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Dredging Processes and Remedy Effectiveness: Relationship to the 4 Rs of Environmental Dredging

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ABSTRACT

Timely and effective remediation of contaminated sediments is essential for protecting human health and the environment and restoring beneficial uses to waterways. A number of site operational conditions influence the effect of environmental dredging of contaminated sediment on aquatic systems. Site experience shows that resuspension of contaminated sediment and release of contaminants occur during dredging and that contaminated sediment residuals will remain after operations. It is also understood that these processes affect the magnitude, distribution, and bioavailability of the contaminants, and hence the exposure and risk to receptors of concern. However, even after decades of sediment remediation project experience, substantial uncertainties still exist in our understanding of the cause–effect relationships relating dredging processes to risk. During the past few years, contaminated sediment site managers, researchers, and practitioners have recognized the need to better define and understand dredging-related processes. In this article, we present information and research needs on these processes as synthesized from recent symposia, reports, and remediation efforts. Although predictions about the effect of environmental dredging continue to improve, a clear need remains to better understand the effect that sediment remediation processes have on contaminant exposures and receptors of concern. Collecting, learning from, and incorporating new information into practice is the only avenue to improving the effectiveness of remedial operations. Integr Environ Assess Manag 2010;6:619–630. © 2010 SETAC

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INTRODUCTION

Across the United States, sediments in lakes, rivers, estuaries, and oceans contain contaminants that have persisted long after their introduction to the aquatic environment and widespread usage has ended (USEPA 1997, 2004). For several decades, the potential risks these sediments pose to human health and the environment have been recognized (Dennis 1976; USEPA 1976; Gustafson 1970; Lee 1976). Yet today, we are still seeking effective approaches to manage these risks. Contaminated sediment sites occur in a range of industrial, residential, and undeveloped settings. These sites can be small, as in cases where a small chemical spill contaminates less than an acre of sediment. However, we are also faced with a number of large and complex sites that encompass entire river systems, lakes, or harbors where contamination results from long-term discharges and distribution of contaminants from 1 or many sources. The societal cost of contaminated sediments is great, both in terms of the loss of beneficial use of the water resources and in potential cleanup costs (Braden et al. 2004, 2006; Great Lakes Regional Collaboration 2005).

Several large sediment remedial activities are currently under way or being planned. For example, a 39-mile stretch of the Fox River in Wisconsin, from Lake Winnebago to Lake Michigan—the largest known source of polychlorinated biphenyls (PCBs) to Lake Michigan—is undergoing sediment dredging and capping. Following 2 small-scale dredging projects during the late 1990s, full-scale sediment remediation has been under way since 2004. Activities in the upper reach, Little Lake Butte des Morts, were completed in 2009 and removed approximately 370 000 cubic yards and capped or covered 260 acres. Cleanup at the entire site will involve dredging over 4 million cubic yards and capping or covering 860 acres. The cleanup cost for all operable units is estimated to exceed $800 million (USEPA 2009a, 2010; USEPA and WDNR 2008). Across Lake Michigan, sediments in a 79-mile reach of the Kalamazoo River in Michigan are also contaminated with PCBs released primarily from paper production and processing industries. Excavation of the river bed sediments in 1 section of the Kalamazoo began in 2007 and was completed in early 2009. This action removed 130 000 cubic yards at a cost of approximately $30 million (USEPA 2009b). The entire 80-mile stretch of the river is undergoing further characterization, with remedial decisions planned for the

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future. In May 2009, the first phase of dredging began in a 40-mile-long stretch of the Upper Hudson River, downstream of historical PCB releases in Hudson Falls and Fort Edward, NY. Mechanical dredging using excavators outfitted with ''environmental buckets'' removed approximately 300 000 cubic yards of sediments (of 265 000 targeted) over 50 acres (of 90 acres targeted). Dredging took place 24 h/d, 6 d/week for approximately 6 months (EPA 2009c). Combined with phase 2 dredging, the entire project is targeting 1.8 million cubic yards of contaminated sediments (QEA 2007). Other large contaminated sediment projects are undergoing various stages of planning or remediation, including the Housatonic River and New Bedford Harbor in Massachusetts, the Passaic and Hackensack River in New Jersey, the Tittabawassee River in Michigan, the Grasse River in New York, Portland Harbor in Oregon, and the Duwamish and Upper Columbia River in Washington State.

It is well known that contaminants in sediments can produce effects through direct toxicity to aquatic organisms and through bioaccumulation in their tissues, which can then pose a risk to consumers of those organisms. Methods to remediate those risks have been sought since the 1970s (see case studies on the Hudson River, James River, and New Bedford Harbor in NRC 1989), yet achieving or documenting success has been difficult. For example, although it is an imperfect measure, very few contaminated sediment sites added to the nation's National Priorities List (Superfund) list since its inception in the early 1980s have ever been delisted. Some sites (e.g., New Bedford Harbor) are still being remediated; other sites (Waukegan Harbor, WI, and Lauritzen Canal, CA) are planning a second remediation after the first failed to meet intended objectives.

These observations have a myriad of possible reasons. Simply put, reducing the risk posed by contaminated sediments presents a complex problem. Substantial difficulties surround 1) accurate characterization of the extent and sources of contamination, 2) understanding the degree to which known sources of contaminants pose adverse effects, 3) predicting the effect of remediation on contaminants in biotic and abiotic compartments, 4) effectively implementing the remedy to lessen risk, and 5) documenting the effect of the remedy on receptors of concern. For example, for PCBs, the class of chemical that drives most sediment cleanup (USEPA 2005), remediation is typically undertaken in an attempt to decrease their concentration in fish tissue. Characterizing the PCB exposures (locations, sources, environmental compartments) that drive fish contaminant burdens is complex and uncertain. Because it is well established that PCBs and other persistent organic contaminants accumulate preferentially in sediments and those contaminants can be transferred up the food chain to fish, contaminated sediment remediation is often the chosen approach. However, it has generally not been established that active sediment remediation has resulted in decreases in fish tissue contaminant concentrations. This is not to say that sediment remediation will not or cannot reduce those levels; rather, the causal relationship between remedy actions taken and risk reduction observed has proved difficult to establish (or that the effect of the operation simply was not assessed). The ability of a remedy to achieve its post-remediation cleanup levels (typically a sediment contaminant concentration) is better understood, but challenges still remain in achieving these targets (see NRC 2007 for an extended examination of the effects and effectiveness of dredging for achieving cleanup levels). However, it is important to distinguish the objective of meeting a cleanup level through the use of a specific technology from the ultimate and intended purpose of a remediation project (i.e., accomplishing risk reduction); satisfying the former is not an adequate substitute for not achieving the latter.

Environmental dredging (dredging performed specifically for the removal of contaminated sediments for the purpose of remediating environmental risks) has historically been most frequently chosen as the remedial option to address contaminated sediments (NRC 2007). An advantage commonly attributed to the removal of contaminated sediments via dredging is greater confidence in the long-term effectiveness of the cleanup, assuming contaminated materials causing the risk are actually removed and risk-based cleanup goals achieved. However, environmental dredging and the associated disposal are generally more complex and costly than other approaches, such as capping, and there are several site-specific conditions and technical issues that can limit the ability of dredging to achieve anticipated and desired risk reductions.

A number of recent efforts have sought to better understand and document the effects of environmental dredging on the environment and the technical and engineering issues that influence those effects (e.g., EPA 2005, NRC 2007). Two more recent efforts have been completed by the US Army Engineer Research and Development Center (ERDC) and the US Environmental Protection Agency (USEPA) Office of Superfund Remediation and Technology Innovation:

- A 2008 ERDC technical report on the ''4 Rs'' of environmental dredging (see Box 1): *resuspension* of sediment resulting from dredging operations; *release* of contaminants from bedded and suspended sediments in connection with dredging; *residuals*, contaminated sediment produced by and/or remaining after dredging; and *risks* that are the target of and associated with dredging (Bridges et al. 2008).
- A 2008 ERDC technical report, Technical Guidelines for Environmental Dredging of Contaminated Sediments, discusses in considerable detail the 4 Rs of environmental dredging and provides a detailed examination of sediment site characterization, predicting the effect of environmental dredging, equipment selection and operating practices, and monitoring (Palermo et al. 2008).

This article seeks to summarize the components of these documents that examine the 4 Rs processes (see Box 1 and Figure 1) and support those descriptions with site-specific information compiled from a variety of sources. The intent is to promote consistency in the terms used to define these challenges, to identify key uncertainties, to recommend future research to better define the linkages between operations and the 4 Rs, and ultimately to support better remedy selection and implementation. A word of caution is warranted, particularly relating to many of the site experiences described herein: the sediment remediation field is dominated by ''gray literature,'' consulting reports and conference proceedings that describe a remedial action and provide some aspects of monitoring. These typically do not probe underlying processes to ascertain cause and effect. Further, they have largely not been peer reviewed, nor are they easily accessible; for various reasons, some remain in perpetual ''draft'' status. Hence, the field suffers from a dearth of structured evaluations designed to test hypotheses

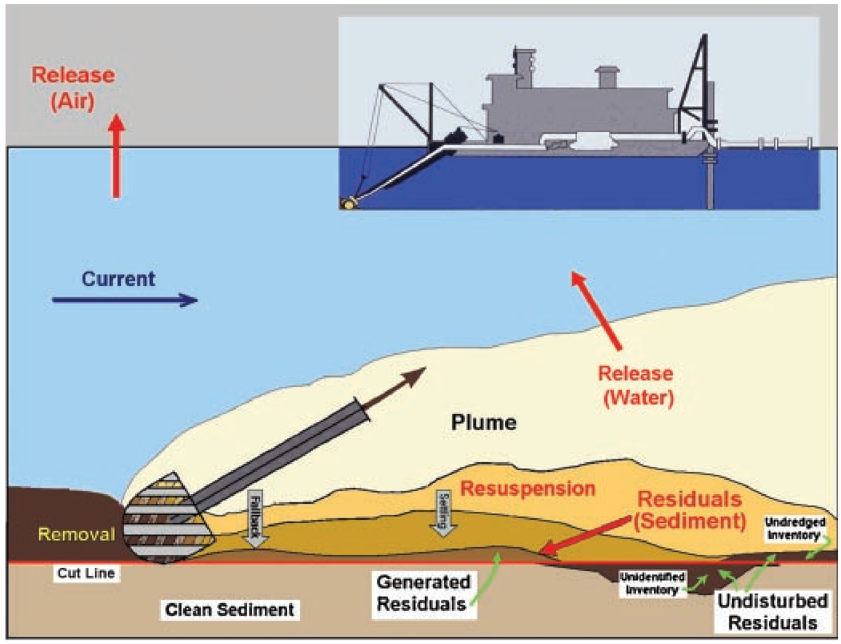

Figure 1. Dredging related resuspension, contaminant releases, and residual contaminated sediments. (Adapted from Palermo et al. 2008).

Box 1: 4 Rs of Environmental Dredging: Resuspension, Release, Residuals, Risk

- **Resuspension:** processes by which a dredge and attendant operations dislodge bedded sediment particles and disperse them into the water column
- **Release:** process by which the dredging operation results in the transfer of contaminants from sediment pore water and sediment particles into the water column or air
- **Residuals:** contaminated sediment found at the post-dredging surface of the sediment profile, either within or adjacent to the dredging footprint; they can be broadly grouped into 2 categories (Figure 1):
  - *Undisturbed residuals:* consolidated or intact contaminated sediments found at the post-dredging sediment surface that have been uncovered by dredging but not fully removed
  - *Generated residuals:* contaminated post-dredging disturbed surface sediments that are dislodged or suspended by the dredging operation and are subsequently redeposited on the bottom of the water body
- **Risk:** likelihood for an adverse consequence or outcome. For contaminated sediments, the risk of primary concern is a function of exposure and effect processes. In the current context, the focus is on changes in contaminant exposures caused by environmental dredging.

Bridges et al. (2008).

and uncover driving factors. Our objective in the present work is to draw information from these diverse sources to identify inferences, conclusions, and needs; however, this article should also not be taken as carte blanche validation of results; rather, it should be taken as a call for increased rigorous investigations of the phenomena described.

THE 4 Rs OF ENVIRONMENTAL DREDGING

Resuspension

Sediment resuspension (see Box 1) refers to the dislodgement and dispersion of sediment particles (not soluble contaminants) and is a by-product of every dredging project. In addition to the dredging itself, many operational aspects of dredging contribute to sediment resuspension including movement of tugs and transport scows, silt screen maintenance, and debris removal. Dredge movement and removal actions induce localized turbulence and shear and resuspend bottom sediments that are not captured. In this process, sediment breaks from the bed as individual particles or larger agglomerations of particles. Immediately after resuspension, large sediment aggregates will rapidly fall back to the sediment bed. Dense slurries will flow to the bottom of the water column and then quickly densify. Smaller particles will disperse in the water column and begin to flocculate and settle. As they approach the bottom, some particles will remain in suspension as part of a near-bottom fluid mud layer, if the environment is sufficiently turbulent or if their composition is mostly organic (McAnally et al. 2007). Other sediment particles will deposit and adhere to the surficial layer of the sediment bed.

Sediment particles that remain in suspension long enough will be transported beyond the dredging operation. Transport of resuspended sediments by dredging operations is conceptualized at 3 zones: 1) the initial mixing zone, where the dredging operation dominates the process with induced currents and suspended sediment concentrations are expected to be relatively uniform; 2) the near field zone (typically within 100 m of the dredging operation), which is dominated by dispersion and rapid settling velocities and gradual changes in total suspended sediments with distance and depth; and 3) the far field zone, where the total load in the plume is slowly varying and where advective diffusion, flocculation, and settling are of the same order of magnitude. Transport of resuspended sediments will depend on environmental and operational factors (e.g., flow velocities and presence of silt curtains) and the settling rate and concentration of resuspended sediment particles. Sediment plumes become progressively dispersed and degraded with increasing distance down current and eventually fade into background concentrations. Where ambient concentrations of suspended solids are relatively low, plume signatures may be visually detectable as far as 1000 m or farther down current; however, plume signatures are seldom measurable at that distance (Mikkelsen and Pejrup 2000).

Engineering and operational controls are often used in an attempt to control the magnitude and duration of resuspension (Palermo et al. 2008). Silt curtains are a common engineering control used to retain suspended sediment plumes (Francingues and Palermo 2005). Their application in moderate- or high-energy areas can be complicated, requiring frequent repair and maintenance (curtains are not secure walls and cannot withstand pressures from currents and tidal fluctuations). Their effectiveness in containing resuspended sediments is not fully understood. Water passes below or around fabric curtains because they are not typically sealed with the bottom. Although costly, metal sheet pile or other structural barriers are occasionally used to contain resuspension during operations, particularly in high-energy environments, although with different technological limitations.

The extent of sediment resuspension will vary based on many factors, such as sediment properties (bulk density, particle size distribution, and mineralogy), site conditions (water depth, currents, and waves), nature and extent of debris and obstructions, and equipment selection (the physics of sediment removal) (Palermo et al. 2008). Operational considerations such as dredging production rate, thickness of dredge cuts, dredging equipment type, method of operation, and skill of the operator also influence the rate and magnitude of resuspension. Their influence can be managed through operational controls such as modifying the speed of removal operations and eliminating spillage from dredge buckets or overflow from transport barges (Palermo et al. 2008). Because of the variability in all these factors, the magnitude, duration, and location of sediment resuspension will vary throughout dredging operations (e.g., see Figure 2).

Sediment resuspension data have been collected from a variety of dredging operations and range from <0.1% to >5% of the fine-grained fraction of the sediment removed (Anchor Environmental 2003; Nakai 1978; Pennekamp et al. 1996). Sediments resuspended during dredging operations pose a variety of water quality and ecological concerns. The sediment plume in the immediate vicinity of the dredging could influence the behavior of fish and impact the health of less mobile aquatic vertebrates and invertebrates. Resettling of suspended particulates could also impact bottom-dwelling organisms. Resuspension can also result in higher concentrations of particulate-associated contaminants in the water column, drive increases of dissolved contaminant concentrations (a contaminant "release" pathway), and disperse contaminants wider in the aquatic environment. Upon settling, resuspended sediments become generated residuals. The interrelated processes of release and residual generation are described below.

Research needs—The multifactorial nature of dredging operations, equipment, sediment properties and site conditions complicates the translation of resuspension data from one site to another. The complexity is exacerbated because most past projects have not collected data to discern factors influencing resuspension. Of particular importance are data on geotechnical properties of the sediment and information on dredge operating characteristics. Many elements of the resuspension process and physics of the sediment removal processes are not known. Additional research is needed to understand the relationship between resuspension, the resulting contaminant release, and residual generation. Resuspension is the easiest of these to measure, but least definitively linked to contaminant risk to receptors. Turbidity (and less often total suspended solids [TSS]) is often used during remedial operations to indicate the presence of sediments or other particles in the water column, but this measure can only be coarsely linked to dredging operations, because it is so highly influenced by measurement location and other site conditions (wind, rain, algal blooms, and recreational boaters). Improved tools and protocols for monitoring dredging-related resuspension and understanding its impacts are needed (Bridges et al. 2008).

Release

Release (see Box 1) is defined as the process by which the dredging operation results in the movement of contaminants into the water column or air. Dredging operations can release contaminants through a variety of mechanisms. The primary sources are contaminant desorption or pore water release from resuspended sediments, dredging residuals, or other fluid layers with high suspended solids concentration (e.g., fluid mud or the nepheloid layer). Other potentially significant contaminant releases are molecular diffusion from the dredging cut face, groundwater advection, and nonaqueous phase liquid (NAPL) exposure. The degree of contaminant releases will depend on several physical and chemical factors including the rate, magnitude, and duration of sediment resuspension; sediment bed composition (e.g., grain size distribution); contaminants associated with the sediment; and resuspension plume dynamics.

Because releases are difficult and expensive to measure at a dredging site, little empirical data are available on their magnitude and the processes that drive them. Research has shown that dissolved and total contaminant concentrations can vary greatly in all dimensions at distances of 100 to 300 m from the dredge head due to variability in the dredging operations and dilution by turbulent diffusion in the water column (Hayes et al. 2000). A few quantitative evaluations of contaminant release have been undertaken at dredging sites. For example, during a 1999–2000 pilot study on the Fox River, WI, monitoring data collected 30 to 60 m from the hydraulic dredge head and outside of silt curtains, suggested that approximately 2% of the dredged PCBs were transported downstream of the pilot project area (Steuer 2000). Roughly

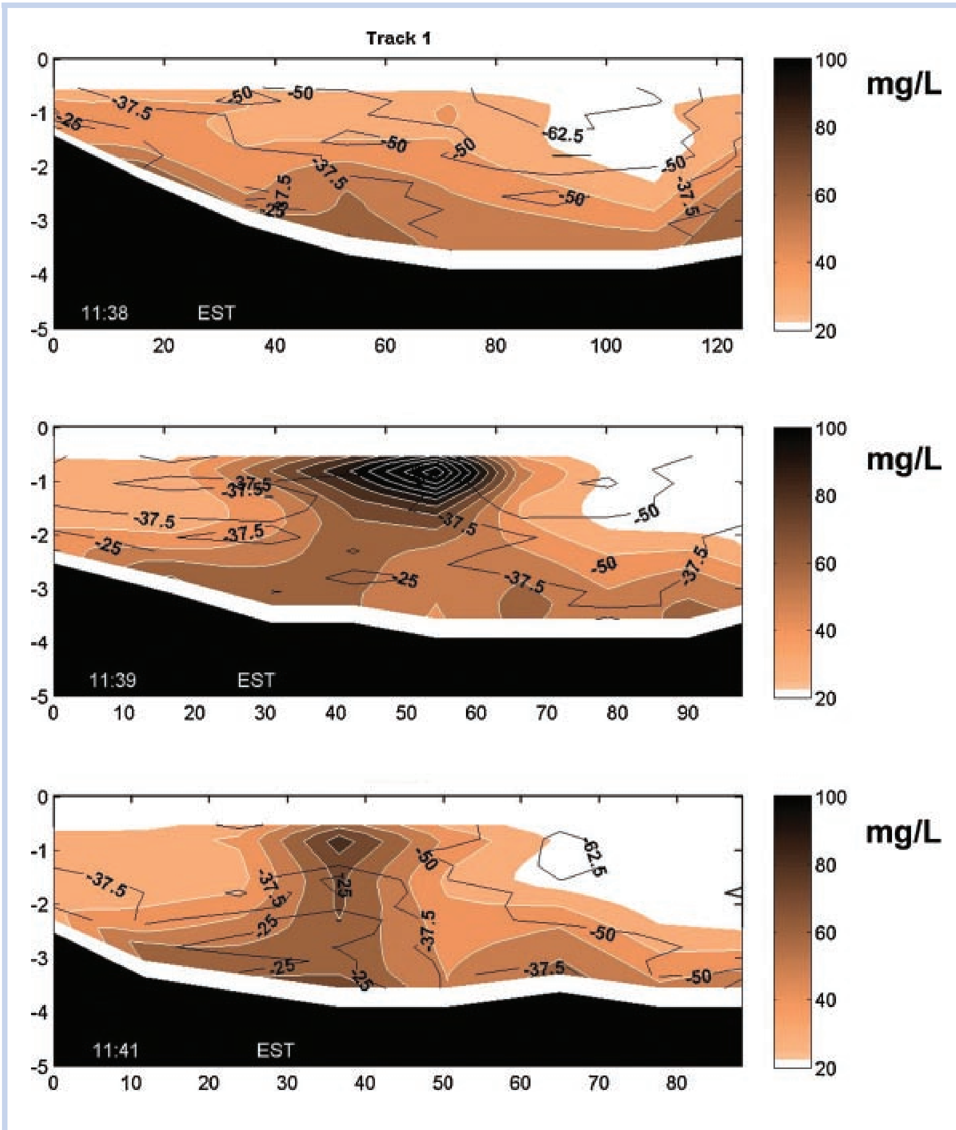

Figure 2. Variability in sediment resuspension during dredging. A series of 2-dimensional cross sections (*x*, *y* distance in meters) of the same location in the Passaic River depicting estimated total suspended solids (TSS) (using acoustic doppler current profiler results) downstream of dredging operations (30–70 m) taken over 4 min of dredging. Note that resuspension, indicated by a plume of elevated TSS, occurred in ''short-lived pulses'' throughout dredging (here, conducted with a mechanical bucket dredge). (Source: Malcolm Pirnie and Earth Tech 2007.)

one-third of the water column load increase was attributable to dissolved PCBs that presumably partitioned from resuspended sediments. Monitoring at a recent pilot dredging project in the Grasse River showed that approximately 3% of dredged PCBs were released during dredging and debris removal (Connolly et al. 2007). The latter study also showed a concomitant, short lived (1-y) increase in fish tissue concentrations downstream of dredging operations, including a station 6 miles downstream of dredging. The intensive monitoring at the Hudson River sediment remediation project that began in spring 2009 has provided a wealth of data on releases from dredging operations (USEPA 2009d). Figure 3 shows water column PCB concentrations taken in the year prior to dredging and during dredging approximately 5 miles downstream of operations (the closest point monitored for PCBs), including 3 excedances of the 500 ppt drinking water standard during operations. The causes of those releases are being investigated. In contrast, monitoring during a small-scale dredging pilot study in the Passaic River indicated that contaminant fluxes could not be detected beyond the natural variation in the contaminant loads carried by the river (Malcolm Pirnie and Earth Tech 2007). In a preliminary study conducted at New Bedford Harbor, researchers found that concentrations of dissolved PCBs in the water column increased during dredging as compared with after dredging had ceased. The increase in dissolved PCB concentrations was limited to the area most immediately near the dredging activity and rapidly decreased with distance from the dredging activity (RM Burgess, personal communication, Sept. 30, 2008; Battelle 2007). However, an earlier study in New Bedford Harbor that evaluated environmental dredging of a 14 000 cubic yards ''hot-spot'' showed no increase in mussel bioaccumulation of PCBs during dredging compared with before or after (Bergen et al. 2005). What drives the apparent differences in some of the above examples—scale of operations, environmental and chemical conditions, measure-

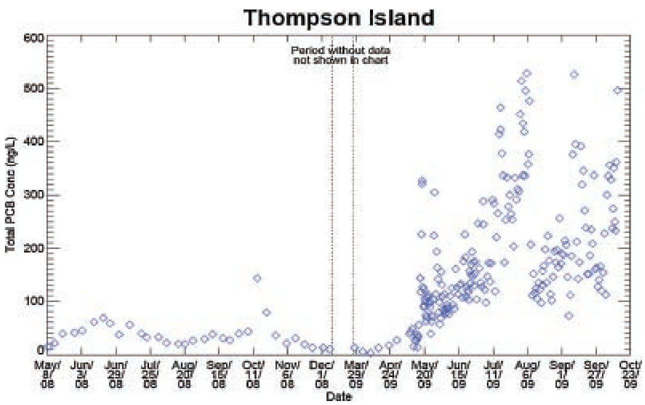

Figure 3. Total PCB concentrations (particulate + dissolved) measured in the water column before and during dredging of the Hudson River, NY. Dredging began May 15, 2009, corresponding with increased water column PCB concentrations. The monitoring station (Thompson Island Dam) was approximately 5 miles from where most of the dredging occurred, although some dredging occurred approximately 2 miles up stream from the station. (Source: Haggard 2009.)

ment procedures and locations, or a combination of factors—remains unclear. That alone suggests the importance of monitoring during operations and, in particular, further investigations to ascertain cause–effect relationships.

The release pathway is particularly important because dissolved contaminants are readily bioavailable to fish and other biota (Eggleton and Thomas 2004). Relevant spatial scales for risks resulting from exposure to released contaminants are on the order of hundreds of meters laterally to thousands of meters longitudinally. The vertical distribution of dissolved releases can also be important, particularly in deeper or stratified systems. In the short term, contaminants desorb from the particulate and colloidal phases into the dissolved phase while in suspension. In the long term, residuals (or sediments remaining in suspension) may continue to slowly release contaminants even after they have been dispersed in the far field. As such, the kinetics of desorption and aggregate and/or floc settling are critical. Studies on the desorption of chlorinated organic contaminants in sediments have shown that it can take weeks to reach equilibrium; however, >10% of the contaminants can desorb in the first hour and 30% can desorb in the first day (Borglin et al. 1996; Lick and Rapaka 1996). Short-term releases directly to the water column from dredging operations may be 1 to 3 orders of magnitude greater than pre-dredging releases from the sediment bed for the same period of time (Sanchez et al. 2002). Because environmental dredging projects may run near continuously for months at a time and span multiple dredging seasons, evaluation of the potential for increased exposure attributable to releases will provide critical input to decisions concerning remedy selection and the design and conduct of dredging operations.

Research needs—Numerous data gaps and uncertainties exist in our understanding of the effects of dredging operations, sediment and water column characteristics, the magnitude of resuspension, and residual production on contaminant releases. As described in Palermo et al. (2008), predictions of contaminant releases are typically theoretical (e.g., based on equilibrium partitioning theory) or based on laboratory measurements such as the dredging elutriate test (DRET) (Digiano et al. 1995), which is commonly used but only validated for PCBs. Focused field and laboratory studies are needed to address these data gaps so that releases during dredging operations can be better predicted and their impact on aquatic receptors and the effectiveness of the remedial action can be better understood. There is also a need to establish best practices for techniques, location, and timing of release monitoring based on environmental conditions (Bridges et al. 2008). Ultimately, we need a sufficient knowledge base so that the magnitude and effect of releases can be predicted and we can appropriately weigh the adverse effects of contaminant release against the benefit of contaminant removal.

Residuals

No removal technology can remove every particle of contaminated sediment and all dredging operations leave some residual contaminated sediment (see Box 1). At many sites, dredging residuals have resulted in a failure to achieve predetermined contaminant cleanup levels in sediments (NRC 2007). In hindsight, this is not surprising given the limitations of most dredging equipment, the variable distribution of contamination found in many sites (including high levels at depth), and the limited degree of predredging characterization. The inevitability of postdredging residuals and their influence on risk has been increasingly recognized over the last decade. Recent technological innovations in dredging equipment (e.g., Green et al. 2007) and methods for reducing residuals have shown improvements over conventional equipment and practices (Fuglevand and Webb 2009; Palermo et al. 2008). Because the purpose of any sediment removal action is to lessen contaminated sediment exposure, dredging residuals, particularly if they are more contaminated than preremediation surface sediment, are a source of serious concern.

The nature and extent of postdredging sediment residuals are thought to be related to multiple environmental factors, including sediment geotechnical and geophysical characteristics, the variability in contaminant distributions, and physical site conditions such as the presence of bedrock, hardpan, debris, or other obstructions. Operational factors that likely affect residuals include dredging equipment size and type, number of dredge passes, selection of intermediate and final cutline elevations, allowable overdredging, dredge cut slopes, accuracy of positioning, operator experience, and the sequence of operations (see Box 2) (Bridges et al. 2008; Palermo et al. 2008; Fuglevand and Webb 2009).

The presence of debris and hardpan and/or bedrock and sediment liquidity appears to be the most important site factors determining the potential for higher generated residuals. Sediment with low dry bulk density (e.g., water content exceeding the geotechnical liquid limit) also appears to increase the potential for dredge residuals (Patmont and Palermo 2007). Complicating factors in the dredging process (e.g., the presence of debris in the sediment bed) can make the sediment removal process and achievement of risk-based cleanup levels difficult as well as costly. See Box 3 for a summary of ''lessons learned'' regarding the generation of residuals at sites.

Box 2: Primary Causes of Dredging Residuals

Undisturbed residuals: primary causes are thought to include:

- Attempts to dredge sediment that:
  - Directly overlies bedrock or hardpan
  - Covers highly uneven surfaces, or debris or boulders that are left in place
  - Is located near piers, pilings, or utility crossings that are left in place
- Incomplete characterization of the horizontal and vertical extent of contaminants and/or inability of geostatistical models to adequately represent the distribution of contaminants
- Inappropriate selection of a target dredge design elevation
- Inaccuracies in meeting targeted dredging elevations due to poor positioning controls
- Development of dredging plans that intentionally do not target complete removal of contaminated sediments (e.g., due to engineering limitations)
- *Generated residuals:* primary causes are thought to include:
- Sediments dislodged but left behind by the dredgehead without being widely dispersed due to site conditions, dredge operation, or equipment limitations
- Destruction of the sediment fabric and stability by debris-removal operations
- Sediments with high liquidity
- Attempts to dredge sediment in settings that limit the operation of the dredge (e.g., in debris fields)
- Sediment that sloughs into the dredge cut from adjacent, undredged areas
- Sediment moved by slope failures caused by the process of dredging
- Sediment loosened by the dredgehead that quickly resettles
- Sediment resuspended by dredging or other dredging-related activities that resettle within or adjacent to the dredging footprint.

The state of practice in modeling dredging processes is not sufficient to make precise predictions of postdredging residual contaminant concentrations. In the absence of such modeling capability, empirical approaches have been used at dredging projects. Existing data suggest that the average concentration of contaminants in generated residuals will approximate the mass-weighted average sediment concentration in the final production cut profile (the concentration present in sediments within the final production cut or cleanup pass will have been influenced by overlying sediments previously dredged) (Palermo et al. 2008; Reible et al. 2003). A few cases of post hoc estimates for the relative mass of contaminants remaining following dredging have been presented recently (e.g., Desrosiers and Patmont 2009). Generated residuals were estimated for 12 projects on the basis of mass balance calculations using site data collected for other purposes. At those sites, the residuals represented approximately 2% to 11% of the mass of solids dredged during the last production cut.

A variety of processes influence the generation of residuals, so their depth and characteristics will vary across a site. At the Head of Hylebos project at the Commencement Bay Superfund Site in Washington (Dalton Olmsted & Fuglevand 2006), residuals in the project area ranged from none to >1 foot (the vertical extent of the sampling); in the Grasse River in New York State, residuals in the dredged area ranged from 3 to 32 inches (NRC 2007, p 126). The thickness of generated residuals at that site was generally limited to a few inches; most of the materials were undisturbed residuals, resulting from incomplete removal. Most environmental dredging operations have not conducted a rigorous evaluation of postdredging residual thickness (much less sought to differentiate between generated and undisturbed residuals). Some recent projects, such as the Stryker Bay cleanup within the St. Louis River/Interlake/Duluth Tar (SLRIDT) site (Russell et al. 2009), have attempted to document the apparent thickness of generated residuals in the removal area with postdredging coring studies. Some sites have also evaluated generated residuals outside of the dredge area. For example, the EPA Office of Research and Development monitored the deposition of sediments adjacent to dredging areas during and after remedial operations in the New Bedford Harbor using sediment traps (Battelle 2007). The 2005 pilot dredging study in the Passaic River used sediment profile imaging (SPI) to qualitatively evaluate residuals resulting from operations (Malcolm Pirnie and Earth Tech 2007). The Duwamish Diagonal project (EcoChem 2005) also sampled sediment beyond the site boundary to document changes in chemical concentrations of surface sediments due to transport of dredge material. The monitoring at these sites supports our understanding that residuals will occur inside and outside the dredge prism and provides a basis for extrapolating that experience to make informed predictions at other areas.

The physical properties of residuals will determine their disposition and the efficacy of any residuals management action. Self-weight consolidation tests and compression settling tests indicate that fluidized fine sediments will consolidate to near surficial in situ densities within a period of a few weeks to several months, depending on sediment characteristics and site conditions (Cargill 1986). Conversely, the physical and geotechnical characteristics of sloughed or plowed materials, as well as undisturbed residuals, will likely not change appreciably after dredging. Depending on site conditions, undisturbed residuals may or may not be amenable to removal by an additional cleanup dredging pass. Because of their physical characteristics (e.g., decreased density and increased liquidity), generated residuals are likely to be more difficult to remove with additional cleanup dredging passes without specialized equipment.

Research needs—Research is needed to improve our understanding of the connections between environmental conditions, remedial operations, and residual generation. To indicate the effect and effectiveness of dredging operations and to provide further real-world calibration of residual estimation methodologies, systematic collection and publication of pre- and post-dredging depth and concentration of residuals inside and outside the dredge prism is needed.

A greater understanding of residual behavior over time is also needed. Palermo et al. (2008) advocate the following: 1) analyzing residual migration as fluid mud or bed load and the duration and effect of residual exposures during and immediately following dredging; 2) monitoring changes in key geotechnical and geochemical characteristics over time (e.g., concentration and density profiles within days to weeks following dredging; mixing rates; stability); and 3) evaluating the efficiency of silt curtain systems in retaining suspended sediments and contaminants within the curtain footprint and potential migration through the bottom of the curtain anchor system or after curtain removal.

Finally, research and guidance are needed to refine monitoring tools and protocols; for example, how to handle fluid surficial material prior to analysis of residuals; methods for discerning generated residuals from undredged inventory; and sampling or visualization techniques that permit assessment of residuals over solid or rocky surfaces.

Risk

Because the purpose of environmental dredging is to reduce risks to an acceptable level, risk assessment provides the context for understanding the significance of the exposures that result from resuspension, release, and residual processes. This risk context can serve as the basis for making predictions about the performance of environmental dredging and input to remedial decision making. Characterizing how dredging will influence risks includes considering which elements or receptors in the ecosystem are affected, how the processes contributing to risk change with time, the spatial scales over which effects would be expected to occur, and the uncertainties associated with the predicted changes and risk reduction.

Receptors—Three receptor groups are relevant to contaminated sediment risks and dredging: organisms living in the sediment (benthos), pelagic organisms (primarily plankton and fish), and consumers of aquatic life (upper trophic-level receptors such as fish, birds, and mammals, as well as humans). These groups share a set of potential adverse effects (e.g., increased mortality, and reduced growth or reproduction), but differ in their dredging-related exposures over the short and long term:

Sediment-dwelling organisms: It is unavoidable that dredging will destroy organisms within the dredging prism (e.g., see Figure 4). Their recolonization rates will be dependent on the suitability of remaining substrate (including physical composition and the presence of contaminated residuals) and other factors such as import of colonizing organisms from surrounding areas, nature of the habitat, and the time of year. Benthos outside the dredging prism will be exposed to contaminants released to the water column during dredging and resuspended sediment that settles outside the dredged area as residuals. The nature of benthic exposures to contaminants in residuals will depend on the chemical, biological, and physical processes operating that influence the burial and transport of sediment, and the contaminant geochemical transformations, partitioning, bioavailability, and degradation processes. Whether dredging residuals have greater bioavailability than native sediments has been researched to a limited extent. Friedman et al. (2009) showed in laboratory studies using New Bedford Harbor sediments that generated residuals (sediments that were resuspended and allowed to redeposit) generally did not have increased contaminant bioavailability of PCBs compared with control sediments.

Box 3: Lessons Learned From Prior Environmental Dredging Projects on Dredging Residuals

- Prior to selection and/or design of a dredging remedy, the probability of encountering debris should be evaluated through historical site use reviews (e.g., aerial photos and old maps indicating the presence of industry, piers).
- Semiquantitative debris survey techniques should be used as appropriate for the specific site, including side scan sonar, subbottom profiling, magnetometer, metal detectors, probing, diver, or underwater video.
- Mechanical dredging or separate debris removal passes may be required, in some cases, to address debris and/or hardpan/bedrock.
- The presence of hardpan or bedrock poses a difficult problem with respect to residuals (neither lends to overdredging for either undisturbed or generated residuals).
- Loose rock and cobbles, uneven surfaces, and bedrock fissures also pose operational difficulties that can impact undisturbed and generated residuals.
- Engineered controls (e.g., silt curtains or sheet pile enclosures) may help control the dispersion of resuspension and residuals and concentrate them within the enclosure footprint; redeployment and removal of these devices can release pulses of suspended material and residuals.
- Specialized dredging equipment designed for residual removal can be effective for managing generated residuals under conditions appropriate for their application.
- Implementing operational controls may greatly complicate the environmental dredging process, with reductions in production efficiencies and increases in costs.

Figure 4. Dredging operations impact to habitat. Dredging shown removing contaminated sediment and eel grass communities. (Source: Kymberlee Keckler, USEPA.)

Pelagic organisms: Pelagic receptors are directly exposed to contaminants through contact with suspended contaminated sediment and contaminants desorbed into a dissolved phase. Adverse effects to aquatic biota can occur either through direct toxicity or by increasing tissue residues of bioaccumulative chemicals within the food chain. Dredging related releases and exposures will last as long as the operation period. Impacts (increased contaminant concentrations in water and fish) have been noted several miles downstream of operations. The magnitude of risks resulting from these exposures will be influenced by a number of variables, including the toxicity and hydrophobicity (octanol-water partition coefficient [K_{ow}]) of the compound, the kinetics of bioaccumulation, the degree to which the chemical is metabolized by organisms, the structure of the food chain, and, of course, the magnitude and duration of the resuspension event. The duration of these effects is not well known, but some observations have shown transient increases in fish tissue contaminant concentrations, where tissue concentrations spike the same season as dredging followed by decreases to pre-dredging values (Connolly et al. 2007; NRC 2007).

Consumers of aquatic life: The effect of contaminated sediments on consumers of aquatic life cannot be readily attained by direct measures such as toxicity testing. Therefore, estimates of risk to these receptors are commonly based on assumptions regarding consumption rates and duration and bioaccumulation modeling to predict contaminant concentrations of consumed organisms. The use of these indirect lines-of-evidence creates significant uncertainty in baseline risk estimates. This problem is compounded for predicting postremediation risks because of the added uncertainty of the effect of the dredging operation on contaminant concentrations in sediments and biota.

Understanding time scales and the spatial dimension of the 4 Rs—Contaminant risks resulting from an environmental dredging project can be thought of in 2 time phases: short-term changes that occur during dredging and until the system attains a new steady state, and long-term changes in risks resulting from the operations. After dredging, contaminant concentrations in water and sediment will approach a new steady state that is determined primarily by the distribution and nature of dredging residuals. The ability to predict changes in postdredging exposure, toxicity, and bioaccumulation will depend on 1) the accuracy of estimates of the efficiency of the operation at removing contaminants, 2) the ability to describe the removal, movement, and disposition of sediments in the dredging prism and surrounding area, 3) the degree to which the predictive models accurately reflect the relationships between sediment, water, and receptor contaminant concentrations, and 4) whether the influence of any contamination from surrounding areas and sources was appropriately quantified. Spatial dimensions of exposure and effect processes are a critical element of a conceptual site model capable of supporting a sound risk assessment. All else being equal, risks being expressed over a larger area are a greater concern than risks being expressed over a smaller area. How the spatial aspects of exposure and effect are characterized across the site will determine how variation in risk across the site is described, what contribution an individual project area is making to overall site risk, and, ultimately, how those risks should be remediated.

Uncertainty and the role of monitoring—Two ''constants'' of sediment remediation projects are that environmental conditions affecting the nature of the problem are dynamic, especially over the large areas covered by many contaminated sediment sites, and that uncertainties will limit the accuracy of predictions about remedial performance with consequent effects on decision-making. Our knowledge of processes affecting the performance of remedial options (e.g., dredging and capping) is relatively coarse, which accounts for the limited power of current tools for predicting the performance of various remedial approaches and the uncertainty of those predictions.

When evaluating remedy effectiveness, there is danger in reacting to changed conditions without a clear understanding of whether the remedy was responsible for the change. A key challenge to understanding resuspension, release, residuals, and their contribution to site risks is distinguishing dredging-related processes from those related to ambient conditions. In this regard, a monitoring plan that includes sufficient baseline sampling is essential for comparing to postremediation monitoring data. Because of the intrinsic variability and likelihood that natural processes affect sediment contamination, baseline sampling should be collected consistently and with sufficient frequency and sample size to demonstrate trends (or lack thereof) over time. A time trend comparison (in contrast to a simple comparison of means before and after dredging) provides confidence that effects in the receptors of concern relate to the remedial activities and not natural, ongoing processes (NRC 2007; USEPA 2005, 2008). The long timeframe of decision making and planning at sediment megasites prior to remediation can easily accommodate such monitoring.

The decision to select a sediment remedy is made in the face of uncertainty about the outcome in terms of risk reduction. This uncertainty derives from the complexities inherent to these projects, variability in relevant processes, and gaps in our knowledge. Data are collected before the remediation to inform the decision and to design the remedy, but ultimately no one can know in advance how effective the remedy will be in actually reducing risk. A well-designed monitoring program, with sufficient baseline sampling, is the only way to reach supportable conclusions about remedy performance in the short and long term. Evaluating other site experiences can also help to bound the uncertainty surrounding predictions. A few such pilot studies with intensive monitoring have helped inform our understanding of dredging in a variety of systems, for example, in Lavaca Bay, TX (Alcoa 2000); the Grasse River, NY (Alcoa 2005); the Ashtabula River in Ohio (Timberlake et al. 2007); and most recently, the Hudson River in New York.

Research needs—A better understanding of the effects and timeframes of resuspension, release and residuals on the risk to receptors is needed. Risk results from an interplay of many factors, including: concentrations of chemicals of concern in sediment and water column, residence time of the residual sediment layer, residual sediment layer thickness, stability (under what conditions will the layer remain in place or move?), the biological availability of contaminants, and exposure of receptors. For residuals, there are few data upon which to base conclusions about how a thin layer (1 to a few cm) of contaminated sediment overlying clean sediment contributes to exposure and risk in the short or long term. At the same time, the factors influencing the effectiveness of covering and diluting dredging residuals with backfill or thin layers of clean soil or sediment have not been subjected to significant study.

Although it may be assumed (or not) that dredging releases will create transient exposures that increase risk in the short term, the magnitude (or reality) of that effect has not been rigorously examined under enough conditions to confidently predict when such phenomena will occur. For example, studies at some sites, such as Lavaca Bay, TX Pilot (Alcoa 2000) and New Bedford Harbor (Bergen et al. 2005), showed no dredging related increases in the body burdens of organisms; in other studies, such as Grasse River (Connolly et al. 2007) increases were apparent (see also examples of releases above). In a similar vein, the long-term effect of dredging (and other remedial options alone or in combination) is not well known. Little conclusive evidence has been collected to establish that, for example, dredging reduces PCB concentrations in fish tissue following operations beyond that expected from preremediation trends (NRC 2007). Systematic evaluations of remedial effectiveness in reducing fish tissue contaminant concentrations and other measures of risk, including the effect of resuspension, release, and residuals, would be very useful in answering this thorny issue. More specific examination of the pathways through which organisms experience exposure and how remedial technologies affect these pathways is needed to reduce the uncertainties associated with remedial project outcomes.

DISCUSSION

The question that haunts the sediment remediation community is ''Can we do better?'' It is more than disappointing that, several decades into evaluating and remediating contaminated sediments, so many uncertainties remain and interfere with our ability to reach confident conclusions about whether our remedial measures can, will be, or were successful. Over that period, opportunities have been missed which would have produced a deeper understanding, through structured monitoring of remedial projects, of the relationship between remedial actions and risk reduction (e.g., did the action taken reduce fish tissue contaminant concentrations? If not, why?).

A first useful step toward more effective decisions and remediation projects is to recognize that predictions about remedy performance may be wrong. Considering the compounded assumptions and uncertainties intrinsic to predicting remedial outcomes, that reality should not be surprising. That recognition also frees us from the significant burden of making the one, right remedial decision (the essence of selecting a remedy in the Record of Decision) and compels us to monitor progress towards our objectives and to use that information to optimize that progress. This is the foundation of an adaptive management approach (Linkov et al. 2006; NRC 2003). Under an adaptive management paradigm, the focus is on reaching a specified objective in a specified amount of time, not selecting a remedial option and assuming it will get us there (Gustavson et al. 2008; NRC 2005; NRC 2007). A remedial approach is the means to an end, but not the end. Too often, establishing whether we achieved our objectives is neglected, a situation fostered and perpetuated by the notion that the Record of Decision (or equivalent document) is the culmination of the process, rather than the next step on the road to achieving remedial action objectives.

At the same time, we need better information on which remedial measures will be most appropriate under a given set of conditions. As emphasized throughout this document and supporting references, the effects of remedial actions are influenced heavily by environmental and operating conditions. Improving our understanding of sediment remediation, as applied to achieving remediation objectives, will provide the basis for improving overall effectiveness. These efforts should include predicting and measuring residuals in real world projects (predredge prism concentrations and postdredge average surficial concentrations) and additional, focused pilot or research studies of resuspension and releases. We also need additional focus on predicting and monitoring responses in our endpoints of concern (often fish tissue contaminant concentrations). Effective monitoring requires a robust baseline (preremediation) dataset that includes sufficient time points and reference sites to permit valid statements about changes over time and inferences about the effects of remedial actions. Such studies also need to be supplemented by contaminant exposure studies to support statements about the factors causing any changes.

Given the nature of the problem, we recognize that the greatest potential for improving both understanding and effectiveness of dredging will result from a closer collaboration between remedial engineers, scientists and risk assessors. Many of the uncertainties at issue concern significant engineering problems that will require a multidisciplinary approach to problem-solving. Integrating risk assessment into this approach will help ensure that the facets of problems with the greatest potential effect on risk reduction are addressed in order of their importance. The result of this collaboration will be an approach that lays out data objectives, experimental designs, and associated monitoring requirements to assess both risk and engineering outcomes. Such a process will be necessary to set expectations for and formally evaluate remedial effectiveness.

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