate and transport processes and document prior recovery rates, and incorporation of these data into relatively simple recovery models based on the Officer and Lynch (1989) formulation outlined above (Port of Tacoma, 1992). These evaluations suggested that recovery rates would likely be substantially accelerated as a result of dredging (i.e., removal of contaminated sediments, thereby eliminating potential contaminated sediment sources to the area requiring natural recovery; Figure 6). When evaluated with the post-dredging data and waterway conditions, natural recovery of the Terminal 7 underpier area was expected within a period of years following dredging.

Consistent with EPA-approved plans, the Port of Tacoma performed focused MNR surface sediment quality monitoring in Year 4 (1998) and Year 9 (2003) following completion of the remedial action (Port of Tacoma, 1998, 2004). Monitoring verified that chemical concentrations (represented by lead and high molecular weight PAHs) in the under-pier area recovered to below cleanup standards, consistent with model predictions (Figure 6). Stormwater source controls are ongoing to ensure the continued success of the remedial action in localized under-pier outfall areas.

Similar to the Bellingham Bay case study presented above, recovery was confirmed to have been accelerated by the Port of Tacoma's remedial dredging action, which provided clean sediment within the channel and berth areas as the primary source material to the under-pier area. The resuspension of these clean source materials and their deposition under the pier has reduced sediment concentrations to cleanup standards within the natural recovery area.

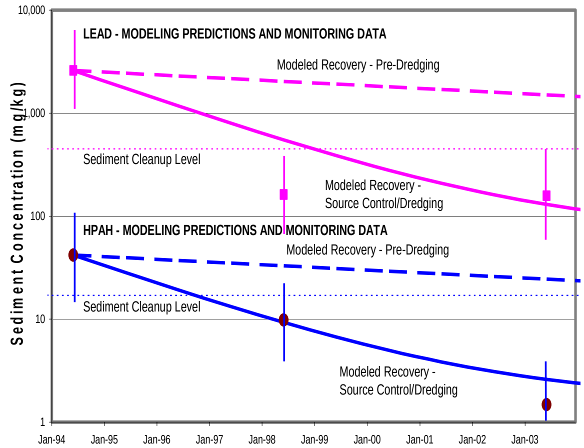

FIGURE 6. Accelerated Natural Recovery After Dredging: Sitcum Under-Pier Area

SUMMARY

Monitoring data available for representative contaminated sediment sites are summarized above in a manner consistent with the RTDF-Sediment workgroup framework. These data provide important case history examples of the effectiveness of MNR following implementation of source controls and remedial dredging, including focused "hotspot" remediation at selected sites. The available monitoring record reveals that MNR has been an effective cleanup method at sites where: 1) sources have been adequately controlled; 2) the sediment bed is largely stable; and 3) sufficient sediment deposition occurs at a site to facilitate reductions in contaminated sediment concentrations over time. Depending on site conditions, MNR can be implemented either alone or in combination with other remedial technologies to achieve long-term effectiveness and risk control. Monitoring data collected at the two case study sites as well as in other similar areas confirm that when applied appropriately, natural recovery processes can effectively reduce over a period of years to tens of years the concentration, bioavailability, and toxicity of contaminants in sediment.

Bioaccumulation and histopathology endpoints were not explicitly evaluated in the two relatively simple example case studies described above. However, the evaluation framework described herein has been similarly applied elsewhere in Washington State and in other areas of the U.S. to address such site conditions (e.g., Spokane River PCB bioaccumulation recovery; Eagle Harbor fish lesion recovery). Detailed review of these relatively more complex case histories was beyond the scope of this framework paper.

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