Principles for Evaluating Remedial Options for Contaminated Sediment Sites

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ABSTRACT: The complexity inherent in contaminated sediment sites requires that they undergo a detailed evaluation of site conditions and sediment management options in order to optimize the effectiveness of their potential remediation and risk reduction. Experiences gained at numerous sediment sites over the last 20 years can be tapped by Project Managers in the form of lessons learned. This knowledge should be integrated into the decision-making process as recommended by the U.S. EPA Contaminated Sediment Remediation Guidance For Hazardous Waste Sites (2005). This paper will review risk management principles for complex contaminated sediment sites and several of the key risk-based decision-making factors necessary to realistically evaluate the potential risk reduction associated with each remedial option.

INTRODUCTION

Contaminated sediment is pervasive across the United States. In 2004, U.S. EPA identified 96 watersheds as containing “areas of probable concern,” defined as areas where fish and benthic organisms may be frequently exposed to contaminated sediment (U.S. EPA 2004). As of September 2005, through U.S. EPA’s Superfund program, remedies have been selected for over 150 contaminated sediment sites, of which over 65 are large enough to be tracked at the national level (U.S. EPA 2008). Investigations are on-going at over 50 other contaminated sediment sites (U.S. EPA 2008).

Sediment sites pose challenging technical problems and addressing these problems consumes an enormous amount of resources. There are over 11 Superfund “mega” sites where the cost of the sediment remedy exceeded $50 million (U.S. EPA 2008). A number of other sites are expected to become “mega” sites as site investigations are completed and remedies are selected for them. An example of the high cost of remediating contaminated sediment is the Fox River’s Operable Units 2 – 5, where the sediment remedy was estimated to cost $390 million in the Amended Record of Decision (U.S. EPA and WDNR 2007). Moreover, the cost estimate for remediating approximately 75 million cubic yards of contaminated sediment within Great Lakes Areas of Concern ranged from $1.5 billion to $4.5 billion, depending on the types of remedies selected (Great Lakes Regional Collaboration 2005).

Due to the number, size, and high cost of sediment sites across the U.S., efficient and effective remediation of these sites will require a decision-making process that integrates the key lessons learned from the remediation efforts at numerous sediment sites over the last 20 years and the application of risk-management principles in a comprehensive remedy evaluation process. Key considerations in remedy evaluation and selection are discussed and key questions to consider when evaluating and selecting remedies are presented.

RISK MANAGEMENT PRINCIPLE #1: SOURCE CONTROL

The first principle for managing risks associated with contaminated sediment sites is to "Control Sources Early" (U.S. EPA 2002). Identifying and controlling sources prior to conducting remediation is critical to the effectiveness of any sediment cleanup (U.S. EPA 2005). Without source control, the site may become recontaminated.

The risk of recontamination is not theoretical. A 2007 survey of recently completed contaminated sediment remedial actions identified 20 sites in which sediment had become recontaminated (Nadeau and Skaggs 2007). Common sources of recontamination are combined sewer overflows, storm sewer outfalls, other point sources, other sediment sources, including upstream sources and unremediated nearby sediments, runoff, atmospheric deposition, and contaminated groundwater advection (U.S. EPA 2002; U.S. EPA 2005; Nadeau and Skaggs 2007). Thus, prior to initiating any sediment cleanup, project managers should identify and control existing sources, consider whether there is a potential for recontamination and factor that potential into the remedy selection process. Table 1 identifies key questions to consider regarding source control.

TABLE 1. Key source control questions to consider during site evaluation and remedy evaluation and selection (from Evison 2008).

- What steps have been taken to identify sources and are these steps sufficient?
- Have continuing sources been identified?
- Will all continuing sources be controlled prior to remediation?
- If not, should remediation proceed and what accommodations/expectations/plans exist about those sources?

A VALUABLE TOOL: CONCEPTUAL SITE MODEL

A conceptual site model (CSM) represents the current understanding of the site conditions by incorporating information about contaminant sources, transport pathways, exposure pathways and receptors (U.S. EPA 2005). The CSM not only summarizes much of the information related to site risks to human and ecological receptors, it identifies the nature and source of the risk. This identification of the site's risk drivers can be used to evaluate which of the proposed remedial alternatives would effectively mitigate site risks to human and ecological receptors by addressing the site elements that are creating the risks (U.S. EPA 2005). Therefore, the value of a CSM for evaluating the potential effectiveness of remedial alternatives should not be underestimated. Table 2 identifies key questions to consider regarding the CSM.

TABLE 2. Key CSM questions to consider during site evaluation and remedy evaluation and selection (adapted from Evison 2008).

- Have the following data been collected and evaluated in developing the conceptual site model?
  -- Sources of contaminants of concern
  -- Human exposure pathways
  -- Human receptors
  -- Biota exposure pathways
  -- Ecological receptors
  -- Contaminant transport pathways
- If not, why not?
- What are the principal contaminants of concern and exposure pathways driving unacceptable risk at the site?
- Which exposure pathways are relatively unimportant and can be excluded from further consideration?

STABILITY OF CONTAMINANTS IN SEDIMENT

A key component of the CSM is its representation of the stability of contaminants in sediment (U.S. EPA 2002; U.S. EPA 2005). Although sediment moves over time in most aquatic environments, the most important consideration is whether movement of the contaminants in sediment is occurring at a scale and rate that poses risks to human health and ecological receptors (U.S. EPA 2005). Thus, it is important to evaluate the stability of contaminants in sediment and how it affects risk rather than just the movement and/or stability of sediment without reference to risk. Table 3 identifies key questions to consider regarding the stability of contaminants in sediment.

TABLE 3. Key stability of contaminants in sediment questions to consider during site evaluation and remedy evaluation and selection (adapted from Evison 2008).

- Have the appropriate lines of evidence been evaluated on the potential stability of the contaminants present in the sediment (as opposed to sediment stability per se)?
- Does contaminant fate and transport through in-place sediment potentially pose an unacceptable risk to human health and ecological receptors? Is movement of contaminated sediment (surface and subsurface) or of contaminants alone occurring or may occur at scales and rates that will significantly change their current contribution to human health and ecological risk?
  -- Are they contributing to risk now?
  -- Are they likely to contribute to risk in the future?
- If yes, can in-situ remedies (e.g., capping, MNR) be designed to adequately reduce risk to human health and ecological receptors?

EVALUATING REMEDIAL ALTERNATIVES AND SELECTING A REMEDY

There are several key concepts that should be applied when evaluating remedial alternatives and selecting a remedy. These concepts are discussed below.

Remedial Action Objectives. To develop and evaluate remedial alternatives, a description should be developed of what risk reduction the cleanup is expected to accomplish (U.S. EPA 2005). These general statements, remedial action objectives (RAOs), are derived from the understanding of exposure pathways, receptors, and risks gained during development of the CSM and from risk assessments. RAOs should reflect objectives that are achievable from remediation of the site. Some goals, such as lifting a fish consumption advisory, may require watershed level actions that are outside the scope of the site cleanup and may not be achievable on a short-term or even a long-term basis regardless of the subject site's remediation success (U.S. EPA 2005). From the RAOs, contaminant-specific risk-based remediation goals and sediment cleanup levels should be developed (U.S. EPA 2002; U.S. EPA 2005).

Comparative Net Risk. U.S. EPA recommends using a risk management process "to select a remedy designed to reduce the key human and ecological risks" (U.S. EPA 2005). Considerations in the risk management process for contaminated sediment sites include (U.S. EPA 2005; Nadeau 2008):

- There is no presumptive remedy for any contaminated sediment site, regardless of the contaminant or level of risk;
- Risks must be characterized over appropriate timeframes;
- Management goals must be framed within a realistic time period;
- Risk management actions must be linked to reduction of significant human and ecological risks;

- Ecological risks are characterized at a level of assessment appropriate for the site;
- All implementation and residual risks of the remedial alternatives must be considered.

An approach recommended by U.S. EPA and the National Academy of Sciences Committee on Remediation of PCB-Contaminated Sediments that incorporates these considerations is comparative net risk evaluation (CNRE) (NRC 2001; U.S. EPA 2005). Use of CNRE ensures that on a site-specific basis decision-makers consider, at the remedy selection stage, not only the benefits of a remedial approach, but also the residual risks associated with the approach and the risks associated with implementing the remedial approach (U.S. EPA 2005; Nadeau 2008). This differs from the traditional approach of either considering implementation risks at the remedy implementation stage or assuming that remedial approaches will be 100% effective on implementation thereby bypassing any consideration of residual risk. CNRE is consistent with the National Oil and Hazardous Substances Pollution Contingency Plan's (NCP) 9 criteria (40 CFR §300.430(e)(9)(iii)), which require evaluation and balancing of short-term and long-term risks and benefits, including residual risk. Failure to account for implementation risks and residual risk during the remedy evaluation stage can skew remedy selection and result in a less effective and less protective remedy than anticipated, a result neither regulators nor the responsible parties should find acceptable.

Specific Remedy Implementation Risks. Each remedy has its own uncertainties and potential implementation risks. For MNR, the risk present at the time of remedy selection should decrease with time (U.S. EPA 2005). The implementation risks associated with MNR are mostly related to continued exposure to contaminants while natural processes work to reduce contaminant bioavailability. Institutional controls may be useful to address risks to human health during MNR implementation (e.g., fish consumption advisories) (U.S. EPA 2005).

For capping, the risk due to direct exposure to contaminated sediment should decrease rapidly as the cap is placed (U.S. EPA 2005). Implementation risks may include contaminant releases during placement of the cap, impacts on the community (e.g., noise, accidents, residential or commercial disruption), construction-related risks to workers during transport and placement of cap materials, and disruption of the benthic community (U.S. EPA 2005). Cap design and placement techniques may be useful in mitigating some construction-related implementation risks (U.S. EPA 2005).

During dredging, risks to human health and ecological receptors may increase due to increased exposure to contaminants resuspended and released to the surface water (U.S. EPA 2005; NRC 2007; Bridges *et al.* 2008). For example, during the 1995 Non-Time Critical Removal Action (NTCRA) in the Grasse River, caged fish deployed along the perimeter of a set of 3 silt curtains for 6 weeks showed several-fold increases in PCB concentrations compared to those observed in the pre-dredging period (NRC 2007). Lessons learned from the 1995 NTCRA and dredging projects at other sites over 10 additional years did not prevent a similar impact to Grasse River fish during the 2005 Remedial Options Pilot Study dredging (NRC 2007). PCB concentrations increased substantially in fish during the 2005 dredging pilot (NRC 2007).

In addition to the effects of releases at the site, resuspended and released contaminants may be transported downstream from the site. For example, at the Fox River Deposit 56/57 dredging project, 2.2% of the mass of contaminants dredged were released downstream (Steuer 2000).

Although there are no standardized best management practices for environmental dredging, lessons learned from other similar sites may yield some useful techniques for reducing resuspension and releases during dredging (U.S. EPA 2005; NRC 2007). Of late, the effectiveness of silt curtains in controlling releases has been questioned (Bridges *et al.* 2008), as evidenced by the Grasse River fish examples. Because some contaminant release and transport during dredging is inevitable, it must be considered during the alternatives evaluation (U.S. EPA 2005).

Other dredging implementation risks may include impacts on the community (e.g., noise, accidents, residential or commercial disruption), construction-related risks to workers during sediment removal and handling, and disruption of the benthic community (U.S. EPA 2005). Implementation risks are site-specific and remedy-specific and must be considered during remedy evaluation and selection (U.S. EPA 2005). Failure to adequately consider implementation risks may skew remedy selection and result in a less protective remedy than anticipated.

Residual Risk. Residual risk is the risk to human health and ecological receptors from contaminated materials or residuals that remain after remedial action has been concluded (U.S. EPA 2005). All remedial approaches leave some contaminants in place after remedial actions are complete (U.S. EPA 2005). The source of residual risk varies for each remedial approach and should be evaluated on a site-specific basis.

For MNR, residual risk is generally related to the possibility that clean sediment overlying buried contaminants may move to such an extent that unacceptable risk is created or that groundwater flow, bioturbation, or other mechanisms may move buried contaminants to the surface in an amount and at a rate that could cause unacceptable risk to human health or ecological receptors (U.S. EPA 2005). Institutional controls and monitoring may be used to address residual risk. Table 4 identifies key questions to consider regarding residual risk following a MNR remedy.

TABLE 4. Key questions to evaluate residual risk from a MNR remedy (adapted from Evison 2008).

• What evidence is there that the system is recovering? Is the pattern of recovery expected to change in the future? If so, how will it change? Will the change result in unacceptable risk? -- If the change may result in an unacceptable risk, can institutional controls reduce human health risks?
• Is the rate of recovery sufficient to reduce risk within an acceptable time frame? -- If no, can the recovery process be accelerated by engineering means? -- If no, can human health risks be addressed by institutional controls?
• Are groundwater flow, bioturbation, or other mechanisms likely to move contaminants to the surface at a rate and concentration that may pose an unacceptable risk?
• Can a monitoring plan be designed to evaluate risk reduction and protectiveness?

For capping, residual risk is generally related to (1) the possibility of cap erosion or disruption exposing contaminants; (2) the potential for contaminants to migrate through the cap; and (3) risks from contaminants remaining in uncapped areas (U.S. EPA 2005). As with MNR, whether erosion or contaminant migration through the cap poses an unacceptable risk depends on the amount and rate of contaminant exposure due to those processes (U.S. EPA 2005). Cap monitoring, maintenance, and design and institutional controls may be used to address residual risk. Table 5 identifies key questions to consider regarding residual risk following capping.

TABLE 5. Key questions to evaluate residual risk from a capping remedy (adapted from Evison 2008).

- Is erosion or disruption of the cap likely to occur in a way that may pose an unacceptable risk?
  -- If likely, can cap design, maintenance, or institutional controls reduce risk to an acceptable level?
- Is contaminant migration through the cap likely to occur at a rate that may pose an unacceptable risk?
  -- If likely, can activated carbon or other material be incorporated into the cap to reduce risk to an acceptable level?
- Is NAPL migration through the cap likely to occur at a rate that may pose an unacceptable risk?
  -- If likely, can an impervious material or reactive material be incorporated into the cap to reduce risk to an acceptable level?
- Is gas migration through the cap likely to occur at a rate that may pose an unacceptable risk?
  -- If likely, can the cap be designed to reduce risk to an acceptable level?
- Can the monitoring plan be designed to detect significant erosion or contaminant movement before unacceptable risk occurs?

For dredging, residual risk is primarily related to residuals, i.e., contaminated sediments remaining in the aquatic environment after the completion of dredging. (U.S. EPA 2005; NRC 2007; Bridges *et al*. 2008). Because residuals will occur to some degree with every dredging project (NRC 2007), they should be considered during remedy evaluation and selection (U.S. EPA 2005). There are two types of residuals, undisturbed and generated, both of which are important. Undisturbed residuals are contaminated sediments found at the post-dredge sediment surface that have been uncovered, but not fully removed as a result of the dredging operation (Patmont and Palermo 2007; Bridges *et al*. 2008). Generated residuals are contaminated sediments that are dislodged or suspended by the dredging operation and are subsequently redeposited on the bottom either within or adjacent to the dredging footprint (Patmont and Palermo 2007; Bridges *et al*. 2008). A series of dredging project results has shown that generated residuals ranged from 2 to 9% of the contaminant mass from the last production pass (Patmont and Palermo 2007). Lessons learned from previous dredging projects indicate that residuals are likely to be higher in areas where there are debris, rocks, bedrock, and/or hardpan as well as in areas with low dry density sediment (e.g., “fluff”) (U.S. EPA 2005; NRC 2007).

Residuals are not inconsequential. For example, during the 2005 Remedial Options Pilot Study at the Grasse River, the average surficial concentration of PCBs increased substantially immediately following dredging (NRC 2007). The increase occurred despite removing approximately 80% of the PCB mass in the dredging footprint (NRC 2007). Thus, mass removal did not equate to risk reduction in this more modern-day pilot (NRC 2007). Table 6 identifies key questions to consider regarding residual risk from dredging.

TABLE 6. Key questions to evaluate residual risk from a dredging remedy (adapted from Evison 2008).

- Is it likely that resuspension will pose an unacceptable risk?
- Is it likely that releases will pose an unacceptable risk?
- Is it likely that residuals will pose an unacceptable risk?
- If residuals are estimated to exceed cleanup levels, should an engineered cap be considered as an alternative to dredging?
- If residuals are estimated to exceed cleanup levels, can cleanup levels be achieved with backfill? If so,

how is the backfill intended to function?
-- If it is intended as a dilution layer
- Is the added material going to change the amount of contaminant mass that is bioavailable?
- Would thin layer placement without dredging be more appropriate?
-- If it is intended as a cap
- Has it been evaluated for erosion potential?
- Has it been evaluated for the effects of groundwater advection?
- Would engineered capping be more appropriate?

- Can the monitoring plan be designed to ensure the backfill is functioning as designed?

Selecting A Remedy. Once the remedial alternatives have been evaluated, a risk-based decision-making process should be applied to select a remedy or combination of remedies that will effectively reduce risks to human health and ecological receptors (U.S. EPA 2005). This risk-based decision-making process includes the 9 criteria from the NCP and complies with the NCP (U.S. EPA 2005; Evison 2008). Table 7 identifies key remedy selection considerations.

TABLE 7. Key remedy selection principles (adapted from U.S. EPA 2005 and Evison 2008).

- There is no presumptive remedy for any contaminated sediment site, regardless of the contaminant or level of risk.
- Risk management goals should be developed that can be evaluated within a realistic time period, acknowledging that it may not be practical to achieve all goals in the short term.
- Evaluate uncertainties concerning the predicted effectiveness of various remedial alternatives and the time frames for achieving cleanup levels, remedial goals, and remedial action objectives.
- Use realistic time frames for remedy design, implementation and completion, and incorporate risks associated with remedy implementation when comparing on-going risks
- The effectiveness of in-situ (capping and MNR) and ex-situ (dredging) alternatives should be evaluated under the conditions present at the site. There should not be a presumption that removal of contaminated sediments from a water body will be more effective or permanent than capping or MNR.
- Contaminants that are deeply buried, have no significant migration pathway to the surface, and are unlikely to be exposed in the future may not need removal because they do not necessarily contribute to site risks.
- No remedy is perfect. A combination of sediment management options may be the most effective way to manage risk.
- Developing accurate cost estimates is an essential part of evaluating alternatives. An important risk management function is to compare and contrast the cost and benefits of various remedies.

CONCLUSION

Contaminated sediment sites pose difficult challenges due to complex technical issues. Addressing these sites requires applying risk-management principles within a risk-management framework to remedy evaluation and selection. To be effective, this risk management framework must include consideration of implementation risks and residual risk at the remedy evaluation and selection phase. U.S. EPA's "Contaminated Sediment Remediation Guidance for Hazardous Waste Sites" provides such a framework.

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