CONTAMINATED SEDIMENT MANAGEMENT TECHNICAL PAPERS

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Sediment Management
Work Group

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SECTION 1.0: INTRODUCTION

BACKGROUND

Over the past two decades, much of the focus of remediation driven by state and Federal regulatory programs (e.g., RCRA, Superfund, TSCA) was on soil and groundwater issues. More recently the focus appears to be shifting to contaminated sediment sites. These sites typically involve more complex scientific issues than their land-based counterparts. For example, in most cases rivers and estuaries defy the traditional definition of "site" as it has been applied to land-based units. Also, in addition to the traditional site and risk assessments, complex questions relating to ecological risk, the effectiveness/capabilities of each sediment management alternative, the implementation risks of each option, and the need to establish clearly defined risk-based remedial action objectives (RAOs) should be, but often have not been, important factors in the decision-making process.

While Superfund has matured, the sediment remediation arena is still in its infancy. To date, although many (40 to 50) dredging projects have been completed, very few large-volume [greater than 50,000 cubic yards (cy)] sediment projects have been completed. Certainly none have been completed in the order of magnitude of those which are now entering into the remedy selection phase at several of our nation's largest river systems. While sediment volumes of 50,000 to 70,000 cy were considered large only a few years ago, sediment volumes at some of the sites facing remedy selection now involve hundreds of thousands and, in some cases, millions of cubic yards of sediment.

Some analogies may be drawn and perhaps even some lessons learned between early Superfund approaches and the current state of contaminated management strategy. For example, during the first decade or so of Superfund, the typical approach to address contaminated groundwater was to rely on pump and treatment remedies. As the science progressed and evidence of the shortcomings of pump and treatment remedies mounted, a greater emphasis was placed on natural attenuation as a potentially viable remedial option. Similarly, with sediment management strategy in its formative stages, present policy seems to strongly favor dredging as the presumptive remedy. With the recent scrutiny of the effectiveness of dredging in managing contaminated sediments, the time is right for serious scientific consideration of other sediment management options.

The need to objectively review all viable sediment management options is underscored by the magnitude of the sediment management issue, which is significant by any conventional standard of measurement. Many U.S. harbors, lakes, estuaries, and rivers contain contaminated sediments, varying in extent, contaminant type, and physical and environmental setting. The United States Environmental Protection Agency (USEPA) recently estimated that 25 to 30% (approximately 400) of the sites targeted for cleanup under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and included on the National Priorities List (NPL) pertain to impacted sediments. In addition, *EPA's Contaminated Sediment Management Strategy* estimates that approximately 10% of the sediment underlying our nation's surface water (approximately 1.2 billion cy in the upper 5 centimeters alone) is impacted with levels of contaminants that pose potential risks to fish and humans who eat fish (USEPA, April 1998). Assuming that this is a reasonable estimate and adding the thickness of the sediment that would practicably need to be managed (2 to over 3 feet) to address this area, an estimated 20 trillion cy of sediment might require some form of management. To further frame the issue, if the sediment management option chosen is removal, costs could easily exceed $5 trillion ($5,000,000,000,000) using a median cost for environmental dredging of $250/cy.[1]

SEDIMENT MANAGEMENT STRATEGY CONSIDERATIONS

Given the magnitude of the contaminated sediment issue it is clear that the best scientific tools available must be used to ensure that the impacts from these sediments are understood and are properly characterized. The cost projections referenced above strongly suggest that alternatives to sediment removal should be given full scientific consideration in the development of an effective national sediment management program. In addition, recent experience can be drawn upon to evaluate the limitations and capabilities of dredging as a remedial technology. While dredging is a tool that merits consideration in contaminated sediment management, it is but one tool, and there is a growing body of evidence that suggests that several dredging projects have experienced problems in achieving removal goals. At some sites, dredging has been shown to actually have exacerbated surface sediment contaminant levels through exposure of more highly contaminated sediments at depth or through resuspension effects.

The following considerations should have a role in future sediment management strategy:

- The management strategy should be based on sound science and risk assessment/risk management principles, taking into consideration site-specific conditions.

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[1] The range for dredging costs for the projects in the survey conducted by the author of the paper, *State of Current Contaminated Sediment Management Practices* (Appendix D), was $44 to $1842 p/cy. The unit cost of managing contaminated sediments depends largely on the degree of environmental controls involved (low production rate) and high costs of disposal.

- RAOs should be developed based on an understanding of contaminant movement and uptake and exposure pathways leading to potentially unacceptable risks in specific receptors. In the history of contaminated sediment management in the United States, all too often RAOs have been based on removal of contaminant mass from aquatic systems without a clear understanding of the benefit of such removal or the detrimental effects of intrusive actions that necessarily accompany such actions.
- Natural recovery should be given greater prominence in the evaluation of sediment management options. At most sites, natural recovery should be viewed as establishing a baseline against which the risks and benefits of more intrusive sediment management actions may be compared. In this manner, actions that have the least potential to disrupt natural systems while still achieving RAOs in a reasonable time frame can be fully evaluated and considered.
- National policy should embrace an "even playing field." Accordingly, no presumptions in favor of natural recovery, containment, dredging or any other viable option or combination of options should be made. Site-specific risk assessment and risk management decisions will need to provide the basis for sediment management strategy. Based on this evaluation, some sites will rely predominantly on natural recovery, some will rely predominantly on dredging, and some will likely require an array of solutions, but all should be selected to meet the needs of the specific site.

SWMG AND DOCUMENT OBJECTIVES

The Sediment Management Work Group (SMWG) was formed in May 1998 to advance risk-based, scientifically sound approaches for evaluating sediment management decisions. The SMWG consists of industry, government, academic, and trade association members whose objectives are to collect, develop, analyze, and share data and information on the effectiveness of sediment management technologies and approaches. For information regarding the SMWG, including a current list of member companies, please visit our web site at http://www.smwg.org. This document is intended to achieve this objective by providing:

- Sound technical guidance that can be used as a tool by members and all who are engaged in developing effective sediment management strategies.
- A framework for evaluating sediment management options.

Technical documentation for regulators and public policy decision-makers establishing the viability, value, and critical importance of applying the USEPA's existing risk-based decision-making guidance when making sediment management decisions and in establishing RAOs.

APPROACH

Many site-specific factors must be considered when implementing a contaminated sediment management program. Understanding and interpreting these factors so that effective remediation, if necessary, is achieved requires the application of a logical and systematic approach that incorporates sound science. Risk-based decision making is an integral part of this approach and is critical to managing contaminated sediments and ensuring that levels of risk are assessed throughout the process.

To address the variety and complexity of contaminated sediment management decision making, the SMWG focused on the following key questions:

- Are there simple actions that can quickly reduce the apparent problem?
- Are ongoing, external sources significant?
- What are the real risks—is there truly a problem?
- When will risks become acceptable via natural recovery?
- Will rare events (e.g., storms) significantly disrupt conditions?
- Can active remediation significantly accelerate the achievement of acceptable risk?
- What impacts will active remediation have on risks?

While many other questions must be answered when dealing with contaminated sediments, these questions are especially important.

To help address these questions, the SMWG commissioned technical papers by leading technology experts. As part of this effort, a decision tree for sediment management was developed (see Figure 1). The tree introduces a step-by-step framework for integrating the various factors associated with contaminated sediments in a manner that results in a coherent management strategy. A more detailed decision tree/framework is provided in Appendix A and serves as the foundation for the remainder of this document. An executive summary of each technical paper is provided in Section 2.0. More detailed strategic and technical information on approaches to address the issues highlighted by the decision tree are provided in the technical papers (see Appendixes B through D), which are the basis for the concepts summarized in Section 2.0 and serve as a resource in developing a contaminated sediment program.

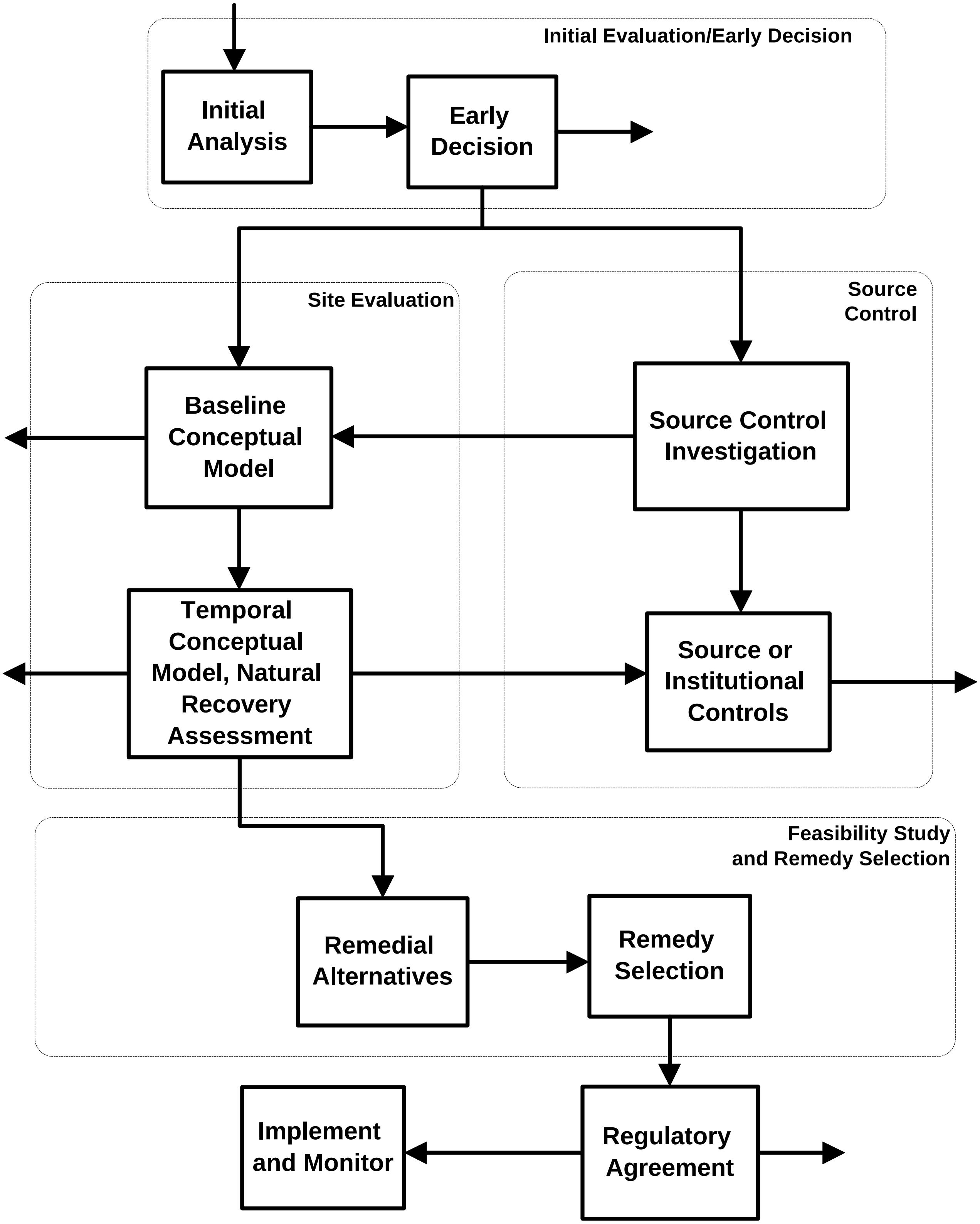

Figure 1. Sediment management decision framework.

SECTION 2.0: EXECUTIVE SUMMARIES

DECISION TREE FOR SEDIMENT MANAGEMENT

Developing an effective strategy for managing contaminated sediment sites requires the integration of a variety of factors, including, but not necessarily limited to, the following:

- An understanding of physical, chemical, and biotic components of the environmental setting
- The occurrence and dynamics of the chemicals of concern (COCs)
- The viability of potential exposure pathways
- The occurrence of potential human and ecological receptors of concern
- An understanding of the range of management technologies available
- The remedial action goals and objectives

Figure 1 outlines a decision tree for integrating these factors in a manner that results in a coherent sediment management strategy. The decision tree provides for early actions, where appropriate, to address more imminent adverse effects or to undertake actions that can be readily conceived and implemented without significant site evaluation. It also provides for early recognition and/or elimination of important ongoing external sources of contamination that could negatively impact the effectiveness and successful outcome of any future actions.

Below is a brief description of the main processes in the decision tree. (The more detailed technical paper on this topic is provided in Appendix A.) It is important to note, however, that the decision tree should be used in an iterative manner to arrive at a long-term sediment management strategy. In some cases, it is more effective to undertake remedial actions within specific portions of a site and evaluate their impact on the system rather than to defer action until the completion of a full-scale feasibility study. Such iterations are usually accompanied by a period of monitoring, which serves to calibrate the temporal conceptual model and enhance its reliability as a predictive tool.

Regardless of how the decision tree is used, discussions with regulatory representatives should occur throughout the process. Obtaining regulatory perspectives at the beginning of the sediment management process allows a more focused strategy to be developed and leads to a more efficient and effective achievement of remedial action objectives and project goals.

- *Initial Evaluation and Early Decision*
  This step is designed to address "new" sites and determine whether immediate action is appropriate, no action is appropriate, or no early decision can be made. Available information regarding physical characteristics, sources,

pathways, receptors, basic data on chemicals of concern, and potential risks are gathered and evaluated. Immediate response actions to mitigate exposure are identified and evaluated, if necessary. Site information is compared with qualitative or generic quantitative criteria to make appropriate risk-based decisions.

- *Source Control*
  Source control actions may be desirable if on-going external sources significantly contribute contaminants of concern to sediments or the water column. It is prudent to identify and prioritize opportunities to control external sources in the context of overall site evaluation and sediment management decision making because contaminated areas are likely to receive continuing impacts unless upstream sources are controlled. External sources are defined as loadings that are external to site sediments, including point sources or nonpoint source loads from outside of the specific study area.

- *Site Evaluation and Risk Assessment*
  The site evaluation is an iterative process with the following three primary objectives:
  — Determine the existing risks to human health and the environment by developing a baseline conceptual model.
  — Determine the future risks to human health and the environment by developing a temporal conceptual model, if necessary.
  — Prioritize the areas and issues of concern based on the developed models.

  When developing the baseline conceptual model and temporal conceptual model, data are collected, and evaluations are conducted, to define site characteristics, sources, extent and distribution of chemicals of concern, fate and transport processes, exposure pathways and uptake, and baseline human health and ecological risk. If necessary, data and models are developed to evaluate future conditions at the site, with consideration of natural processes. It is at this point in the process that the potential adequacy of natural recovery as a remedial choice is preliminarily addressed. The result is a site conceptual model that describes the nature, magnitude, and extent of the contamination and characterizes the risks of and uses impaired by the contamination. As such, the site conceptual model serves as the basis for determining whether remedial actions or improvements are necessary or beneficial and, if so, where these actions should be focused.

- *Feasibility Study/Remedy Selection*
  A feasibility study is conducted if the site evaluation reveals that baseline risks and future risks warrant remediation and that feasible alternatives are available. The feasibility study process

involves developing remedial objectives; identifying, screening, and developing technologies and alternatives; and conducting detailed analyses of alternatives and comparative analyses of alternatives. The approach of a sediment feasibility study follows the typical feasibility study process and relies on the nine National Contingency Program (NCP) criteria as the primary basis for decision making. However, because of the complex nature of sediment sites, emphasis is placed on comparatively evaluating alternatives in the areas of absolute and relative reductions in "real" risk over time, implementation risks, permanence, and cost. The natural recovery alternative serves as the baseline by which the effectiveness, implementability, and cost of "active" alternatives are compared and evaluated.

To select the most appropriate remedy, a tiered approach is applied that moves from qualitative evaluations and comparisons to detailed quantitative and predictive approaches. As necessary, quantitative models developed in the site evaluation are applied to simulate the effects of different remedial alternatives and to serve as a quantitative means of comparison. Similar to the site evaluation, the feasibility study should be focused on the areas of highest priority (areas of highest exposure or source areas), as determined in the site evaluation process. The primary criteria for comparison are as follows:

— Overall protection of human health and the environment
— Compliance with applicable or relevant and appropriate requirements (ARARs)
— Long-term effectiveness and permanence
— Toxicity, mobility, or volume reduction through treatment
— Short-term effectiveness
— Implementability
— Cost
— State agency acceptance
— Community acceptance

Upon completion of the feasibility study and given that sufficient information is generated, a remedy is selected and proposed based on balancing the evaluation criteria.

- *Implement and Monitor*
  After agreement is reached among stakeholders, implementation of the remedial action can proceed. Following implementation, it may be necessary to conduct an effective monitoring program to
  — Ensure that remedial action objectives (RAOs) are met.
  — Reestablish RAOs based on the practical limitations of selected technologies.
  — Revisit the remedy selection in the event that the selected technologies prove to be ineffective.

EFFECTIVE DECISION-MAKING MODELS FOR EVALUATING SEDIMENT MANAGEMENT OPTIONS

The USEPA, through its contaminated sediment management strategy (USEPA 1998), advocates a quantitative scientific approach to evaluating and remediating contaminated sediment sites. Although the strategy presents a sensible strategic approach, it does not provide the needed decision-making framework. The USEPA Great Lakes National Program Office proposed a framework as part of the Assessment and Remediation of Contaminated Sediments (ARCS) Program (USEPA 1993). This framework was implemented in several ARCS studies, but it has not been applied routinely, possibly because detailed guidance was not presented.

The typical approach to developing a contaminated sediment management plan has been to focus efforts initially on the feasibility of various remedial options. Typically, the efficacy of remediation is assumed or given cursory evaluation. Most notably, sediment removal is presumed to be an effective method to accelerate recovery at many sites and to be necessary to prevent the possibility that an increase in risk could occur following a catastrophic event. Evidence indicates that presumptions of efficacy are not always correct. The lack of efficacy of sediment removal in some cases likely was due to some combination of the following:

- The sediments may not have been the dominant source of the COC loadings to the ecosystem. For example, the contributing source may have been widespread low level concentrations of COCs, rather than definable “hot spots” or the COCs targeted by dredging were at depth and, consequently, were not contributing to the system or external continuing sources were still contributing COCs to the system.
- The removal action itself may have resulted in increased exposure. For example, surface sediment COC concentrations may have increased either because all of the higher concentrations in sediments at depth were not removed or because of resuspension or redistribution of higher concentration COCs (often found at depth) during the dredging operation.

The extent to which either or both of these circumstances are likely to occur can be determined if the assessments are guided by a decision framework grounded in sound science. This paper (provided in its entirety in Appendix B) outlines a framework that provides the information needed to answer the following questions intended to guide the final remedial decision for the site:

- When will the site recover to acceptable conditions via natural processes (i.e., natural recovery)?
- Will sediment removal accelerate the recovery? If so, by how much?
- Are there other remedial options more effective at accelerating recovery?

- What risks exist from rare event phenomena if the COC-containing sediments are left in place?

The answers to these questions are derived from an understanding of the relationship between the COC concentration in the sediment and risks to human health and relevant ecological receptors. This exposure concentration-risk relationship is characterized on the basis of a conceptual model of the fate, transport, and bioaccumulation of the sediment-associated contaminants. The model characterizes the site-specific exposure concentration-risk relationship, the relevance of buried contaminants, and the manner in which risks will change in the future under natural attenuation or the various options for active remediation. It is developed and applied through baseline and prospective assessments of the site. The complexity and degree of such assessments are a function of the site-specific conditions and the quality/quantity of data needed to reach a risk-based decision.

The baseline assessment involves evaluations of the COC distribution, exposure pathways, the routes and rates of COC migration, the contemporary natural recovery rate, and baseline risk. The data needs for these analyses pertain to the bioavailable surface sediments, the vertical gradients within the sediment column, and the specification of concentration in units meaningful to fate and exposure.

The sediment data, along with measurements of COC in the water column and biota, form the basis for estimating COC exposure to aquatic biota, wildlife, and humans. These data must be spatially and temporally averaged to determine relevant exposure concentrations. The regions over which spatial averages are computed are defined by the habitat and movement of the organisms for which risk is being calculated. The time over which averages are computed is defined by the toxicokinetics of the COC within these same organisms. COC concentrations must be expressed in units relevant to risk. In general, the appropriate units are mass of COC per mass of sediment organic matter (typically quantified as organic carbon). For many metals, it is appropriate to contrast the metal concentrations to the concentration of sulfide available for metal complexation.

The rate of natural recovery is established based on historical measurements of COCs in water, sediment, and biota. In the absence of a sediment, water, or biota data record of sufficient length to establish the rate of natural recovery, the rate may be established from the vertical profile of the COC in sediment cores taken from areas of the site where continual deposition has occurred. By dating the various layers of such cores, the vertical concentration profile is converted to a temporal concentration profile.

An understanding of the degree to which natural recovery processes may ameliorate COCs in surface sediments requires an understanding of the potential role and overall significance of external sources of COCs. External COC sources may exert control over the rate and extent of natural recovery as well as affect the success of active remediation efforts. Therefore, external COC sources such as contaminated groundwater discharges, nonpoint surface water runoff, surface water discharges, nonaqueous phase seeps, or process discharges must be quantified.

Estimation of the efficacy of remedial actions involves reanalyzing the baseline risk assessment with predicted future concentrations of COC in water, surface sediment, and aquatic biota. This has been referred to in the text as a prospective risk assessment to distinguish it from the baseline risk assessment. Future conditions are predicted using the understanding of the site and the COC levels, trends derived in the baseline assessment, and knowledge of the scheduling and engineering details of the potential remedial action plans. The prospective assessment involves two types of predictions: (1) natural recovery and active remediation and (2) impact of a rare storm or high flow event.

Various approaches may be taken to predict future COC concentrations. Levels of complexity range from Tier 1 (qualitative/semiquantitative approach) to Tier 2 (quantitative approach). The appropriate approach depends on the complexity of the problem and the degree of accuracy desired. Complexity arises from the hydrodynamic and sediment transport characteristics of the site and from the existence of significant external or internal sources. In complex cases, the appropriate approach involves detailed data analyses and the development of quantitative mass balance models, particularly if the collateral impacts of the considered remedial options are significant. This Tier 2 approach has four modeling components:
(1) hydrodynamics, (2) sediment transport, (3) COC fate, and (4) COC bioaccumulation. In simpler cases, correlation and extrapolation of site data and generic data may be adequate for decision making. Both types of approaches are outlined in the paper “Effective Decision-Making Models for Evaluating Sediment Management Options” (see Appendix B) as part of a proposed two-tiered approach to prospective assessment.

RISK-BASED MANAGEMENT PRINCIPLES FOR EVALUATING SEDIMENT MANAGEMENT OPTIONS

This paper (provided in its entirety in Appendix B) presents a tiered approach to risk assessment and risk management as an appropriate and efficient process for addressing human and ecological health concerns surrounding sediment contamination. Risk management input is critical to framing risk assessment issues and defining the types of risks that must be evaluated and solicited early in the assessment process. In particular, the selection of relevant human and ecological receptor groups, development of exposure scenarios, and specification of assessment endpoints for ecological receptors require discussions between risk managers and risk assessors. Contaminated sediment risk assessments and risk management decisions usually require consideration of both human health and ecological concerns due to the close links between many ecological processes and sources of food and drinking water for human receptor groups.

Decision Framework Overview

The risk assessment decision framework is presented in Figure 2 and includes parallel evaluations for both human and ecological receptors. The decision framework highlights the importance of considering both direct toxicity to exposed receptors and bioaccumulative effects of COCs in sediments. Based on sound science and consistency with regulatory guidance, there are a number of places to exit the decision path. Specific steps at each level are discussed in more detail in the paper “Risk-Based Management Principles for Evaluating Sediment Management Options” (see Appendix B). It is important to specify the considerations appropriate for evaluating each site as the specific deliberations are somewhat different for human and ecological assessments. For human health risk assessments, it is important to specify the appropriate receptor group(s) and exposure scenario(s). For ecological risk assessments, it is essential to agree on the relevant receptors and exposure scenarios and appropriate assessment endpoints for the ecological receptors at a particular site.

Selecting human and ecological receptors and scenarios involves a significant amount of discussion between risk assessors and risk managers. In particular, human health risk assessments focus on individuals among local populations or at-risk subpopulations within the local community. Ecological risk assessments focus on sustaining populations or communities within the local ecosystem except when it is necessary to protect individuals among rare or threatened species that have been identified as relevant receptors. Once receptors are defined, assessments of their exposure and potential resulting effects are used to estimate the severity, magnitude, and duration of potential risks. These estimates usually are conducted in a tiered manner, moving from generalized assumptions and conservative estimates of exposure and effects to more site-specific, refined estimates. Using this approach minimizes the risk assessment effort, yet provides risk assessment resources commensurate with the magnitude of issues and scale of remedial options. There are various decision points in the process to evaluate the most appropriate subsequent path. At each decision point there are three potential outcomes:

- Risk estimations demonstrate that no further action is required.
- Risk estimations developed suggest that additional characterization or risk analysis is needed to better define risk estimations, determine if remedial action is appropriate, and, if so, determine the nature of the effort.
- Risk estimations demonstrate the need to develop RAOs to reduce risks to acceptable levels, and efforts to further refine the risk estimates are not cost effective in the overall decision process.

The evaluations can be performed on several levels, first as a quick screening assessment and then, if warranted, as a more quantitative and site-specific assessment. The decision process described in the detailed technical paper on this topic (see Appendix B) relies on a considerable amount of technical and regulatory literature for guidance. The approaches described in these guidance documents must be combined with sound science to ensure that the potential risks estimated for a site are representative of reasonable risk scenarios. It also is necessary to develop the risk assessment to the extent that risk managers understand the levels of uncertainty associated with any decision to expend remedial resources.

The components of the risk-based decision framework depicted in Figure 2 are outlined below. For more detailed discussions of these steps, see the technical paper “Risk-Based Management Principles for Evaluating Sediment Management Options” in Appendix B.

Initial Collection of Site Information and Definition of Receptors

The first step in the risk-based decision framework is to collect site information and define receptors. For this step, it is necessary to build a conceptual model, identify relevant receptors and exposure pathways, compare COC levels to background levels, and make a first decision as to whether relevant human and ecological receptors are present at the site. The decision process at this stage requires discussions between risk managers and risk assessors and involves the following four questions:

- Are potentially exposed, relevant receptors present at the site, and do conditions exceed background exposures?
- Is a no natural recovery option appropriate?
- Are there sufficient uncertainties to warrant a Tier 1 risk assessment?
- Can RAOs be developed to guide remedial option development?

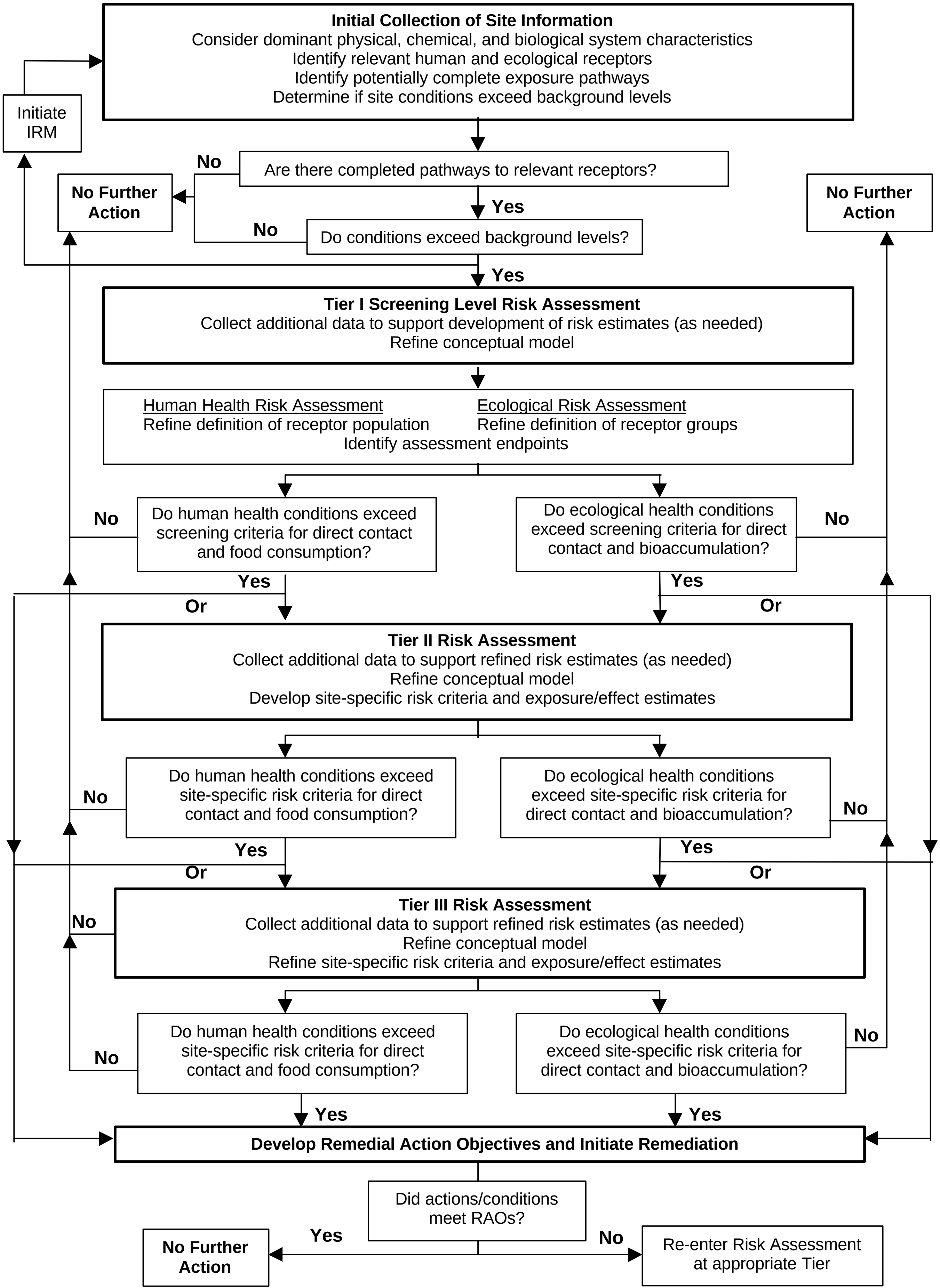

Figure 2. Generalized decision framework.

The answers to these questions require discussions between risk managers and risk assessors, considering all of the technical, scientific, political, social, economic, and policy aspects of a risk management decision.

Tier 1 Risk Assessment

If the decision is made to proceed with a Tier 1 screening level risk assessment, additional effort may be needed to define the dominant physical, chemical, and biological characteristics. This effort can range from better organizing and sorting existing information to collecting additional data. Regardless, the goal is to develop a conceptual model that allows better definition of relevant receptors at the site and characterizations of their exposure pathways using conservative exposure assumptions. During a Tier 1 risk assessment, the following activities occur: depicting relevant receptors, selecting screening level benchmarks, developing screening values, and determining the relationship between the benchmark screening and the RAOs. The decision process at this step requires additional discussions between risk managers and risk assessors and involves the following five questions:

- Are potentially exposed, relevant receptors present at the site, and do conditions exceed background exposures?
- If risks do not exceed screening criteria, is a natural recovery option appropriate?
- Are there sufficient uncertainties to warrant a Tier 2 risk assessment?
- Are the risks sufficiently defined to support development of RAOs to guide remedial option development?
- Will remedial option risks be less than those of current conditions? (If not, the situation warrants further consideration of no further action.)

If the decision is made to proceed with additional effort and refine the risk estimates in terms of site-specific conditions and receptor attributes, the efforts can be organized in several ways. One approach is to collect specific information to address areas where assumptions in the previous efforts have been most unrealistic. Another is to address the greatest uncertainties, focusing specifically on exposure or hazard estimates for the receptors of concern. The exact sequence of analyses necessary to reach a decision as to whether the risks need mitigation and, if so, to what extent, depends on factors such as the magnitude of preceding efforts, the nature of the receptor groups at risk, resources devoted to the assessment program. At less complex sites, a more streamlined approach using a qualitative risk assessment may be employed, avoiding the need to calculate site risk numbers. At other sites, a more detailed quantitation risk assessment may be necessary. In this situation, efforts proceed in an incremental fashion until the risk manager is comfortable with the risk estimations; the remedial options are presented; and the technical, policy, and social relevancy issues are addressed. The underlying theme of these higher tier efforts is to allow more accurate and quantitative characterizations of exposure pathways and understanding the dynamic nature of the system. With new data, the decision process can return to earlier discussions regarding factors such as exposure pathways and background comparisons and can reevaluate the relevancy of these decisions. The basic activities performed in these higher tier assessments are similar for human health and ecological risk assessments and are as follows: refine target receptor groups, develop enhanced exposure estimates, and evaluate hazard data used in the risk assessment.

The decision process at higher tiers should incorporate a path that parallels earlier discussions between risk manager and risk assessor. Decision-makers should ask the following questions, based on this new information:

- Are potentially exposed, relevant receptors present at the site, and do conditions exceed background exposures?
- If risks do not exceed site-specific criteria, can a no further action option be defended?
- Are there sufficient uncertainties to warrant an additional tier of risk assessment?
- Are the risks sufficiently defined to support development of RAOs to guide remedial option development?
- Will remedial option risks be less than those of current conditions? (If not, the situation warrants further consideration of no further action.)

Conclusions and Recommended Applications

The decision framework is aligned more closely with the emerging American Society for Testing Materials (ASTM) guidance for risk-based corrective action than existing risk assessment guidance from regulatory agencies. More importantly, the framework presents a strong focus on up-front identification of relevant human receptors and ecological assessment endpoints that should be used as the basis for all subsequent evaluations. Typically, risk assessments evaluate many or all of the human receptors and assessment endpoints presented in the decision trees without seeking risk manager/risk assessor discussion as to what issues are at the crux of remedial decisions.

USING NATURAL PROCESSES TO DEFINE EXPOSURE FROM SEDIMENTS

Natural fate and transport processes normally control the recovery of unremediated contaminated sediments, the effectiveness of in situ remedial processes, and the amount and fate of any residual contamination after disturbance of the sediment. For example, deposition and biological degradation processes control the natural recovery of sediment, COC desorption and migration generally controls the effectiveness of in situ containment or treatment processes, and COC desorption and deposition significantly impact the effectiveness of any removal action. Natural processes determine the exposure and risks resulting from any activity involving contaminated sediments. Ultimately, it is the portion of the COC that moves via natural processes into the water or food chain that is the source of exposure and potential risk even if human actions increase the amount of COC available for these processes.

The fate, transport, and biouptake of contaminants in sediments is controlled by a number of physical, chemical, and biological processes. When viewed as a whole, these processes can be quite complex and overwhelming. However, significant progress in understanding each of these processes has been achieved allowing many to be described by basic principles and equations. Integration of these processes together into computer models, coupled with the use of site specific data for calibration permits the development of a tool that allows one to provide reasonably accurate representations of these systems so that well informed management decisions can be made. This paper summarizes the key processes affecting contaminants in aquatic systems.

Among the more important processes are the natural release processes due to exposure, removal, or resuspension of sediment. These dynamic processes serve to relate COC concentration levels found in the overlying water body with that found in the sediment (Valsaraj, Thibodeaux, and Reible 1997). Thus, natural fate and transport processes define the availability of COCs and the potential for exposure and risk to human and ecological receptors. The purpose of the paper in Appendix C is to summarize these natural processes and compare their importance in attenuating COC migration and exposure.

Any attempt to summarize and compare natural attenuation processes in sediments must recognize the different environments in which contaminated sediments are found. The relative importance of these processes differ significantly between lacustrine, riverine, estuarine, and coastal environments. The range and significance of natural processes are influenced heavily by site-specific characteristics. The detailed paper in Appendix C titled “Using Natural Processes to Define Exposure from

Sediments" attempts to identify all of the potentially important natural attenuation processes and builds a matrix relating sediment and water body characteristics to these processes. The individual processes are discussed, including a means of assessing the importance of each process in particular field situations.

The most important natural fate and transport processes at contaminated sediment sites include the following:

- In-bed fate processes, including irreversible adsorption and chemical or biological reactions
- In-bed transport processes, including diffusion and advection as influenced by reversible sorption/desorption and colloidal transport
- Interfacial transport processes, including sediment deposition and resuspension, bioturbation, and water-side mass transfer

Table 1 summarizes the relative importance of these processes in various sediment environments. These processes and the reasons for their importance in the individual environments are discussed in more detail in subsequent sections. The most important factor in defining the fate and transport processes influencing COCs in sediment is the energy of the overlying flow. In high energy environments, the sediment tends to be coarse grained and noncohesive with little sorptive capacity and low depositional rates. These sediments pose little barrier to advective transport and allow oxygen transport deep within the sediment. In low energy environments, a significant deposition of fine-grained sediments exists, providing high sorptive capacity and significant slowing of advection and oxygen transport. Somewhat offsetting these differences is the fact that many organisms, especially head-down deposit feeders, prefer fine-grained sediments. Therefore, bioturbation (i.e., the mixing associated with the normal life-cycle activities of sediment-dwelling organisms) is often enhanced in areas of finer-grained sediments, which may be repositories of hydrophobic COCs such as polychlorinated biphenyls (PCBs) and some heavy metals.

Table 1
Sediment Processes and their Relationship to Various Sediment Environments

Environment	Environmental Characteristics	Key Fate and Transport Processes
Lacustrine	Low energy environment Generally depositional environment Groundwater interaction decreasing away from shore Organic matter decreasing with distance from shore Often fine-grained sediment	Sediment deposition Water-side mass transfer limitations Groundwater advection in near-shore area Bioturbation (especially in near-shore area) Diffusion in quiescent settings Metal sequestration Aerobic and anaerobic biotransformation of COCs Biotransformation of organic matter (e.g., gas formation)

Environment	Environmental Characteristics	Key Fate and Transport Processes
Riverine	Low to high energy environment Depositional or erosional environment Potential for significant groundwater interaction Variable sediment characteristics (fine to coarse grained)	Local and generalized groundwater advection Sediment deposition and resuspension Aerobic biotransformation processes in surficial sediments (potentially anaerobic at depth) Bioturbation
Estuarine	Generally low energy environment Generally depositional environment Generally fine-grained sediment	Bioturbation Sediment deposition Water-side mass transfer limitations Aerobic and anaerobic biotransformation of COCs Biotransformation of organic matter (e.g., gas formation)
Coastal Marine	Relatively high energy environment, decreasing with depth and distance from shore Often coarse sediments	Bioturbation Sediment erosion and deposition Localized advection processes

The exposure and risks to fish and higher level organisms depend on the availability of the COCs in the sediment. Generally, it is assumed that the only portion of the COC that is directly available is the fraction that partitions into the dissolved phase of the water. In this molecular form, the COC can move across biological membranes and accumulate in fish and other animal tissues. The risks of sediment contaminants to higher organisms can arise via one of the following three pathways, which are discussed below:

- Direct exposure to fish and higher animals by COC release from resuspended contaminated sediment or by incidental ingestion of contaminated bed sediments
- Indirect exposure to higher animals by predation and harvesting of plants and animals living directly exposed at the contaminated sediment-water interface
- Direct exposure to fish and higher animals from COC release from bed sediment to the overlying water or through consumption of filter-feeding or benthic infaunal organisms that obtain their food via the water column

The first pathway, direct exposure to resuspended sediment, can be described generally by assuming chemical equilibrium between the suspended sediment load and water. The second pathway, indirect exposure to contaminated sediment through the food chain, can be described generally by chemical equilibrium between the bed sediment and the benthic organisms that inhabit the sediment-water interface. The third pathway, direct exposure to fate and transport processes from stable sediments, requires analysis of the fate and transport processes in the sediment.

While many of the fate and transport processes vary significantly in importance from site to site, it is possible to rank the potential importance of each mechanism using characteristic times. Characteristic times are order of magnitude estimates of time required to remove COCs from an initially uniformly contaminated layer of height (H) by each of the various transport mechanisms. In most cases, the characteristic times represent 1/e times (i.e., times required to achieve 37% of the initial sediment bed concentration or 63% percent recovery). In the case of advective processes, the characteristic times represent complete removal times. Table 2 summarizes the relationships comparing the characteristic recovery times of contaminated sediment by each of the processes. Processes that exhibit a shorter characteristic time are likely to be the most important transport processes.

Table 2
Summary of Characteristic Times of Sediment Fate and Transport Processes

Process	Characteristic Time Relationship	Typical Range of Key Parameter Values	Illustrative Value of Characteristic Time[1]
Diffusion	$t_{diff} = \frac{4}{p^2} \frac{H^2 R_f}{D_{eff}}$	$R_f > 1{,}000$ (Hydrophobic organics) $D_{eff} \sim 10^{-6}$ cm^2/s	1,280 years
Advection	$t_{adv} = \frac{H R_f}{v}$	Groundwater velocity, v, widely variable	100 years
Sediment Erosion	$t_{ero} = \frac{H}{U}$	Bed erosion rate, U, widely variable	10 years
Bioturbation	$t_{bio} = \frac{4}{p^2} \frac{H^2}{D_{bio}}$	0.3 cm^2/yr$<D_{bio}<$30 cm^2/yr	13 years
Reaction	$t_{fate} = \frac{1}{k_{rxn}}$	Reaction rate, k_{rxn}, widely variable	100 years

[1] Assumes a 10 cm thick surficial layer contaminated with a hydrophobic organic with an effective retardation factor of 1,000. A groundwater velocity of 1 meter/yr, a bed erosion rate of 1 cm/yr, an effective bioturbation diffusion coefficient of 3 cm^2/yr and a reaction rate of 0.01 yr^{-1} are assumed for purposes of illustration.

In general, active sediment processes in which COCs are transported by bulk movement of pore water or particles exhibit the shortest characteristic transport times and, therefore, the fastest sediment recovery times. These processes also exhibit the highest sediment to water fluxes and the potential for relatively high exposure and attendant risk to fish and higher animals. For example, in Table 2, sediment erosion and bioturbation are the only sediment bed processes occurring at significant rates. For hydrophobic or other strongly sorbed COCs, the processes that result in particle movement are much more significant than transport via pore water processes. In high energy environments, sediment resuspension and movement are likely to be dominant factors in particle transport; in low energy environments, bioturbation is likely to dominate COC movement in the upper layer of sediments. It is important to note that short characteristic times imply short sediment recovery times, but may also result in higher exposure and risk to fish and higher animals in the overlying water during the period of recovery.

Although Table 2 provides general guidance as to the relative importance of various fate and transport mechanisms, it is important to note that each site is different and that only through detailed studies can the dominant process at a particular site be identified and quantified, allowing the evaluation of the effect of these processes on natural recovery and more active remedial options.

THE ROLE OF NATURAL ATTENUATION/ RECOVERY PROCESSES IN MANAGING CONTAMINATED SEDIMENTS

When considering how to reduce human health and ecological risks posed by contaminated sediments within an aquatic ecosystem, it is important to recognize the considerable capacity of natural processes continuously at work within the system to reduce those risks. Technically referred to as natural attenuation, this approach to sediment remediation relies on the powerful natural processes that are inherent within all aquatic systems to reduce COC bioavailability and potential transport. The natural attenuation of aquatic systems is driven most often by quantifiable physical mechanisms such as the mixing and in-place burial of contaminated sediments with progressively cleaner solids delivered by the watershed. This natural sedimentation process can effectively reduce the physical availability of COCs for potential transport downstream and similarly reduce the biological availability of COCs for potential exposure to human and ecological receptors. Other potentially significant mechanisms include chemical processes such as adsorption and redox reactions and the complex biological processes involved in biodegradation.

Despite today’s apparent emphasis on applying active remedial technologies in managing contaminated sediment, there is ample evidence that natural attenuation can be applied as an effective remedial alternative or to enhance the protectiveness of other alternatives selected for aquatic sites. While the regulatory community and public tend to view the natural recovery of sediments as a no action alternative, this paper discusses the capacity for natural attenuation processes combined with performance monitoring to be a protective, feasible, and cost-effective alternative that should be considered and fully evaluated against other potential remedies.

Unique to natural attenuation as a remedial alternative is its ability to reduce the mobility, toxicity, and potential exposure of COCs through inherent physical, chemical, and biological processes without the need for intervention typified by technologies such as sediment capping or dredging. Although natural processes are known to be active in all aquatic ecosystems, full recognition of the power of these natural forces in healing those systems and reducing human and ecological exposure is lacking. In recognizing that natural attenuation is increasingly relied on for addressing environmentally persistent COCs in soil and groundwater, the use of monitored natural attenuation can and must play a wider role in contaminated sediment management. To that end, this paper (which appears in its entirety in Appendix C) concludes by offering several recommendations, which are summarized below.

- *The natural attenuation alternative can be a protective remedy; it is not a no action alternative.* Currently, natural attenuation is reducing risks posed by contaminated sediments to some degree at virtually all contaminated sediment sites. The natural attenuation alternative which, as a risk management tool necessarily includes monitoring and appropriate institutional controls, can be a protective and preferred approach to managing contaminated sediment site risks.

The policy-level recognition of the natural attenuation alternative as an effective remedy needs to be communicated to regulatory personnel in the field. In doing so, the key applicable principles of the USEPA guidance on using monitored natural attenuation for soils and groundwater can and should be adopted and promoted. The USEPA and other federal and state agencies have recognized the applicability of natural attenuation at the policy level, but actual selection and application of the alternative is lacking.

The role of natural attenuation in addressing environmentally-persistent COCs in soil and groundwater is well documented and is increasingly relied on as one component of a site's overall remedial package. In addition, the USEPA has formally selected natural attenuation as a whole or partial remedy at several sediment sites. Fundamentally, it must be recognized that natural attenuation is an intrinsic set of processes that operate continuously within all aquatic ecosystems. Given that premise, natural attenuation is necessarily already relied on before, during, and after other more intrusive remedies. However, additional effort is needed in the site assessment phases of remedial planning to discern what portion of overall recovery gains (or reversals) are attributable to natural processes versus source control, intrusive remedial action, and other actions.

- *Empirical evidence and model projections should be used to evaluate the effectiveness of natural attenuation in reducing risks.* Site data that identify the mechanisms and rates of ongoing natural attenuation are critical to establishing the feasibility of the natural attenuation alternative. These data are needed not only to establish the basic proof that attenuation is occurring but to calibrate and optimally to verify fate and transport models that predict future bioavailable COC concentrations. Empirical information such as sediment deposition rates, sediment mixing layer thickness, and time series data documenting changes in COC bioavailability or toxicity over time are important. Multiple lines of such empirical evidence should be sought. Organizing site data into a mathematical model that can predict how the system will change over time is an important extension of the basic understanding of the processes that are reducing risk at a site. Deterministic modeling may be the only practical way to address such issues as assessing the reliability of natural attenuation processes to continue to reduce risks under conditions other than those which have been observed (e.g., rare extreme hydrologic events) or to address the combined effectiveness of source controls and natural attenuation.

- *The natural attenuation alternative should be evaluated in comparison to other action alternatives for sediments on the basis of effectiveness, implementability, and costs.* Defining a reasonable time frame for natural attenuation to meet remediation objectives is a site-specific process that weighs among other factors the extent of current risks and impacts to resources, availability, and reliability of institutional controls to manage risks; uncertainties associated with predicted time frame; and the implementability, effectiveness, and costs of other alternatives. For example, levels of risk reduction produced by intrusive technologies may not be achieved significantly sooner than allowing ongoing natural recovery processes to proceed uninterrupted. This is especially true when many years are required to fully design, permit, and construct large-scale capping or removal remedies, including the potential need to design and permit a proper disposal facility. Again, even after such remediation is complete, natural recovery processes would be relied on to attenuate remaining risks posed by the residual materials left behind by intrusive technologies.

  Comparative evaluation of remedial alternatives is necessary. Simple pass/fail decision criteria for natural attenuation that have been suggested (e.g., surface sediment COC levels within a factor of two of remedial objectives as suggested by Templeton et al. 1993) that implicitly assume capping or dredging alternatives to be more effective should be avoided.

- *Where irreconcilable differences of opinion exist regarding the time frame or reliability of natural recovery, performance-based natural attenuation should be selected along with a contingent remedy.* A contingent remedy would be an alternative such as containment or dredging that would be implemented at a specified future date (e.g., the five-year review of a Record of Decision) if a natural attenuation remedy fails to meet appropriate performance standards. Considering the potential consequences of being wrong in making a determination that natural attenuation is not performing (i.e., the high financial cost as well as social and environmental costs associated with implementation of active sediment remediation), the decision maker should be highly confident that natural attenuation is not working and that other remedial options will significantly reduce risk before deciding to abandon the natural recovery option. Consequently, some lower confidence limit on performance measurements such as fish contaminant trend monitoring data would be appropriate for use for triggering decisions to implement the contingent remedy. Performance standards should include at a minimum those that relate directly or indirectly to the expected rate of risk reduction needed to achieve risk-based remedial objectives for the site. Development of the performance standards should minimally address the lines of empirical evidence that supported the original decision. In general, promoting contingent remedies might help bring to closure to the different opinions regarding sediment remedies that are rooted in different expectations regarding the effectiveness, implementability, and costs of sediment remediation technologies.

- *The social and environmental benefits of the natural attenuation alternative may outweigh those perceived to flow from intrusive technologies.* The final word on natural attenuation in sediments is the need for risk managers to come to realize that natural systems have a substantial capacity to attenuate and recover from the presence of contaminants. Conversely, experience with remedial dredging highlights the fact that technology, while powerful, is not necessarily as effective as the nonintrusive natural processes. In making a final determination on this pivotal question, the overall social and environmental benefits and costs must be evaluated. If empirical and predictive lines of evidence indicate that natural attenuation can achieve risk reduction goals within a time frame similar to technological approaches, the benefits of avoiding habitat destruction, avoiding the technical and administrative limitations of construction and landfilling, and avoiding the sometimes extremely high social cost of paying for technological intervention may indeed clearly signal that natural attenuation is the most appropriate remedy for many of the nation's contaminated sediment sites.

SEDIMENT STABILITY AT CONTAMINATED SEDIMENT SITES

Peak inputs of hydrophobic COCs (e.g., PCBs, heavy metals) to many aquatic systems occurred over 20 years ago. Generally, higher COC concentrations are found below cleaner sediments that were deposited after historical inputs occurred. Subsequently, naturally occurring processes (e.g., sedimentation, bioturbation) typically caused significant reductions in surficial bed concentrations. Thus, peak bed COC concentrations are often sequestered from the bioavailable zone in many aquatic systems.

The possibility exists, however, that a rare storm (e.g., 100-year flood in a river or hurricane in coastal waters) can cause sufficient erosion to allow elevated bed COC concentrations to be introduced into the bioavailable zone and, thus, negatively impact system biota. Depth of scour during these storms is determined by evaluating hydrodynamic processes (i.e., generation of bottom shear stress) and site-specific erosion properties of the sediment bed. Cohesive sediment deposits (i.e., muddy sediments composed of varying amounts of clay, silt, and fine sand) are of particular importance to a contaminated sediment stability evaluation because hydrophobic COCs preferentially adsorb to finer sediment particles and organic carbon associated with this sediment type. Thus, the stability of cohesive sediment deposits during a rare storm is a critical component in evaluating remedial options at a contaminated sediment site. The key question is as follows: what scour depths will be caused by the rare storm? Estimating scour depths during a rare storm and the resulting surficial bed layer concentrations is necessary to compare the efficacy of various remedial alternatives.

Effective and correct evaluation of sediment stability can be accomplished using rigorous and scientifically credible sediment transport analyses that employs quantitative procedures. This approach yields a methodology that can be used to objectively evaluate different remedial scenarios. Qualitative analyses or conceptual models can be useful for developing and validating quantitative analysis tools; however, qualitative techniques alone typically are insufficient for conducting remedial alternative evaluations that are scientifically defensible.

Two tiers of quantitative analysis are discussed in the technical paper “Sediment Stability at Contaminated Sediment Sites” in Appendix C. A Tier 1 analysis involves the use of approximate equations to estimate scour depths during a rare storm. The accuracy of these equations and associated parameters is such that only order-of-magnitude estimates result. The second tier of this analysis scheme employs the development and application of a comprehensive sediment transport model to evaluate bed stability. Tier 2 analyses produce the most accurate results, but require significantly more time and effort than Tier 1. The level of analysis used for a specific site depends on data availability, level of accuracy required, and time and budget constraints.

State-of-the-science sediment transport models have been effectively used as management tools for evaluating remedial options at several contaminated sediment sites. It should not be presumed that rare storm events will have catastrophic impacts on the site under review. In fact, two case studies described in detail in the technical paper in Appendix C clearly demonstrate that a rare storm is not necessarily catastrophic; significant increases in surficial bed concentrations caused by reexposure of elevated concentrations buried at depth in the bed will not necessarily occur during a rare storm. However, it is important to note that sediment stability is site specific. Contaminated sediment sites with elevated bed concentrations caused by historic discharges buried at depth in the bed may not be severely impacted by a rare storm. Depending on the site-specific hydrodynamic and sediment transport factors, the effects of a flood or hurricane can be significant at sites where relatively recent discharges have occurred and elevated bed concentrations are near the sediment surface.

ADVANTAGES AND DISADVANTAGES OF REMEDIATION TECHNOLOGIES FOR CONTAMINATED SEDIMENTS

The advantages and disadvantages of various sediment remedial technologies are provided in Appendix D. A table lists a general technology description, typical process options, specific parameters to consider, potential benefits and limitations, and precedent for in-place containment, removal, and management technologies. Fact sheets describing the technologies listed below and their implementation scale, including documented effectiveness toward risk reduction, critical engineering design issues influencing effectiveness, and short- and long-term issues are also provided in Appendix D.

- Engineered capping
- Particle broadcasting
- Hydraulic modifications
- Dredging
- Dry excavation
- Treatment / Disposal

STATE OF CURRENT CONTAMINATED SEDIMENT MANAGEMENT PRACTICES

In the 1990s, the management of contaminated sediments is a complex and politically charged subject. The magnitude of the problem is continuing to be quantified and confirmed. The focus of this paper (provided in its entirety in Appendix D) is to foster a more rigorous technical discussion and exchange on this subject by evaluating contaminated sediment projects to determine both the types of remedial goals selected for such projects and the effectiveness of the implemented remedies. Data are identified and summarized on the characteristics and size of 44 implemented projects, the remedial methods, the costs, the goals of the projects, the methods used to verify whether the goals were met, and the degree of success in meeting the goals.

The evaluation shows that the sediment remediation projects implemented to date have been small (as compared to traditional navigational dredging), costly, and difficult to implement. Furthermore, the projects typically had vaguely or inconsistently defined targets and goals, and the success of the respective projects or benefit derived from the remediation often has not been demonstrated. This finding contradicts the more scientifically grounded approach for sediment remediation emphasized in government-sponsored strategy documents. Key issues influencing contaminated sediment management are discussed, including the following:

- Application of sound science
- Identification of the proper goals and target
- Selection of remedial methods
- Verification of achievement of the goals
- Understanding of the limitations of mass removal

Key Findings

The 44 projects identified for evaluation represent the majority of the sediment remediation projects implemented in the U.S. It is noteworthy that documentation of the outcome of these projects has, in varying degrees, been incomplete and not widely disseminated. There is no central repository or clearinghouse for such information; information transfer on this subject between governmental agencies or even between regions of the USEPA does not seem to be occurring with any consistency. There is no evidence of lessons learned on prior projects being applied by regulators to subsequent projects. Particularly problematic is the availability and quality of final reports. To fill this information void, a data base was assembled using information from a wide variety of oral and written sources. Detailed descriptions of the content of this data base is provided in the complete paper in Appendix D.

A variety of remedial methods are candidates depending on the severity and extent of the problem. These methods range from source control and natural recovery to full-scale remediation.

These methods should be evaluated in a hierarchical approach, progressing from an evaluation of source control, then in situ methods such as natural recovery or engineered burial (capping), and finally removal and disposal using methods such as dredging or wet or dry excavation. Overriding the evaluation of remedies is the need to determine whether a proposed remedy, particularly a removal remedy, will (1) result in more harm than benefit in its implementation ("more harm than good"), (2) withstand scrutiny from a cost-benefit standpoint, and (3) achieve the identified goals.

Removal is the method of choice at the vast majority of the projects (40 of 44), despite the disruptive nature of removal and the repeated inability to achieve low cleanup levels. This propensity toward removal as a remedy is likely a follow-on to the traditional "dig it up and haul it away" approach used for soil at Superfund and other targeted sites. This approach does not translate easily to contaminated sediment; although there is a tendency on the part of regulators and other involved parties to ignore or be unaware of this fact. The differences are dramatic when sediment is involved, and these differences are worth emphasizing. They include the fact that:

- The underwater environment presents a lack of visibility and a need to manage the water phase.
- The target areas are often no longer located on the responsible party's property; access difficulties are introduced.
- The contamination is often spread out and diffuse.
- The bottom area of most water bodies is an ecologically sensitive environment.
- The water environment mobilizes and transports contaminants back into and away from the target area during removal.
- All of the impacted sediments may not be capable of being removed, which can result in residual contaminants at the surface, sometimes at higher than original levels.

The costs for removal projects cover a wide range. Costs are highly variable due to differences in goals from project to project; differences in production (i.e., removal) rates, which are influenced by a wide variety of site-specific variables; and wide differences in disposal costs, which are influenced by disposal method and location and type of contamination and concentration.

Landfilling or containment predominates as the method of disposal. Containment (a type of landfilling) includes use of disposal ponds or nearshore confined disposal facilities (CDFs). Treatment is seldom used. Final treatment technologies have failed to make inroads as a component of sediment remediation projects primarily due to the following factors:

- An inconsistent or nonexistent track record at full-scale
- High unit costs

- The need for extensive land-based area for managing dredged material including for staging, size-reduction, dewatering, and treatment
- Concerns that regulatory-required low residual contaminant levels will not be able to be achieved.

The 22 remedial dredging projects involved relatively small volumes of sediment, certainly by navigational dredging standards. The largest remedial dredging project (at Bayou Bonfouca, Louisiana) involved removal of 169,000 cubic yards (cy). Half of the 22 projects resulted in 40,000 cy or less of sediment removal. The total volume removed for all dredging projects is 940,000 cy (rounded). This grand total, not a large total for even a single navigational dredging project, emphasizes the great difference in the character of and approach required for remedial dredging projects as compared to conventional dredging projects.

Overall costs for the remedial dredging projects ranged from $44 to $1,842 per cy, with a median of about $200 to $275 per cy. The high overall cost is due to two primary factors: low production rates and high costs for disposal. Little or no economy of scale exists. Repetitive difficulties that cause low production rates (and long implementation times), but that do not usually impede navigational dredging include the following:

- Rocks, vegetation, and debris
- Shallow water
- Floating oil
- Resuspension and associated controls
- Limited on-land water holding and treatment capacity

Dry excavation was performed predominantly in small shallow streams or ponds, amenable to dewatering. Dewatering was performed by diverting the water around the target area or draining the water body. Wet excavation was accomplished in shallow, narrow streams using excavators on the banks. Sixteen of the dry and wet excavation projects involved small volumes (i.e., 1,800 to 165,000 cy). Two larger projects, the removal of 588,000 and 450,000 cy, involved the draining of a lake and two ponds, respectively.

Overall costs for the dry/wet removal projects ranged from $21 to $1,500 per cy, with a median of about $450 per cy. The high overall cost is due to the following three primary factors:

- Lower production rates than for traditional earth moving projects due to difficulties with accessibility and wet terrain
- Additional water control and handling requirements imposed for maintaining the dry condition
- High costs for disposal

Natural recovery as a remedy was selected in whole or in part for six projects. The few projects with natural recovery remedies consist of those with one of three identifiable types of conditions, namely the following:

- Lengthy rivers characterized by pervasive but diffuse contamination too extensive for a removal remedy to be feasible
- Contaminated areas of unusual aesthetic value or sensitivity or comprising dense habitat and rich feeding grounds
- Contaminated areas in a region (e.g., Washington State) that allows areas to be designated for natural recovery if recovery is predicted to occur to acceptable levels within 10 years

Selection and Achievement of Goals

The 25 largest of the 44 projects were evaluated—those targeting 10,000 cy of sediments or greater. The following key questions that are basic to any major sediment remediation project were examined:

- Was the primary remedial goal selected to achieve risk reduction, with the basis being to achieve protective levels for receptors within a specified time period?
- Was the remedial target derived from the primary remedial goal?
- Was achievement of either the remedial target or the primary remedial goal demonstrated?

Findings showed a variety of primary goals were applied to the 25 projects; for at least one-third of the 25 projects, no protective endpoint was defined by the primary goal. In these instances, the goal was simply to in effect "show progress" by reducing contaminant levels, reducing ecological impacts, or removing contaminant mass. Further, for 10 of the 25 projects, the selected sediment remedial target was not clearly tied to the primary goal. Clearly, a consistent application of sound science and careful consideration of such important principles as contaminant availability and proper goal/target selection were lacking in varying degrees. A sound scientific approach with clear goals is needed for future projects to define in advance an appropriate and beneficial goal, target, and remedy.

In response to the questions, "were goals achieved" or "will goals be achieved" the following is concluded at this time:

- Mass removal projects, by definition, achieved their goal.
- Low cleanup levels were either not achieved or were not verified at 14 of the 22 removal projects.
- No risk reduction protective endpoint goal has demonstrably been met on any project, either due to no verification sampling or no postremedy monitoring being implemented or due to monitoring still being in progress.

- Often preremedy data are limited and unsuitable for comparison with postremedy data. Often the postremedy monitoring is unscientific, opportunistic, or nonexistent. In either instance, no technically defensible measure of the success for such projects is possible.

MEASURING EFFECTIVENESS OF REMEDIAL ACTIONS AGAINST REMEDIAL ACTION OBJECTIVES AT CONTAMINATED SEDIMENT SITES

A critical element of a site-specific sediment management strategy is that it be results-focused. That is, the degree of success achieved by implementation of the selected remedial approach should be measurable. Measurement forces the definition of targets or RAOs. As suggested in a number of the papers, but particularly in "Effective Decision-Making Models for Evaluating Sediment Management Options," the initial step in defining an effective management strategy is developing a plausible site conceptual model addressing, for example, the following questions:

- What are the potential COCs?
- What are the specific exposure pathways that give rise to unacceptable risk?
- Are there any ongoing sources releasing COCs to sediments?

Once the model has been developed and validated, it is important to consider it during the development of RAOs which, once achieved, will result in reduction of risk to acceptable levels.

Measuring the success of remediation efforts for contaminated sediments can be accomplished through the following routes, which are discussed in further detail in the sections below:

- Strict comparison of postremedial conditions with conditions existing prior to the contamination event
- Comparison of postremedial conditions with preremedial conditions (i.e., definition of incremental improvement, potentially quantified by degree of long-term risk reduction achieved by remediation, but without a specific risk reduction target)
- Comparison of postremedial conditions with a target concentration in sediments or biota based on a site-specific risk assessment
- Comparison of postremedial conditions with what may often be a relatively conservative regulatory standard, derived with little site-specific analysis
- Achievement of remediation goals defined in terms of removal of a prescribed quantity of contamination from the system or destruction of that contamination without necessarily having an understanding of the role that such removal has in reducing risk
- Accomplishment of specified remedial actions without confirmatory analysis to define any risk reduction achieved

Comparison to Uncontaminated Conditions

It may be extremely difficult to define conditions extant prior to the contamination event. Frequently, contamination may be attributable to a series of overlapping, historical events. To compound the difficulty, the degree of impact to the natural system is often evaluated on the basis of environmental condition factors (e.g., benthic diversity, species abundance, overall condition of the biota).

Degree of Incremental Improvement

While the degree of improvement in specific indicators of environmental quality and in actual sediment and biota COC concentrations may be quantified, incremental improvement alone may be insufficient to define a threshold that returns the impacted area to productive use or addresses the risk posed by the presence of the contamination.

RAOs Based on Site-Specific Risk Assessment

The risk assessment approach may provide an objective basis for definition of RAOs, assuming the following:

- The conceptual model is robust enough to define the linkage between sediment contamination and that in biota.
- Food chain relationships can be adequately defined.
- Dose-response relationships for the COCs are defined sufficiently to establish cleanup thresholds.

Even if some uncertainty exists, a site-specific risk assessment aids in prioritizing the areas of a site to be included in remedial action. For example, if sediment contamination is relatively widespread yet the conceptual model indicates that uptake is occurring in select areas of the site, an RAO can be developed to prioritize efforts on such areas.

The role of risk assessment and a sound scientific foundation is to

- Avoid remedial actions that may actually exacerbate the problem.
- Avoid actions that offer relatively little benefit when compared with the associated costs.
- Enable definition of the most appropriate action or, more commonly, a range of viable response actions, in the fewest possible number of iterations.

RAOs Based on Regulatory Standards

Basing RAOs on a regulatory standard that does not recognize site-specific conditions often leads to overly conservative remediation targets. It may be appropriate to utilize such regulatory standards as conservative screening level criteria, especially where the standards are based on protection of receptors from unacceptable risk. If remedial action is not triggered by these standards, then the site may be judged a candidate for no further action. If these screening standards are exceeded, then a site-specific risk assessment is generally undertaken to determine appropriate RAOs. Only in very few instances should regulatory standards be used to define RAOs without a supporting site-specific risk assessment.

RAO Based on Performance Standards Not Derived from Risk Assessment

Removing contaminated sediments may be an appropriate RAO if all or a significant quantity of the sediment contamination has a high degree of vulnerability to physical disturbance (e.g., severe wave action, storm events, disturbance via boat props, ice scour). In reality, the prediction of the consequences of severe events to bodies of contaminated sediments is often a complex problem with little ability to generalize results even across similar environmental settings.

In general, mass removal of contaminated sediment cannot be justified as an RAO without further characterization of the system and an understanding of the risks posed, not only by permitting the status quo to be maintained, but also of the implementation risks associated with the removal itself, the potential that removal will be insufficient to meet RAOs or may even exacerbate surface sediment contamination levels, and the net effect of events that may give rise to widespread distribution of the contaminated sediments.

RAO Based on Implementation of Specific Practice Not Based on Risk Assessment

Similar to the performance standard-based approach without reliance on risk, determining that a specific remedial technique (e.g., dredging, capping) should be employed without an understanding of the system or risks posed generally does not lead to a technically satisfactory resolution of the problem. In the current regulatory environment, the risk of the liability being reopened generally reduces the likelihood that this approach will lead to final closure of the liability.

Summary and Suggested Approach

RAOs should be developed based on an effective conceptual model and a site-specific risk assessment. The RAOs should provide a realistic opportunity for the responsible party to reach closure on future liability. Postremediation monitoring likely will be required to demonstrate compliance with the targets and document that risks are either at or trending toward acceptable levels.

A general approach to measuring the success of remedial action based on a specific target RAO in sediment or biota should include documentation of baseline (i.e., preremediation) conditions; monitoring and evaluation of potential external releases to the system and development of norms as a basis for comparison so that any unusual conditions can be readily identified during remedial implementation; and an ongoing evaluation of the success of the remedial action in achieving RAOs so that any appropriate modifications to the approach can be implemented.

SECTION 3.0: REFERENCES

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