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The Four Rs of Environmental Dredging: Resuspension, Release, Residual, and Risk

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Steven C. Nadeau, Michael R. Palermo, Clay Patmont, and
Paul Schroeder

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Abstract: A workshop sponsored by the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency was held at the U.S. Army Engineer Research and Development Center, Waterways Experiment Station, in Vicksburg, MS, in April of 2006. Fifty experts from government, the private sector, and academia participated in the workshop, which focused on four issues (the four Rs) relevant to environmental dredging: (1) sediment resuspension resulting from dredging operations, (2) release of contaminants from bedded and suspended sediments in connection with dredging, (3) residual contaminated sediment produced by and/or remaining after dredging, and (4) the environmental risks that are the target of and associated with dredging.

Goals for the workshop were to: (1) promote consistency in the terms used to define the challenges represented by the four Rs, (2) develop consensus for a conceptual model that relates the relevant processes, (3) identify current resources and needs regarding data and methods/models to better describe and understand the processes, and (4) identify key uncertainties and make recommendations regarding future research to resolve those uncertainties.

This technical report summarizes analysis and synthesis of the results of the workshop.

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Preface

This report summarizes the results of a workshop on the four Rs of environmental dredging: resuspension, release, residual, and risk. The workshop was held at the U.S. Army Engineer Research and Development Center, Waterways Experiment Station, in Vicksburg, MS, on 25-27 April 2006. The workshop was supported by the Dredging Operations and Environmental Research Program, the Sediment Management Work Group, and the U.S. Environmental Protection Agency.

Thanks are extended to each of the participants of the four Rs workshop for their contributions to our discussions and their willingness to share their time and intellect. The workshop participants, in alphabetical order, were: Frank Bohlen, Tom Borrowman, Todd Bridges, Rob Burgess, Scott Cieniawski, Doug Clarke, John Connolly, Steve Ells, Bob Engler, Trudy Estes, Leah Evison, Jay Field, Rick Fox, Norm Francingues, Tom Fredette, Paul Fuglevand, Joe Gailani, Ed Garvey, Marc Greenberg, Nancy Grosso, Karl Gustavson, John Haggard, Jim Hahnenberg, Don Hayes, Earl Hayter, Karen Keeley, John Lally, Willy Lick, Victor Magar, Marc Mills, Russ McMillan, Larry McShea, Ram Mohan, Dave Mount, Steve Nadeau, Skip Nelson, Mike Palermo, Clay Patmont, Danny Reible, Ken Richter, Carlos Ruiz, Paul Schroeder, Mel Skaggs, Jeff Stern, Louis Thibodeaux, Dennis Timberlake, Tim Welp, and Rick Wenning.

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COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Contaminated sediments pose potential risks to human health and the environment at many sites nationwide, and the problem has received growing attention in recent years (U.S. Environmental Protection Agency (USEPA) 1998; National Research Council (NRC) 1989, 1997, 2000). Options commonly considered and implemented for remediation of contaminated sediments include monitored natural recovery (MNR), in situ capping, and environmental dredging followed by disposal.

Although dredging has been conducted for centuries to maintain navigation depths in harbors and waterways, the concept of environmental dredging is relatively new. Use of the term *environmental dredging* has evolved in recent years to characterize dredging performed specifically for the removal of contaminated sediments for the purpose of remediating environmental risks. The various objectives being pursued in navigation dredging and environmental dredging can result in significant differences in evaluating the effectiveness of dredging and in establishing performance metrics (e.g., success measured as production in cubic yards per hour versus waterbody acres or river miles where risk has been substantially reduced).

Environmental dredging is intended to remove sediment contaminated above certain action levels while minimizing the spread of contaminants to the surrounding environment during dredging (NRC 1997). Much of the publicly available information on environmental dredging has been developed within the past 10 to 15 years. The USEPA, in cooperation with the U.S. Army Corps of Engineers (USACE), published general guidance on environmental dredging as early as 1994 (USEPA 1994), and EPA published additional guidance in 2005 (USEPA 2005). The International Navigation Association (PIANC) and the U.S. National Research Council and National Academy of Sciences have also published reports dealing with contaminated sediments, all of which included general guidance on environmental dredging (PIANC 1996, NRC 1997, 2000, 2007).

One of the advantages commonly attributed to the removal of contaminated sediments via dredging is greater confidence in the long-term effectiveness of the cleanup, assuming that the risk-based action levels can be achieved. However, there are also significant limitations to environmental dredging: implementation of environmental dredging is usually more complex and costly than other sediment management approaches and uncertainties associated with its long-term effectiveness have been underestimated in some cases.

Experience gained with environmental dredging over the last several years has revealed the existence of a number of factors that complicate our ability to evaluate the effectiveness of dredging to achieve environmental objectives. These complexities served as the motivation for a workshop sponsored by the U.S. Army Corps of Engineers and the Environmental Protection Agency in April of 2006 at the U.S. Army Engineer Research and Development Center, Waterways Experiment Station, in Vicksburg, MS. Fifty experts from government, the private sector, and academia participated in the workshop, which focused on four issues relevant to environmental dredging: 1) sediment **resuspension** resulting from dredging operations, 2) **release** of contaminants from bedded and suspended sediments in connection with dredging, 3) **residual** contaminated sediment produced by and/or remaining after dredging, and 4) the environmental **risks** that are the target of and associated with dredging.

It is well accepted that all dredging (in addition to naturally occurring and man-made disturbance events) will result in some resuspension of sediment. Resuspended particulate material may be redeposited at the dredging site or transported to other locations in the water body. Some resuspended contaminants may also dissolve into the water column and be available for uptake by biota. Particulate and dissolved release of the contaminant(s) of concern into the water column represents a potential dredging-related environmental exposure concern.

Perhaps the most significant issue associated with dredging's potential effectiveness is the extent of residual contamination following dredging. No dredging operation can remove every particle of contaminated sediment, and field results to date for completed environmental dredging projects suggest that post-dredging residual levels, expressed as contaminant concentration in surface sediments, have often been greater than the cleanup levels. This experience suggests that in many situations achieving low risk-based cleanup levels may pose significant engineering and cost challenges. It is believed that the nature and extent of post-dredging residuals will be related to the dredging equipment used, dredging methods, sediment characteristics, and physical site conditions. However, currently there is no commonly accepted method to accurately predict post-dredging residual concentrations. Moreover, while developing empirically based estimations of residuals is often recommended, to date such estimates are rarely made. This situation should change with time based on the direction in USEPA sediment guidance (USEPA 2005) that RPMs should estimate and evaluate the probable range of post-dredging residuals as part of the remedy evaluation phase of the site.

Post-dredging residual, combined with resuspension and release, will result in some level of short-term and/or continuing risk at the site. 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. In this way, establishing the risk context for environmental dredging provides the basis for making predictions about the performance of environmental dredging that could be used as input to a remedy selection process based on a comparison of predicted net risk reduction of all remedial technologies under consideration (e.g., dredging, capping, monitored natural recovery) (USEPA 2005).

Given that there were no widely accepted methods/models to reliably predict, evaluate, or measure the relationships and interactions among the four Rs of environmental dredging, the goals for the four Rs workshop were to 1) promote consistency in the terms used to define the challenges represented by the four Rs, 2) develop consensus for a conceptual model that relates the relevant processes, 3) identify current resources and needs regarding data and methods/models to better describe and understand the processes, and 4) identify key uncertainties and make recommendations regarding future research to resolve those uncertainties. The results of the four Rs workshop are analyzed and synthesized in this paper.

2 Sediment Resuspension during Dredging

Resuspension defined

Resuspension is defined as the processes by which a dredge and attendant operations dislodge bedded sediment particles and disperse them into the water column. Dredge-head movements associated with normal dredging operations dislodge some bed sediments that are not captured as part of the dredging operation. Sediment resuspension also results from other activities directly associated with dredging (e.g. spillage, prop wash from tugs and attendant vessels, spuds, dredge movement, and anchoring systems) and ancillary activities associated with environmental dredging operations (e.g., debris removal and management of silt curtains). Resuspended sediments can include native bed sediments and “fall-back,” i.e. sediments loosened by previous dredge actions, but not captured.

Sediments resuspended during dredging operations pose a variety of water quality and ecological concerns. The visible contiguous turbidity plume in the immediate vicinity of the dredging operation could influence the behavior of fish and other receptors sufficiently mobile to avoid the plume and potentially 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. Furthermore, particulate-associated contaminants can repartition, thereby increasing dissolved contaminant concentrations in the water column.

Available resuspension data

Sediment resuspension data have been collected from a variety of dredging operations and provide useful insight into typical resuspension rates. Resuspension rates have been reported ranging from less than 0.1 percent to over 5 percent (Anchor Environmental 2003, Hayes and Wu 2001). However, the mechanisms of sediment resuspension depend heavily on the specific nature of the dredging operation. Thus, resuspension rates are inherently dredge specific, i.e. sediment resuspension from a cutterhead suction dredge bears little relation to the sediment resuspension that may result from a horizontal auger dredge, even though they are both hydraulic dredges. The same is true for different varieties of mechanical dredges and even different bucket types.

Sediment resuspension is a by-product of every dredging project. The extent, however, varies tremendously based upon many factors such as:

- *Sediment properties such as bulk density, particle size distribution, and mineralogy.* Resuspension and transport characteristics of high water content, organic, silty sediments are significantly different from sediments with significant clay or sand content. Sediments are often stratified; so resuspension rates and contaminant concentrations can vary dramatically between layers.
- *Site conditions such as water depth, currents, and waves; and, presence of hardpan, bedrock, or loose cobbles or boulders.* Areas with high ambient currents or significant tidal fluctuations influence the transport of sediments much differently than quiescent water bodies. Water depth and salinity are also significant factors.
- *Nature and extent of debris and obstructions.* The presence of debris – both type and density – can greatly influence dredging operations and, thus, sediment resuspension rates.
- *Operational considerations such as production rate, thickness of dredge cuts, dredging equipment type, method of operation, and skill of the operator.* The relationship between resuspension and each of these operational mechanisms is not fully understood. However, it is generally anticipated that resuspension is not particularly sensitive to production rate except at very high levels, i.e. although extremely aggressive dredging operations may increase resuspension at a rate similar to the increase in production, resuspension losses as a percentage of the mass of fine-grained sediment dredged seem to be relatively constant over a wide range of normal production rates; thus, resuspension rates may increase as production increases.

In addition to the dredging itself, other operational aspects of dredging can contribute to sediment resuspension; many of these potential sources of resuspension activity have not been characterized or monitored in past dredging operations. Tugs are often used to move the dredge, transport scows to and from the operation, tend pipelines, move anchors, tend silt screens, aid in debris removal, and other miscellaneous tasks. The extent of sediment resuspension from prop-wash associated with these movements is uncertain, although some methods for estimating these impacts exist. Other operations such as spud operations and silt curtain management may also contribute to sediment resuspension, but their contribution has not been quantified.

The multi-factorial nature of dredging operations 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 the entire suite of data that influence resuspension. For example, few projects have collected dredge operation data to match measures of resuspension. Many past monitoring efforts have collected only a few water samples and those had very low concentrations of suspended sediment near the reliable quantification limit. Still, data for a few common dredge types are sufficient to draw some general conclusions. Data from the most comprehensive studies show resuspension rates for cutterhead dredges are generally less than 0.5 percent and less than 1 percent for bucket dredges without barge overflow (Hayes and Wu 2001). These rates are for suspended sediment flux from the dredging zone and exclude fall-back and fluid mud/density flows. While these rates include the impact of debris where encountered, most of these projects were navigational dredging projects with only sparse, and typically light, debris present.

Transport of resuspended sediments

Sediment resuspended by dredging operations is available for transport by ambient and induced currents. Transport of suspended sediments can best be characterized at three zones:

1. *Initial Mixing Zone* - the area where the dredging operation dominates the process and where the induced currents are more important than the ambient currents.

   The initial mixing zone is dominated by erratic water movements induced by the dredging operation. Suspended sediment concentrations are expected to be relatively uniform within this zone, although vertical stratification may occur. The time associated with resuspension and deposition in the initial mixing zone is short (on the order of minutes) when compared to transport in the near field and for deposition in the far field. The length of time that the dredge operates contributes to a sustained rate of resuspension and to the nature of exposure receptors may experience to sediment-associated contaminants. The nature of this exposure will be a direct function of site characteristics, sediment characteristics, dredge equipment type (mechanical or hydraulic), and operating time.

2. *Near Field Zone* - the plume area dominated by rapid settling velocities, changes in sediment total suspended concentration and load with distance from the dredging operation.

   Near-field plume dimensions depend on a number of factors. Prevailing hydrodynamics, presence of silt curtains, and properties of the sediments in suspension entering from the initial mixing zone influence the down-current horizontal distance over which suspended sediment concentration changes; these changes result mostly from gravity settling and less by advection and diffusion. Thus, the near field will expand in higher current velocities and contract under conditions of enhanced settling. In the majority of dredging scenarios, the near-field transition to far field will occur within 100 m of the dredging operation.

   The lateral extent of the near-field plume depends on the nature of sediment distribution in the water column, taking into consideration not only the instantaneous width (e.g., cross-sectional area of bucket, cutterhead, etc.), but the movement of the dredge in relation to the flow field. Lateral expansion of the detectable plume within the near field will generally be limited to a scale of tens of meters, but the observed swath of the plume may shift laterally in response to the lateral movement of the dredge across the contaminated site within the flow field. This spatial scale is an important consideration in selecting appropriate monitoring methods.

   Exposure times in the near-field zones seldom exceed an hour and will depend upon the spatial extent of the resuspension footprint. Site conditions such as hydrodynamics (currents, degree of mixing, etc.) directly influence transport times, and, thus, potential exposure times. It is also known that after the dredging stops, the ability to monitor or track a resuspension plume in the water column is a direct function of ambient conditions (i.e., suspended material in the water column, and the distance from the dredge).

3. *Far Field Zone* - the area where the total load in the plume is slowly varying and where advective diffusion and settling are of the same order of magnitude.

Vertical dimensions of the detectable plume are likewise dependent on multiple factors including type of dredge, use of silt curtains, depth of the water column, and the vertical distribution of sediment injection into the water column. Significant releases high in the water column will have a significantly different plume signature than releases primarily just above the substrate unless constrained by shallow water depth.

Far-field plume dynamics are driven by advection and diffusion as much as by gravity. The ability to detect a plume signature sets the bounds on determining maximum plume dimensions in any plane. Lateral extent of detectable plumes may expand to 100 to 200 m or more when driven by stratified flows in response to changes in bathymetry. In the vertical plane, almost invariably, the detectable components of plumes become progressively bottom-oriented features with increasing distance down current. Whether measured by optical, acoustic, or other sensor technologies, suspended sediment concentrations eventually fade into background concentrations. Where ambient concentrations are relatively low, plume signatures may be visually detectable as far as 1,000 m or further down current, although the TSS concentrations may not be measurable against background concentrations. In systems with high background suspended sediment concentrations (e.g., periods of high river discharges or estuarine turbidity maxima), plumes may be difficult to spatially characterize.

Far-field exposure times are typically measured in hours. Even under extreme hydrodynamic conditions, most resuspended sediments will have resettled to the bottom within a few hours. A critical point to be made is that plumes are highly dynamic, heterogeneous phenomena. Within the spatial footprint of plumes, concentration gradients in either the near or far field can be very complex on small spatial scales. Although the decay rate of concentration gradients is generally rapid, some degree of variation, albeit in small absolute magnitudes, is maintained into the far field. Plume spatial dynamics must be considered in context with appropriate temporal scales. In terms of suspended sediment exposures, plumes may be viewed as repetitive pulses on relevant temporal scales. Pulses vary considerably over spans of minutes near the source. Pulses in tidal systems may vary over hours. Integrating a cumulative exposure therefore is predicated upon a basic understanding of the dynamic nature of plumes in time and space.

Assessing sediment resuspension

A good understanding of the physical, chemical, and biological characteristics of the project site is considered essential to successful remediation. This combination of factors affects selection of optimum remedial methodology and ultimately the extent to which the selected methods are able to isolate or remove the contaminants of concern and reduce environmental risks. Reviews of existing projects suggest that many projects would benefit from improved site characterization including high-resolution measurements in both the water and sediment columns.

Within the water column, quantitative predictions of the dispersion, transport, and deposition of sediments placed in suspension by dredging and/or capping operations require accurate specification of the density field and the associated flows. Time series observations of water temperature, salinity, suspended material concentrations and flow speed and direction should be obtained at multiple points on the vertical over times comparable to the dominant site-specific forcing factors (e.g. astronomical tide, streamflows, winds). When combined with historical data detailing regional meteorological and hydrological characteristics (with particular emphasis on the frequency and intensity of periodic storm events) these observations provide a basis for accurate definition of pre-project baseline conditions as well as boundary shear stresses, water column advection, and turbulent dispersion acting to affect the distribution of project resuspended materials and the associated contaminant exposure.

Water column measurements should be supplemented by detailed profiling of the sediment column to provide a comprehensive mapping of sediment grain size, water content, contaminant distributions, biogenic activity, and the extent and character of anthropogenic debris. Within many sites this latter factor has the potential to significantly influence project success affecting both dredge production times and the mass of sediment placed in suspension. The sediment column characteristics should be mapped using a combination of direct sampling at selected locations and acoustic profiling sufficient to provide 1.0- to 10-cm resolution over the vertical and sub-meter scales on the horizontal. Satisfaction of these requirements directly complements accurate quantitative analysis of project-induced resuspension and transport and the associated contaminant exposure levels.

Resuspension control measures

Silt curtains[1] are commonly used to retain suspended sediments in the immediate vicinity of the dredging operation (Francingues and Palermo 2005). Their application in moderate- or high-energy areas can be complicated, requiring constant repair and maintenance. Further, the effectiveness of silt curtains is not fully understood. Flows typically pass below or around fabric curtains not securely fastened to the bottom.

A variety of operational control measures have also been applied in attempts to reduce or control resuspension. Examples include limiting swing speed for cutterhead dredges and cycle times for bucket dredges. Although such controls can directly influence productivity, their effectiveness at controlling sediment resuspension is uncertain.

Resuspension research needs

Mechanisms from dredging operations

Mechanisms for introducing sediment into the water column are conceptually known for different dredge types. For a bucket dredge, they include, but are not limited to

- The erosion of bed sediments due to the pressure wave generated by a falling bucket and the impact of the bucket in the sediment bed
- Leaking through the seals (especially if debris is present) and vents of buckets as they ascend through the water column
- Spillage of sediment as the bucket slews to the disposal barge
- Adhesion and detachment of cohesive material to the outside of the bucket

Several studies have attempted to ascertain the rate of sediment resuspension from dredging operations near the point of dredging by various downstream sampling methods. These efforts have led to source strength predictions that vary by over an order of magnitude between sites and do not always incorporate variations in operational characteristics, debris, or sediment type.

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[1] Silt curtain is used here to refer to any porous or non-porous fabric or air-generated partition that restricts flow.

The relative importance of these discrete sediment introduction mechanisms is not known. The nature of the sediment when it is introduced to the water column via the different mechanisms (i.e. solid clumps, small aggregates, virtually fluidized) is not known. The likelihood of a sediment's introduction to the water column based on its position in the cut is not known. Individual sediment introduction processes must be understood before accurately predicting source strength based on sediment characteristics, dredging operational characteristics, and ambient conditions.

Contamination is often stratified in the sediment bed. It is suspected, but not known, that the vertical location of contaminated sediment in the cut will influence the amount of contaminated sediment resuspended dredging. A series of laboratory experiments, going up in size from benchtop to near-prototype, using different sediments and different densities would provide insight here. Fluorescent tracer could be inserted in different layers of the sediment bed to quantify how much sediment is lost (relatively) from each layer.

Characteristics of suspended sediments

It has been clearly demonstrated that dredging operations resuspend sediment to the water column. The properties of these suspended sediments are not known. The location in the water column where sediment is resuspended is only partially understood. Several items must be better understood to define plume transport and settling to address exposure and risk issues. To be of benefit, collected data must be quantifiable in terms of sediment, dredge equipment type, and hydrodynamic conditions. Developing algorithms that are a function of these properties will constrain model parameters that might otherwise vary by orders of magnitude. Only with these constraints can models be developed that are truly predictive of the behavior of resuspended sediment and the resulting plume. It is essential that plume behavior be predicted prior to dredging so that all alternatives and possible dredging operation methods can be assessed and compared. This information also will permit the project manager to evaluate and consider the potential risks associated with the remedy implementation as part of the remedy selection process as directed in USEPA sediment guidance (USEPA 2005).

Suspended solids concentration

As dredging occurs, sediment is resuspended into the water column at time-varying rates. These rates probably vary over orders of magnitude. An understanding must be developed for 1) this variance over time, and 2) the resulting total or time-averaged resuspension over some period of dredging. Further research through data collection and laboratory experiments can support quantifying these terms. First, what is considered resuspension from the dredge must be defined. This can include either 1) all material that is resuspended, even if only momentarily, from the sediment bed to the water column, or 2) sediment that remains in the water column at some distance from the dredge head as well as the overall dredging operations (e.g., barge/tug travel areas). Using the second definition, large clumps that settle back down to the bottom immediately can be ignored. However, using the second definition also requires the assumption that what happens in the area immediately surrounding the dredge will not significantly influence exposure and risk because of the small volume of water being impacted. The important issue for resuspension purposes is the rate and concentration of resuspended sediment particles that are not captured and removed from the environment in the near-field and far-field zones.

The vertical distribution of suspended solids concentration must also be quantified. For example, it is known that most resuspension during cutter-head dredging is near-bottom, while resuspension from a clamshell occurs throughout the water column resulting in a bimodal distribution, with peaks at the bottom and top of the water column. Resolution of the concentration profile is best achieved by giving careful thought to collecting sufficient field data during dredging operations. These data can be collected through arrays of acoustic or optical measurements that are calibrated to bottle samples. Dredging method, sediment type, and debris will all heavily influence the final value of the loss term and the distribution of concentration through the water column. However, a source of error will be introduced here because the devices will be influenced by the state of sediment flocculation or aggregation. The bottle samples will not be influenced by these.

State of sediment aggregation and impact on settling speed

Another area of additional potential research is the state of sediment aggregation and its impact on the sediment particles' settling speed. Dredged sediment is extracted from the bed at the bed density. However, it is mixed with water during the dredging process. During this process, some sediment will break from the bed as individual particles and some as aggregates. Both of these materials will be resuspended into the water column at some rate, although the rates for each are not known. Immediately following resuspension, the sediments (both particles and aggregates) will begin to flocculate due to the high concentration in the resuspended sediment/water mixture. The state of aggregation and the time-dependent flocculation processes in this high-concentration mixture must be understood to quantify resettling of the resuspended material in the near field. Flocculation and aggregation are complex processes that are very difficult to measure in the field. Samples collected for later analysis will transform into different aggregate/floc states, rendering the measurements nonrepresentative. Therefore, field analysis is required. The U.S. Army Engineer Research and Development Center is building an in situ, high-speed floc camera that will measure settling speed and the size of these flocs and aggregates as they settle. The system will initially be deployed at approximately 100 m from the dredging operation. It can be brought closer to the dredging operation if deemed necessary. This system will quantify near-field aggregate and floc settling speeds, which are required to accurately represent near-field processes. The system can be deployed at specified depths so the vertical distribution of flocculation/aggregation is understood. The system will first be tested in a controlled environment where sediment bed properties and dredging rates can be easily controlled.

Deposition and development of the dredge plume footprint

As the settling flocs and aggregates approach the sediment bed, they enter the bottom boundary layer. This is a high-shear stress zone where current velocity falls from a near-mean value to zero at the sediment/water interface. There is significant turbulence in this zone that can tear apart flocs. Many of these de-flocculated particles will not remain deposited on the sediment bed and will be part of a near-bottom suspension. Other material will deposit, and particle-particle bonds will adhere these flocs or aggregates to ones that are already part of the surficial layer of the sediment bed. These processes are part of a broader set of questions related to transport of the sediment. Bottom boundary layer processes have been measured, but rarely with the high concentrations of suspended particles that occur in a dredge plume and rarely with dense aggregates resuspended from a dredging operation. In future research projects, a first step to resolving this issue could involve repeating bottom boundary layer settling experiments that are well documented using high-concentration material and aggregates similar to those resuspended during dredging operations.

3 Release of Contaminants during Dredging

Release defined

Release is defined as the 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. Contaminants adsorbed on and absorbed to resuspended particles may partition to the water column and be transported great distances downstream in dissolved form along with dissolved contaminants in the released pore water. Resuspended sediment particles will settle and become part of the dredging residuals. Contaminants in the residuals may be released to the water column by densification, diffusion, and bioturbation. Although this release might be assumed to involve a short-term exposure, in reality, this release may have significant implications for long-term flux of sediment-associated contaminants into the water column.

Contaminant release from dredging operations needs to be quantified to estimate short-term exposures and risk of dredging and potential impacts on long-term risk following completion of dredging. Risk prediction requires estimates of short- and long-term exposures in the form of estimates of contaminant concentrations on a time scale of days for short-term risks and weeks to months for long-term risks. Relevant spatial scales for these risks are on the order of hundreds to thousands of meters longitudinally and laterally. Vertical distribution of exposure is needed over a coarse grid.

Field and laboratory studies and models are needed to develop estimates of contaminant release. Laboratory and field data are required to better understand the release phenomena and to develop and verify predictive models. These models typically focus on describing releases of bioaccumulative, non-polar organic contaminants more so than inorganic contaminants (e.g., copper, cadmium, lead, mercury), but predictive models must also be able to predict releases of inorganic contaminants.

Release factors and processes

Contaminant releases associated with dredging can occur in particulate, colloidal, dissolved, or volatile fractions, each characterized by a different transport and/or exposure pathway (Thibodeaux 2005). During the dredging operation, some resuspended fine particles have low settling velocities and can remain suspended in the water column for many hours. Resuspended sediment particles and associated contaminants will be transported with currents from the dredging area into the surrounding environment. Resuspension of sediment will also result in introduction of contaminants into the dissolved phase of the water column by release of contaminants from the sediment pore water and by desorption of contaminants from suspended sediment particles. The release pathway is a particularly important pathway to consider given that dissolved contaminants are readily bioavailable (Eggleton and Thomas 2004). While the exposures and resulting risks associated with contaminant release would be expected to be shorter than those associated with bedded sediments, the magnitude and temporal extent of these risks will depend on a number of factors. These factors include the duration of the dredging operation, composition of the sediment being dredged (e.g., grain size distribution), contaminants associated with the sediment, current velocities, and a range of other physical and chemical factors.

In addition to introduction of contaminants into the water column, other release mechanisms may also be a concern, e.g., releases to the air through volatilization. Floating oils are sometimes released to the water column during the dredging process (e.g., non-aqueous phase liquids (NAPLs)), providing another mechanism of contaminant transport.

Contaminated sediments that merit remedial dredging are most often in depositional environments and primarily composed of fine-grained sediments. Contaminants normally associated with these sediments tend to remain tightly bound to the particles, so control of sediment resuspension will also help to control contaminant release. However, once in the dissolved phase, released contaminants are subject to far-field transport. So, releases of dissolved phase contaminants result in different exposures and risks than releases of contaminants sorbed to suspended sediment particles.

Due to the nature of dredging operations, particulate and dissolved releases of contaminants vary widely, both temporally and spatially. As such, releases and their variability can be quite difficult and expensive to measure at a dredging site. Consequently, very little empirical data is available on the magnitude of contaminant releases and contaminant release processes/sources, and understanding of contaminant releases is limited.

In practice, contaminant releases have been estimated from measurements of dissolved and total contaminant concentration from samples collected from a sparse spatial grid with limited frequency (e.g., Steuer 2000, Alcoa 2006). Typically, samples are taken at distances of 30 to 300 m from the dredge head, corresponding to average travel times of 5 to 60 min in the water column. The location of the sampling often corresponds with the mixing zone and water quality compliance boundaries where monitoring can be performed safely. Thus, available measurements of dredging-related releases have been operationally defined, to date, by such practical and regulatory-driven spatial and temporal scales. While sampling programs have not normally been designed to quantify release processes, Fox River water quality monitoring data collected 30 to 60 m from the dredge head, and outside of silt curtains, were used to characterize the magnitude of off-site PCB transport during a hydraulic dredging pilot study (Steuer 2000). The monitoring data suggested that approximately 2 percent of the dredged PCBs were transported downstream of the pilot project area. Much (roughly one-third) of the water column load increase was attributable to dissolved PCBs that partitioned from resuspended sediments. Approximately 0.3 percent of the dredged PCBs were volatilized to the atmosphere, while roughly 0.02 percent returned to the river from the treated dewatering facility discharges. Similar results were reported from a pilot dredging monitoring project performed in the Grasse River (Alcoa 2006).

Measurements of particulate releases of contaminants can vary widely depending on the distance from the dredging operation, owing to rapid sedimentation processes that often occur near the dredge head [Dredging Research Ltd., HR Wallingford. 2003]. Conversely, measurement of releases of dissolved contaminants into the water column may not be nearly as affected by the distance from the dredging operation. Dissolved contaminants exiting the dredging zone will attempt to establish a concentration in equilibrium with the solids or organic carbon in suspension. However, it can take days to reach equilibrium and, therefore, the mass of dissolved contaminants in the water column changes slowly. However, dissolved as well as total contaminant concentrations can vary greatly temporally, vertically, and laterally at distances of 100 to 300 m due to variability in the dredging operations and dilution by turbulent diffusion in the water column (Hayes et al. 2000).

Operational aspects of the dredging project, including schedule and duration, are important considerations in predicting (i.e., modeling) contaminant release during dredging operations, in addition to the sediment characteristics at the site and specifics related to contaminant behavior. Both the temporal and spatial characteristics of the entire project should be factored into the evaluation of short-term release and the impact of such release on long-term consequences and risk.

Release processes in time and space

A number of processes and mechanisms contribute to contaminant releases during and after dredging. Figure 1 illustrates the release processes during dredging operations.

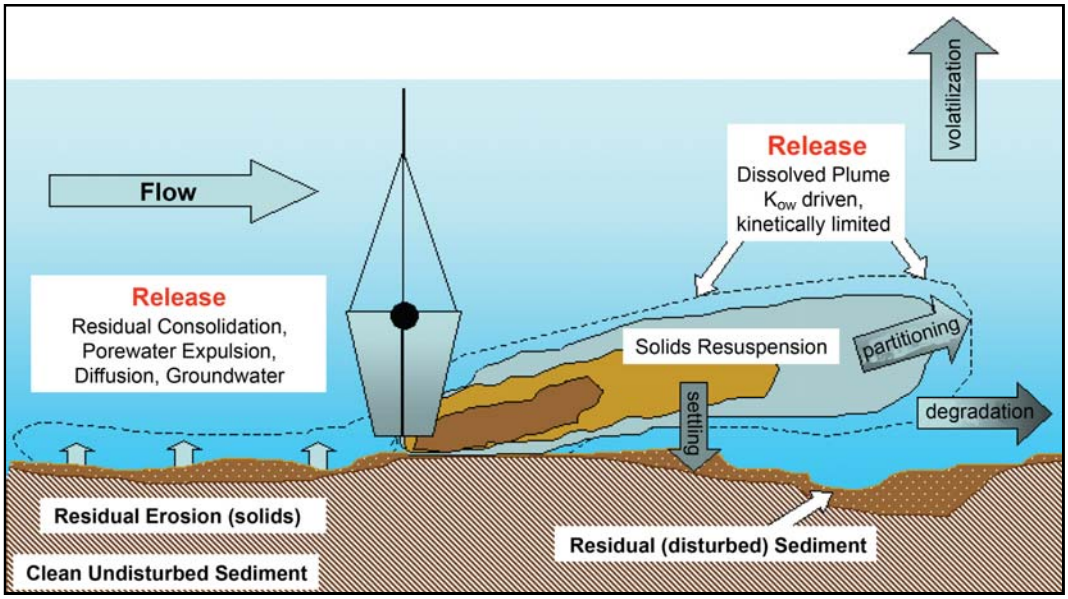

Figure 1. Schematic of contaminant release sources and mechanisms.

The primary release sources applicable to all dredging operations are:

- Resuspension and dispersion of bedded sediment particles and pore water by dredging operations, including dredge head, boat props, anchors, etc.
- Erosion/resuspension of dredging residuals and other high solids concentration layers on the bottom, including fluff layers (e.g., nephelloid) and fluid mud

These primary release sources are only relevant to risk in the short term after contaminants desorb from the particulate and colloidal phases into the dissolved phase while in suspension. In the long term, these phases may continue to slowly release contaminants to the dissolved phase after they have been well dispersed in the water column and sediment bed in the far field.

A number of additional release sources may be significant for a limited range of site conditions, sediment properties, equipment types, and contaminant classes, including:

- Release of dissolved contaminants and dispersed solids from densification of the high solids concentration layer on the bottom including fluff layers, fluid mud, and residuals
- Molecular diffusion from the dredging cut face and residuals
- Groundwater advection
- Pore water expulsion from sediment and dredged material
- NAPL exposure

With the exception of NAPL exposure, these additional release sources are likely to be significant only for contaminants with low partitioning characteristics (e.g., log octanol-water partition coefficient (K_{OW}) < 4.5). The release rates from densification are more important when thick, extensive layers of fluff, fluid mud and residuals are created. Their creation would be both equipment- and material-dependent. Release rates by molecular diffusion increase with porosity of the sediment and the areal extent (i.e., surface area) of the cut face and residuals. Pore water expulsion rate increases with the permeability of the sediment and dredged material.

For hydrophobic contaminants with partitioning coefficients in excess of 10,000 L/kg, release of contaminants by expulsion of sediment pore water is smaller than or similar to the magnitude of diffusion from the residuals (depending on the size of the dredging project and the production rate). Considering resuspension rates of 0.1 percent to 1 percent, the potential release of contaminants by desorption from the resuspended solids are two to three orders of magnitude larger than all of the other processes. As such, the kinetics of desorption, aggregate/floc size and aggregate/floc settling rates are critical. Desorption studies have shown that it can take weeks to reach equilibrium; however, more than 10 percent of the contaminants can desorb in the first hour and 30 percent of the contaminants can desorb in the first day (Borglin et al. 1996, Lick and Rapaka 1996). Particle settling takes only a few hours to a few days; therefore, equilibrium partitioning conditions will not be achieved for most particles and aggregates before settling occurs.

In the long term (following dredging operations), erosion, bioturbation, and diffusion in the residual layer and groundwater advection through the residual layer continue to provide contaminant releases that contribute to risk from the near field (Thibodeaux and Bierman 2003). Contaminants that have been well dispersed in the water column and sediment bed (as residuals) in the far field can continue to contribute to risk as they diffuse and partition to the water.

Short-term releases directly to the water column (during dredging operations) may be one to three orders of magnitude greater than pre-dredging releases (Sanchez et al. 2002). Although "short-term" in this context refers to the releases occurring during the immediate time frame of the dredging operation, since many environmental dredging projects can run 24/7 for 4-10 months seasonally and span multiple dredging seasons, it is important to evaluate the overall potential impact of the increased exposure attributable to releases, particularly in light of some of the earlier studies showing loss of 2-3 percent of the PCB mass dredged. For example, 3 percent of 10,000 lb of PCBs would be 300 lb of PCBs released.

Long-term releases (post-dredging) are strongly dependent on the residual layer and the surface weighted area concentration following remediation. In the near term, the releases should be similar or less than before dredging (depending on the original vertical distribution of the contaminants) until the site is recolonized by benthic organisms. In time, thin residual layers could be diluted by bioturbation and burial, while thicker residual layers would yield releases that are similar to or greater than pre-existing releases for decades until sufficient deposition/burial occurs (Aziz et al. 2007). Risks would be expected to be linearly proportional to the release rates. The risk attributable to releases caused by the remedial action under consideration in this case, dredging, should be estimated, evaluated, and considered as part of the remedy selection process (USEPA 2005).

Fate and transport processes

In the far field, contaminant fate and transport processes are not unique to dredging operations. A large amount of data and experience exist for describing and predicting these processes [e.g., Thibodeaux 2005, Sanchez et al. 2002]. The dominant processes are:

- Settling of particle-associated contaminants

- Bed erosion/resuspension, exchange with suspended and bed loads, and deposition/burial
- Hydrodynamics (at the simplest level – flow rates)
- Partitioning and kinetic rates of adsorption and absorption/desorption
- Bioturbation
- Molecular diffusion
- Groundwater advection
- Volatilization
- Biogeochemical transformation (e.g., oxidation, complexation, precipitation, biotic and abiotic transformation, diagenesis, etc.)

The key near-field processes affecting contaminant concentrations are erosion, hydrodynamics (advection and turbulent diffusion), settling, and partitioning. The dredging operation itself can affect settling characteristics of particles (due to flocculation and shearing of aggregates at the source) and partitioning (due to desorption kinetics of aggregates).

Data gaps and uncertainties

There are numerous data gaps and uncertainties in our understanding of the effects of dredging operations, sediment and water column characteristics, magnitude of resuspension, and production of residuals that are critical to predicting the release and bioavailability of contaminants and the resulting risk. Included in these data gaps are:

- Fraction of contaminants released into the water column that are truly dissolved (absent constituents associated with dissolved organic carbon or colloids)
- Nature, cycling, and distribution of sediments released during dredging; specifically, fine-grained individual particles versus large aggregated clumps or clods
- Residuals formation
- Source strength and mechanisms
- Partitioning and kinetics of particle desorption in the water column
- Rate of sediment mixing and pore-water pumping due to benthic organisms
- Compaction/consolidation of residual sediments
- Gas content of sediments

Field and laboratory study needs

Both field and laboratory studies are needed to address the data gaps outlined above. The following studies are of particular interest for predicting contaminant release, particle settling, calibrating models, and verifying predictions.

Field studies

1. Measurements of the dissolved chemical concentrations C_w and the particulate chemical concentrations C_s immediately upstream and downstream of the dredging area during operation. These measurements should be made at multiple depths in the water column to estimate depth-averaged concentrations.
2. Measurements of the flow velocity, suspended solids concentrations, particle and floc sizes/density, and floc settling speeds at multiple depths in the water column at a location downstream of the dredging site. These measurements will enable determination of floc formation and properties (e.g., mean settling speed) for the flow conditions that exist at the time of the measurements (during a dredging operation).
3. Measurements of the sediment-water flux from the residual layers during and immediately following dredging operations. These measurements, in conjunction with the laboratory studies described below, will quantify the flux that is commonly estimated using literature values.

Laboratory studies

1. Measurements of contaminant adsorption and absorption, and desorption rates. These measurements are needed to model non-equilibrium partitioning of contaminants to solids both in the water column and sediment.
2. Measurements of flocculation formation rates and floc settling speeds. Flocculation rates are functions of the localized fluid shear and suspended sediment concentration. The purpose of these laboratory studies would be to determine how floc sizes, floc densities, and settling speeds change as a function of these parameters. This will enable prediction of how these quantities change in the field as fluid shear and suspended sediment concentrations change.
3. Sediment-water flux studies with and without benthic organisms. The purpose of these laboratory studies would be to quantify the flux of chemicals from sediment to the water column as a function of the number (i.e., spatial density) and type of benthic organisms, bulk density and organic con-

tent of the sediment. If the site contains both freshwater and estuarine environments, then these studies should be conducted using sediment, water and organisms from both environments.

4. Verification of the dredging elutriate test (DiGiano et al. 1995) and application methodology. The purpose of this study would be to verify the dredging elutriate test for a variety of contaminants and to determine whether it is best to use the test in a predictive mode or for parameterization of predictive models. In addition, the study should further examine the effects of particle concentration and contaminant desorption kinetics.

Recommendations for addressing data gaps and uncertainties

In addition to studies on contaminant release, kinetics and partitioning of desorption, and settling, additional laboratory studies are needed to predict particle source strengths for release predictions. The following procedures are needed:

- Development of a laboratory procedure for prediction of erosion characteristics for residuals
- Development of laboratory procedures for prediction of residual, fluid mud and fluff layer characterization (densification) as a function of time
- Procedures to predict resuspension total suspended solids (TSS) source strength based on sediment and equipment characterizations

Recommended tools and models for prediction

Tools and models are needed to evaluate contaminant release in the dredging zone and near field where the sources and releases are dynamic. Several models are available and sufficient to address dredging-related issues in the far field. Tools recommended for development are:

- Screening model assuming worst case conditions (e.g., instantaneous equilibrium) /analytical models estimating desorption of contaminants from the resuspension source term in the water column
- Analytical model estimating pore water flux and resuspension from compacting residual sediments to serve as a near-field source model
- More complex near-field model to consider differential settling and desorption kinetics and to serve as a source model for far-field models

4 Environmental Dredging Residuals

Background

One of the more significant limitations currently associated with predicting the effectiveness of environmental dredging is the uncertainty associated with estimating the nature and extent of residual contamination following removal. No removal technology can remove every particle of contaminated sediment, and field results to date for completed environmental dredging pilots and full-scale projects suggest that post-dredging residual contamination levels have often not met desired cleanup levels. This is not surprising given the limitations of even the most modern dredging equipment and due to the variable distribution of contamination found in many sites – where typically higher concentrations occur in deeper sediments. It is logical that the nature and extent of post-dredging sediment residuals are related to dredging equipment, dredging methods, sediment geotechnical and geophysical characteristics, the variability in contaminant distributions, and physical site conditions (including hydrodynamics). Complicating factors (e.g., the presence of debris) can make the sediment removal process and achievement of risk-based clean-up levels particularly difficult as well as costly. Unfortunately, currently there is no method to accurately predict post-dredging residual concentrations after the implementation of a dredging remedy. Moreover, while empirically based estimations of residuals are often recommended, to date such information has been difficult to access. Recently, however, progress has been made in assembling data from completed projects and in developing methodologies to predict the percentage of residual contaminant mass (Patmont and Palermo 2007).

***Dredging residuals** in the context of this paper refers to contaminated sediment found at the post-dredging surface of the sediment profile, either within or adjacent to the dredging footprint.* Because there are numerous potential sources of residual sediment contaminants, residuals can be broadly grouped into two categories: 1) undisturbed residuals (R_u); and 2) generated residuals (R_g) (Figure 2).

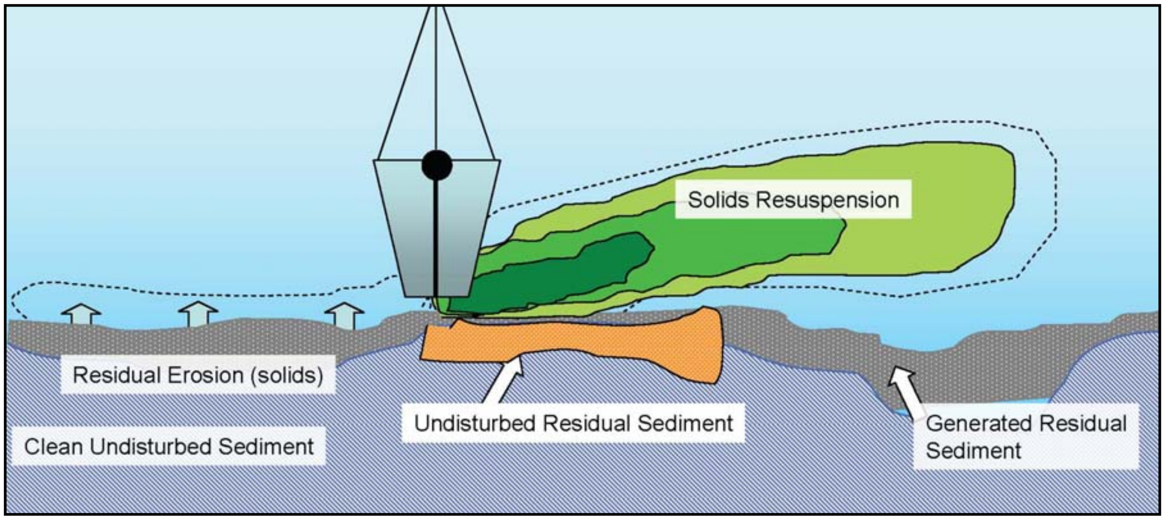

Figure 2. Dredge residual schematic.

Undisturbed residuals (R_u) are contaminated sediments found at the post-dredging sediment surface that have been uncovered by dredging but not fully removed. The primary causes of undisturbed residuals include:

- Attempting to dredge sediment which
  - Directly overlies bedrock or hardpan
  - Covers highly uneven surfaces, or debris or boulders which are left in place
  - Is located near piers, pilings, or utility crossings which are left in place
- Incomplete characterization of the horizontal and vertical extent of contaminants and/or ability of geostatistical models to adequately represent the distribution of contaminants
- Inappropriate selection of a target dredge design elevation
- Inaccuracies in meeting targeted dredging elevations
- Development of dredging plans that intentionally do not target complete removal of contaminated sediments (e.g., due to engineering limitations)

Generated residuals (R_g) are contaminated post-dredging surface sediments that are dislodged or suspended by the dredging operation and are subsequently redeposited on the bottom of the water body. The primary causes of generated residuals include:

- Sediments dislodged but left behind by the dredgehead that fall to the bottom without being widely dispersed

- Sediment dislodged but left behind by debris-removal operations
- Attempting 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
- Sediments resuspended by the dredgehead that quickly resettle
- Sediments resuspended by dredging or other dredging-related activities that resettle within or adjacent to the dredging footprint

It can be important to distinguish the differences between undisturbed residuals and generated residuals, as they may pose different risks, may require different methods for prediction, and may require different monitoring and management responses. Depending on their origin, undisturbed residuals may or may not be amenable to removal by an additional cleanup dredging pass. Because of their physical characteristics (discussed below), generated residuals may be even more difficult to remove with an additional cleanup dredging pass. Depending on the risk posed by the residuals and the regulatory approach to cleanup at a particular site, residuals that may accumulate outside of the dredging footprint may or may not trigger a need to actively manage such materials. Furthermore, assessment of risks posed by residuals remaining within the dredging footprint may influence decisions regarding subsequent removal or management efforts.

Understanding residuals is important at a number of different stages of the cleanup process and somewhat different approaches may be needed at each stage. For example, during the Feasibility Study, it is important to be able to predict the nature and extent of residual contamination in order to predict the likely effectiveness of a dredging alternative and supply information to help select the most appropriate remedy for the site (USEPA 2005). During Remedial Design, an understanding of the sources and characteristics of likely residuals can be important for development of appropriate construction contingency plans (e.g., determining the likely need for and costs of additional cleanup pass dredging or cover/backfill placement). During and following Remedial Action, assessment and management of residuals may be important to comply with project-specific clean-up level requirements.

The level of concern surrounding residuals is dependent on many factors, including:

- Concentrations of chemicals of concern (COCs) (e.g., are the concentrations high enough to cause significant risk?)
- Residence time of the residual sediment layer (e.g., does it exist as an identifiable layer for periods of time likely to result in significant exposure and risk?)
- Residual sediment layer thickness (e.g., is bioturbation likely to cause the layer to be mixed with underlying sediment?)
- Dry density, as a measure of stability (e.g., is the layer likely to remain in place?)
- COC variability (especially vertical profiles) (e.g., if the layer is thick, what are biota exposed to?)
- Geochemical availability (e.g., are contaminants bioavailable in their present form?)
- Mobility and fate (e.g., what's likely to happen in the future?)

Characteristics of dredging residuals

Undisturbed and generated residuals may have similar or very different characteristics depending on the process by which they were created. For example, dislodged sediment not picked up by the dredge that generally settles to the bottom relatively close to the point of dredging may have characteristics similar to undredged residuals, whereas resuspended sediment that has been transported as a plume may have very different characteristics after it has settled to the bottom. Generally, undisturbed residuals remain below the dredging elevation at a higher dry density than generated residuals; their dry density may be similar to those of the in situ/native sediments. In some cases, undisturbed residuals may exist as relatively thick layers amenable to further cleanup pass dredging. In contrast, generated residuals are the result of the dredging process itself, and such dislodged materials accumulate at the sediment/water interface in thin layers at relatively low dry density.

Field results to date for completed environmental dredging pilots and full-scale projects suggest there are common geotechnical and geochemical characteristics of residuals, as follows:

- **Physical and geotechnical characteristics**
    - Generated residuals (excluding sloughed materials) are prone to resuspension immediately after dredging. Sloughed materials and undisturbed residuals are likely to be less erodable than the pre-dredging surface (a function of geotechnical properties and layering)
    - At some sites, there is a potential for downslope migration of fluid mud portions of the generated residual
    - After the initial consolidation period (i.e., within a period of several days to a few weeks, depending on sediment characteristics and site conditions), generated residuals (excluding sloughed materials) typically occur as a thin veneer (1 to 10 cm thick) of fine-grained material, with relatively low dry bulk density (ranging from approximately 0.2 to 0.5 gm/cm^3), the typical dry bulk density for fine-grained sediment is 0.5 to 0.9 gm/cm^3
    - The physical and geotechnical characteristics of generated residual layers (excluding sloughed materials) will significantly change immediately following completion of dredging. Column settling tests indicate that fluidized fine sediments will self-consolidate to near surficial in situ densities within a period of a few weeks to several months, depending on sediment characteristics and site conditions. Conversely, the physical and geotechnical characteristics of sloughed materials and undisturbed residuals will likely not change appreciably after dredging
    - There is often a discernable (i.e., measurable) difference in dry bulk density characteristics between generated residuals and underlying in situ sediments (including undisturbed residuals). However, sloughed material that contributes to generated residuals may have physical and geotechnical characteristics that are similar to in situ conditions, and thus may not be easily discernable from undisturbed residuals
    - Mixing due to bioturbation of surficial residuals into the biological mixing zone (typically 2 to 5 cm in freshwater environments and 10 cm in saltwater environments) generally occurs within a period of several months to several years. Recolonization data and bioturbation depths and rates are available from multiple sources (e.g., Boudreau (1997) and Clarke et al. (2001))
    - During this mixing period, sedimentation, biodegradation, and other natural recovery processes may also contribute to overall reductions in the 0- to 10-cm sediment concentration.

- **Geochemical characteristics**
  - Existing data suggest that the average concentration of COCs in generated residuals can be reasonably approximated based on the average sediment concentration in the final production cut profile (the concentration of the final production cut would in turn be influenced by the entire sediment column dredged)
  - Immediately after the consolidation period (i.e., within a period of several days to a few weeks, depending on sediment characteristics and site conditions), and before bioturbation/mixing, generated residuals are present at the sediment/water interface
  - Little research has been performed to date on the bioavailability of generated residuals (e.g., geochemical processes and biological uptake/food web transfer)

Prediction of dredge residuals

Currently there is no commonly accepted method to predict the nature and extent of generated residual sediment resulting from a given dredge type removing a given sediment type under given site conditions. Data on post-dredging residual thickness and concentration are available for at least a dozen environmental dredging projects, but the basis for monitoring residuals has varied considerably across these and other projects. In most cases, the measurement of a residual concentration has been based on analyses of a specified surficial sediment thickness (e.g., 0 to 10 cm below mudline) collected by grab sampling or coring. Further, there have been few studies that have precisely differentiated undisturbed and generated residuals. The ability of sampling equipment to capture a fluffy (i.e., low dry density) thin veneer of residual sediment and the method of handling the sample can affect monitoring results.

In the absence of predictive models, a mass balance-based measure of residuals from a series of relatively well-documented dredging projects can be used to develop initial “bounding-level” expectations of generated residuals. A wide range of environmental dredging projects conducted in the United States over the past 10 years have been reviewed by various parties, focusing on compilation and analysis of the following parameters:

- Validated pre-dredge core samples collected from the dredge prism
- Dredge plan basis of design
- Complicating factors (e.g., debris, slope, and underlying hardpan/bedrock)

- Removal equipment and operational practices
- Bathymetric surveys during and following dredging operations, and comparison with dredge plans
- Sediment removal volume and mass
- Visual observations of post-dredging sediment conditions in core samples
- Validated post-dredging core and surface samples collected and analyzed

Mass balance data meeting general minimum criteria to support residuals calculations are available from at least 11 dredging projects:

- Fox River Pilot Project, WI (SMU 56/57)
- Lavaca Bay Pilot Project, TX
- New Bedford Harbor Pilot Project, MA
- Reynolds Aluminum, NY
- Three Hylebos Waterway Projects, WA (Mouth, Middle, and Head)
- Middle Waterway, WA
- Todd Shipyards, WA
- Two Fox River OU 1 Projects, WI (Subarea A and C/D2S)

For these environmental dredging projects, generated residuals could be generally distinguished from undisturbed residuals based on visual observations and/or geotechnical measurements of post-dredging core sections, supplemented with bathymetric data (e.g., elevation of the post-dredging surface relative to the dredge plan) and focused post-dredging chemical analyses. Based on mass balance calculations performed for each of the 11 project sites (Patmont and Palermo 2007), generated residuals represented approximately 2 to 9 percent of the mass of contaminant dredged during the last production cut. The available data suggest that multiple sources contribute to generated residuals, including resuspension, sloughing, fallback, and other factors. However, on a mass basis, sediment resuspension from the dredgehead appears to explain only a portion of the observed generated residuals, suggesting that other sources such as cut slope failure/sloughing could be quantitatively more important. The available mass balance data also indicate that the presence of hardpan/bedrock, debris, and relatively low dry density sediment results in higher generated residuals (Figure 3). Inconsistent use of standard operational controls (e.g., bucket overfilling) can also increase generated residuals. The mass balance estimates derived from these projects, when combined with site-specific data on sediment concentrations, dredge cuts, dry density, and key operational factors (e.g., debris, hardpan/bedrock, and in situ dry density) can provide bounding-level predictions of generated residual concentrations and thicknesses. These estimates can be utilized in the Feasibility Study to evaluate the likely effectiveness of dredging and to assist in the selection of the most appropriate remedy for some or all of the site (USEPA 2005).

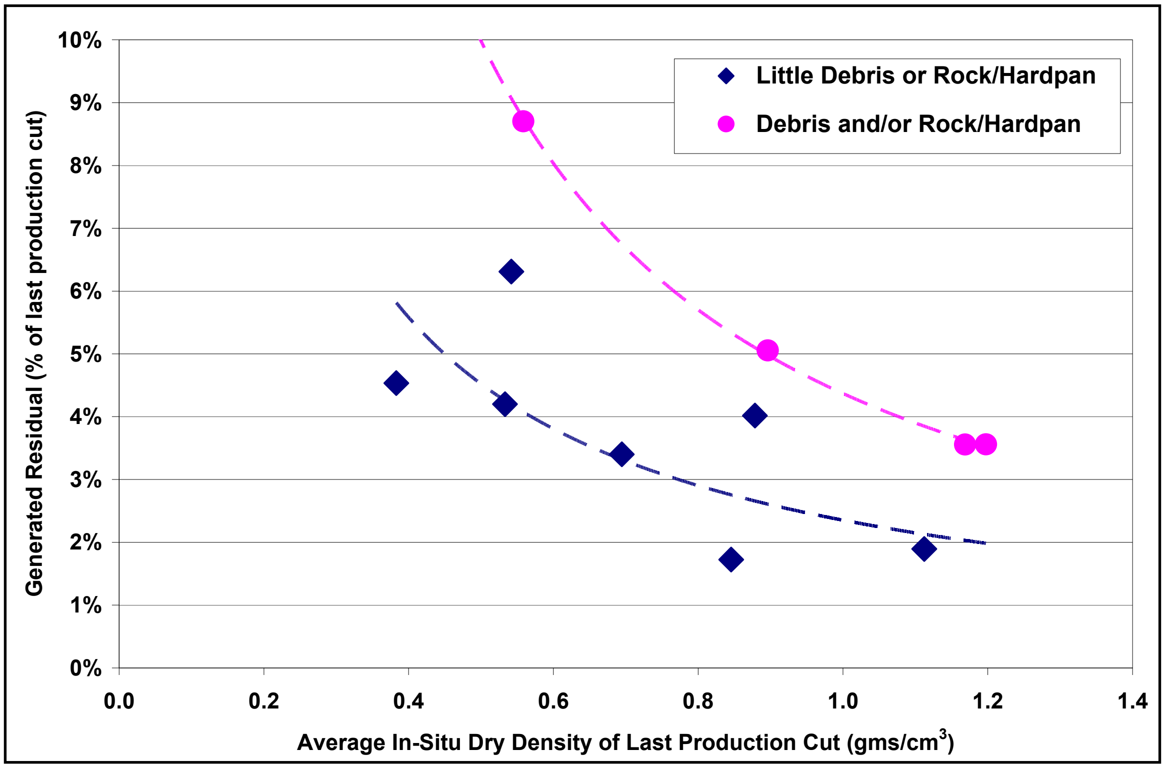

Figure 3. Case Study Summary of Generated Residuals from 11 Projects (from Patmont and Palermo (2007)).

Further refinements to the predictive approach may occur as additional case study data are compiled and analyzed. The uncertainty of predictions and the consequences of uncertainty will need to be assessed as predictive models are refined.

In addition to refinement of this predictive methodology and others, continued collection and publication of actual residuals data, together with the average contaminant concentrations found in the pre-dredging prism, should be undertaken (Nadeau and Skaggs 2007). This data could serve to calibrate the predictive methodologies and also should be utilized in the FS stage and in remedy selection, as part of the evaluation of the potential effectiveness of dredging due to its limitations in achieving cleanup levels, as a result of resuspension, release, and residuals (USEPA 2005).

Operational factors and generated residuals

Lessons learned from prior environmental dredging projects can be summarized as follows:

- Based on the available data, the presence of debris and hardpan/bedrock appear to be the two most important site factors determining the potential for higher generated residuals. Lessons learned include:
  - 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, etc.)
  - Semi-quantitative debris survey techniques should be used as appropriate for the specific site, including side scan, 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 residual (neither lend 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
  - Debris, hardpan/bedrock, and other physical site conditions can also significantly impact dredging production rates and costs
- Based on the available case study data (see above), the presence of sediments with low dry bulk density (e.g., water content exceeding the geotechnical liquid limit) appears to increase the potential for dredge residuals.
- Other possible operational factors that could affect the amount of generated residuals include equipment type; number of dredge passes; size of dredge; selection of intermediate and final cutline elevations; allowable overdredging; matching production with equipment capability with respect to the rate of advance; slopes (e.g., box cuts typically result in sloughing); accuracy of positioning; experience of operator; and sequence of operations.

- Possible adverse impacts of engineered controls (enclosures) on residuals include silt curtains or sheet pile enclosures, which tend to hem the materials in and concentrate residuals within the enclosure footprint; production is reduced; redeployment can release pulses of suspended material and residuals.
- Implementing operational controls may greatly complicate the environmental dredging process, with reductions in production efficiencies and increases in costs.

Remedial actions with performance standards related to residual contaminant concentrations normally have provisions for multiple production and/or cleanup passes of the dredge to attempt to achieve cleanup levels. A common approach for multiple passes is to focus on mass removal of contaminated sediment with the first passes of the dredge, followed by one or more passes used for "cleanup.” A cleanup pass is more likely to result in lower residuals if conditions allow for removal of some cleaner material below the limits of contamination as part of the cleanup pass (contamination lying directly on bedrock or hardpan is problematic in this regard). Repetitive cleanup passes have often failed to meet project-specific action levels. There is generally diminishing operational and economic efficiency with multiple cleanup passes, since they require taking a higher proportion of underlying clean/cleaner sediment. This is especially true for generated residuals. In the soft sediment environment and in the hardpan or bedrock environment, cleanup pass reduction in contaminant concentrations is often limited and expensive.

Generated residuals and undisturbed residuals should be managed based on an operational evaluation of what can practically be done (i.e., cost-benefit analysis). Management options include:

- Operational controls to reduce residuals as a part of operations
- If cleanup levels are not met – possible management options include:
    - Monitored natural recovery – consider burial and mixing
    - Residual covers (e.g., 6 in. of sand or topsoil) – long-term intention may be sediment dilution, but can also be designed and constructed as necessary to provide an isolation component
    - Engineered caps – intention is physical and chemical isolation
    - Re-dredging (if practicable; re-dredging will likely be less effective for generated residuals, but may be a reasonable management

option if significant thicknesses of undisturbed residuals are present)

Post-dredging verification monitoring

Post-dredging verification monitoring data for residuals collected in a consistent manner and across a range of project conditions are needed to allow for improved predictive capability and better decisions on future environmental dredging projects.

- Sample collection – use suitable sampling equipment (e.g., Powergrab or piston core) to obtain an intact vertical profile to a depth at least equal to the biologically active zone. Verification sampling may need to be performed within the dredging prism plus areas outside the dredging prism. Sampling densities are typically site-specific. As practicable, wait for initial consolidation of high water content residual before confirmatory sampling for compliance (subject to refinement if further research is conducted; see below). In the absence of additional information, siphon off water prior to sample analysis (e.g., Puget Sound Estuary Protocols).
- Processing – analyze sample equivalent to a depth equal to the biologically active zone. Where detailed post-dredging characterization is desired (e.g., for research purposes), cores may be sectioned at visual transitions between the surficial generated residuals layer and undisturbed sediment if this occurs shallower than the defined biologically active zone. During the post-construction verification phase, if the sediment sample(s) collected within the biologically active zone is below the action level, then no further action is required. If the action level is not met, analyze deeper to characterize the nature and extent of generated and/or undisturbed residuals exceeding the action level.
- Testing – dry bulk density, moisture content, total organic carbon (TOC), and COCs should be analyzed on collected samples.

Research and field data collection needs

General research needs to improve our understanding of contaminant fate and transport processes relative to environmental dredging actions have larger programmatic objectives. For example, gaining further information on the migration of residuals along the bottom as fluid mud or bed load and the transient nature of residual-related exposure during and immediately following dredging, and the need for and scope of possible management options, should be addressed in a research context. Research efforts should also define the timeline of changes in key geotechnical and geochemical characteristics (e.g., concentration and density profiles within days to weeks following dredging; mixing rates; stability, etc.) that influence the bioavailability of residuals. Other research topics might include a review of existing data and development of a study plan for determining efficiency of silt curtain systems (in retaining suspended sediments and COCs), potential influence on residuals distribution within the curtain footprint, and potential migration through the bottom of the curtain anchor system. Finally, research is needed to refine the technical basis for discarding fluid surficial material prior to analysis of residuals. Several research investigations, case study analyses, and associated publications are currently in progress by a number of parties to further address some of these research needs.

As noted earlier, collection and publication of pre-dredging average prism concentrations and the post-dredging average surficial concentrations should continue in order to provide further real-world calibration of the estimation methodologies currently under development.

5 Risk

The risk context

***Risk** is defined as the probability or likelihood for an adverse outcome.* In the context of environmental remediation of contaminated sediments, risks are both assessed and managed. *Risk assessment* is the process used to develop a quantitative understanding of the physical, chemical, and biological processes shaping the scope and nature of environmental risks at a site. *Risk management* refers to the actions taken to reduce risks to acceptable levels and manage uncertainties in a manner that is informed by quantitative information about the site-specific processes contributing to risks at a site.

The risks that are relevant to decision making at a contaminated sediment site are varied. The risks most directly connected to the site are those related to toxicological effects on ecological and human receptors exposed to contaminants from the site (Direct Risks). More indirect risks posed by a site can be defined in terms of consequences on social systems (loss of cultural practices or recreational opportunities) and economics (e.g., effects on property values) (Consequence Risks). Implementing a remedy at a site can introduce other risks, including those resulting from habitat modification/destruction at the site (Implementation Risks).

While all of these risks may be relevant to decision making at a site, this report, as well as the Four Rs workshop, focuses on the influence of remedial dredging on direct risks.

Risk-based evaluation of dredging

A site investigation, e.g., remedial investigation, that includes an ecological and a human health risk assessment develops information to describe whether unacceptable risks are present at the site and what processes are contributing to the existence of those risks. In most cases involving contaminated sediment, multiple remedial options will be available to manage unacceptable risks (e.g., capping, dredging, monitored natural recovery). Recent USEPA guidance encourages the use of a comparative approach to guide the selection of remedies based on the concept of net risk reduction (USEPA 2005). Such an analysis involves using existing data and models to predict the performance of potential remedies followed by a comparison of predicted performance among the potential remedies.

Characterizing how dredging will influence direct risks includes considering how the processes contributing to risk change with time, which elements or receptors in the ecosystem are affected by these changes, the spatial scales over which effects would be expected to occur, and the uncertainties associated with the predicted changes and risk reduction.

Scales and dimensions

Temporality

Contaminant risks resulting from an environmental dredging project can be thought of in two time phases: 1) short-term changes in risks that occur during the active dredging phase primarily due to resuspension and other mechanisms affecting the release of chemicals; and 2) long-term changes in risks resulting from contaminated sediment removal and exposure to resuspension, releases, and residuals within and beyond the boundary of the site.

Short-term phase

Short-term contaminant risks can be expected primarily from increases in water column exposure. In most situations where sediment contamination is from historical chemical releases, contaminant partitioning behavior and disequilibrium between the water column and sediments results in chemical concentrations in the water column that are far lower than those in the sediment interstitial water. Dredging and resuspension will introduce interstitial water into the water column, as well as facilitate desorption of contaminants from suspended sediment particles into the water column. The resulting increase in water column exposure can result in adverse effects to aquatic biota either through direct toxicity to the exposed organisms, or by increasing tissue residues of bioaccumulative chemicals within the food chain. When dredging deeper sediment deposits that are more contaminated than surficial deposits (which is commonly the case), water column exposures during dredging could increase substantially as dredging progresses. The magnitude of these increases will depend in large part upon the physical setting of the dredging activity, as well as the technologies and practices applied.

The consequences of short-term increases in exposure will vary among contaminants according to their physical and toxicological properties. Contaminants with higher potential to cause direct toxicity during resuspension include readily labile compounds such as ammonia and hydrogen sulfide, which are common constituents in fine-grained sediments. Cationic metals, which may be present in deeper, anoxic sediments in sulfide complexes and other forms that are less bioavailable, could be liberated through contact with oxygenated water during dredging. Some organic contaminants with the potential to cause acute toxicity, e.g., certain pesticides, could pose a significant risk during short-term resuspension events even where there is little risk from the same chemical in existing bedded sediments.

In addition to risks from direct toxicity, increases in bioaccumulation may result from elevated water column contaminant concentrations during dredging. Small organisms such as phytoplankton and zooplankton may see rapid increases in tissue burdens of bioaccumulative chemicals, which can then be transferred to other receptors through the food chain. The magnitude of these risks will be influenced by a number of parameters, including the toxicity and hydrophobicity (K_{ow}) of the compound, 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. Time-varying bioaccumulation models can be used to predict changes in accumulation resulting from temporally fluctuating exposure. Data on contaminant concentration in the water column over time is a required input to such predictive modeling; when conducted to support a comparative assessment in advance of remedial decision making, data on water column contaminant concentrations would come from other models describing resuspension and contaminant release processes. In some cases, bounding analyses based on (overly) protective assumptions about contaminant releases may be useful in determining whether more detailed analysis is even warranted or, if so, to focus the analysis on the most problematic contaminants or dredging scenarios.

Long-term phase

Longer-term exposures affecting site risks and risk reduction trajectories following dredging operations will occur over time scales relevant to the transport of sediment particles resuspended during dredging. After dredging, contaminant concentrations in water and sediment will approach a new steady state as determined by the post-dredging conditions. Thus, post-dredging risks will be determined primarily by changes in the exposure field resulting from the distribution and nature of dredging residuals. The ability to predict changes in post-dredging exposure, toxicity, and bioaccumulation will depend on 1) the ability to describe the movement and disposition of sediments from the dredging prism, and 2) the degree to which the models being used accurately reflected the relationships between sediment and water contaminant concentrations and receptor exposures at the site. For example, if hotspot removal by dredging fails to result in the expected amount of risk reduction, two explanatory hypotheses are possible: 1) dredging residuals are making a larger contribution to post-dredging risk than expected, or 2) the models describing the relationships between sediment and water concentrations and exposure did not adequately capture the processes operating at the site. Some remedial dredging will access deeper, more contaminated sediments, and thus residual sediments on the new, post-dredging sediment surface may contain higher concentrations of contaminants than the pre-dredging surface. It is also reasonable to expect that the degree to which hotspot removal will contribute to risk reduction will vary from site to site; at some sites, lower-level but broader contamination outside the hotspots may make a more significant contribution to overall risk than the hotspots themselves. Developing a sound understanding of how the site will change with time is critical to developing reasonable expectations about the rates and magnitude of risk reduction that can be achieved at a site.

Remediation projects give attention to both short- and long-term risk reduction; this fact emphasizes the need to carefully consider the temporal scales of exposure and effect processes before, during, and after dredging. This distinction is particularly important in the case of dredging, as compared to other remedial alternatives, because estimates of short-term increases in risk must be balanced against projections about long-term risk reduction. In addition to the long-term risk posed by residuals, releases of contaminants to the water column and resuspension of contaminated sediment particles can pose long-term risks at the site or elsewhere in the water body. Correctly understanding risks and benefits in both the short and long term is obviously critical to making sound management decisions.

Spatiality

Developing an understanding of the spatial dimensions of exposure and effect processes at a site is a critical element of sound risk assessment. All else being equal, risks being expressed over a larger area are a source of greater concern than risks being expressed over a smaller area. In fact, developing an understanding of the spatial dimensions of exposure and effect processes provides an important input to reaching conclusions about the magnitude of risk present at a site. Significant exposures and effects occurring over only 1 m^2 of sediment at a site would pose an insignificant risk in ecological terms. This relationship between space and risk raises a practical dilemma: Can we define an area of contamination that is small enough that the triviality of the parcel's contribution to site risk overrides the pragmatic impulse to "clean it up" because the costs of doing so are judged to be insignificant.

Resolving issues of spatial scale and pattern at contaminated sites provides key inputs to risk assessment and remedy selection. Consider, briefly, contamination in the horizontal and vertical dimensions. At many sites, the range in surficial contaminant concentrations over several kilometers can be small in comparison to the range observed vertically at one spot over scales of centimeters to meters. However, much more effort is commonly devoted to understanding the source and consequence of variation in the horizontal than in the vertical. Given that exposure processes are dominated by what happens in the top several centimeters of sediment and that concentration gradients in the vertical can be quite steep, it would seem that developing a greater understanding of the processes shaping vertical variation, e.g., sediment transport and mixing, can profoundly affect our conception of sediment risks and the selection of remedies.

The spatial dimension of both exposures and effects will vary among receptor groups. Exposures to sessile or relatively immobile receptors will vary more significantly across the site than will exposures for relatively mobile species. This is because the exposure of relatively immobile receptors (e.g., a worm) will occur over smaller areas than more mobile species that will experience and average exposure over larger areas. In this sense, an entire population of amphipods, or an entire benthic community, will experience exposures and effects over spatial scales comparable to that experienced by an individual fish. 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.

Receptors

Three receptor groups are relevant to contaminated sediment risks and dredging: organisms living in the sediment, pelagic organisms, and consumers of aquatic life. The groups share a set of common hazards (e.g., increased mortality, reduced growth or reproduction), but differ in regard to how they experience exposures associated with dredging in both the short and long term. For these reasons, risks will vary among the groups and for different contaminants. For example, effects associated with many cationic metals (e.g., copper) would be expected to manifest themselves relatively rapidly and be most pronounced in organisms in direct contact with bedded and suspended sediments. In contrast, effects associated with contaminants such as dioxins and PCBs would more likely be expressed through indirect exposures in the food chain over longer periods.

Sediment-dwelling organisms

Tools for assessing effects and baseline risk for benthos prior to undertaking remediation include measurement of tissue levels, sediment toxicity testing, benthic community surveys, and comparisons to chemical-specific guidelines. However, these tools are only as effective as the measures of exposure (e.g., sediment chemistry) on which they are based. As discussed elsewhere, methods and models for predicting changes in surficial sediment concentrations post-dredging are being developed, but currently significant uncertainties are associated with predicting the nature of residuals. As the ability to confidently predict post-dredging exposure increases, predicting risk reduction will become correspondingly less uncertain.

During and after dredging, the primary exposure pathway for most benthos will be from residuals within and beyond the dredging prism. However, some exposure to contaminants released to the water column (associated with sediment particles or desorbed into the liquid phase) will occur; this route of exposure will be more significant for surface-dwelling benthos and suspension/filter feeders. It is unavoidable that dredging will destroy benthos within the dredging prism; therefore the primary factors influencing the trajectory of risk reduction after the completion of dredging will be the nature of the residuals remaining after dredging and the rates and stages of recruitment and recolonization within the area dredged. As discussed previously, a range of factors will contribute to the chemical and physical qualities of residual sediments. In addition to the presence of contaminants in residuals, any changes in the geotechnical properties of the new sediment surface, topography, or hydrodynamics of the site will also affect biological recovery. Recruitment and recolonization processes will vary as a function of the nature of the habitat (e.g., estuarine, riverine, lacustrine), geography, and the time of year when the dredging occurs.

The nature of benthic exposures will be different outside the dredging prism. Since resident benthos will not be removed outside the dredging prism these receptors will be exposed to any contaminants released to the water column during dredging as well as resuspended sediment particles that settle onto the sediment surface outside the area of active dredging. Exposures associated with the residuals have the potential to occur over longer periods than releases to the water column.

The nature of benthic exposures to residuals will depend on the chemical, biological, and physical processes operating at the site. The geochemical and partitioning behavior of the contaminants in the residual, as well as the susceptibility of the contaminants to degradation processes, are key chemical factors driving contaminant exposure to benthos. The biological processes influencing residual quality would be those affecting rates of sediment bioturbation and mixing. The dominant physical processes affecting exposures to residuals will be those processes influencing sediment transport into and out of the project area. Both sediment erosion and deposition within the project area have the potential to lower contaminant concentrations, albeit in different ways, i.e., by removing contaminated sediments away from the site or by diluting the sediment residuals with imported, clean sediment. Some environmental dredging projects have incorporated a form of capping into their designs to reduce benthic exposures to residuals by covering and diluting dredging residuals with several centimeters of clean soil/sediment. However, the factors contributing to the effectiveness of this approach have not been subjected to significant study. For example, the nature of the cap material would be expected to affect exposure. Capping residuals with sand that contains either very low or no organic carbon will do little to reduce the fugacity and exposure to organic contaminants in residuals. This scenario exposes a weakness in using cleanup targets expressed in the form of contaminant mass (e.g., milligrams contaminant per square meter or kilogram sediment), which fail to consider processes controlling bioavailability and exposure.

The need to take management actions to reduce benthic exposures to residual sediment should be supported by risk modeling results and field data that provide evidence for the need for management intervention. The decision to place a sand cover or a cap over dredging residuals has been made, in several cases, based either upon no post-dredging residual quality data or on data that have been collected very soon after dredging (days). With respect to the biology and ecology at the site, which will take weeks to months to establish a consistent trajectory toward a new steady state, it would be more reasonable to base management decisions on risk predictions based on data collected over a comparable period (weeks to months). This period would also provide time for natural sediment processes (as discussed above) to stabilize and potentially reduce residual contaminant concentrations and exposures.

Pelagic organisms

Pelagic receptors, primarily plankton and fish, experience direct exposure through contact with contaminants associated with suspended sediment particles and contaminants desorbed from those particles into a dissolved phase (either associated or not with dissolved organic carbon in the case of organic contaminants). While the flux of contaminants from the sediment bed will make some contribution to exposure before, during, and after dredging, the dominating exposure pathway during dredging will be from contaminants introduced into the water column through resuspension of sediment.

In contrast to exposures experienced by benthos, those experienced by pelagic receptors are, in general, transient. The transience of pelagic exposures is due to the fact that water and pelagic organisms move. Both turbulence and directional flows will work to attenuate contaminant concentrations with distance from the site or the operating dredge. The magnitude of this attenuation will be a function of the hydrodynamics at the site and operational aspects and duration of the dredging. The role of the movement of individual receptors will be most evident in the case of highly mobile species, e.g., fish, which may range over areas much larger than the area/volume under the influence of a dredge (or the site itself) over periods of time ranging from minutes to days to weeks, depending on the behavioral characteristics of the species.

An additional source of variation in pelagic exposures is the pulsing nature of contaminant exposure during dredging. As discussed in previous sections of this paper, a range of physical interactions among sediment, water, and the dredge head/bucket have the potential to introduce sediment and interstitial water into the water column. This introduction will come in the form of sediment/contaminant pulses influenced by swing speeds in the case of hydraulic dredges or cycle times in the case of mechanical dredges, as well as the time required to move dredges to new areas within the dredging project. While there may be interest, from the standpoint of engineering and source-term definition, in characterizing the nature of this pulse at distances very close to the dredge, the more relevant scales for estimating risk to pelagic receptors are probably at spatial scales of tens to hundreds of meters, corresponding to exposure periods of hours to days or even weeks. These averaging areas will also more closely correspond to an area that would be large enough to represent a significant or meaningful ecological impact. How large an area/volume would be encompassed by such an averaging time will, of course, depend on the nature of the dredging operation and site characteristics influencing local hydrodynamics and mixing. This averaging period (hours to weeks) also corresponds to the duration of most toxicity data for pelagic species, making the integration of exposure and effect data more straightforward and less uncertain.

Consumers of aquatic life

Consumers of aquatic life would primarily include upper trophic-level receptors such as fish, birds, and mammals, as well as humans. In most cases these receptors will have only limited direct contact with contaminated sediments, so their principal pathway of exposure will be through bioaccumulation and trophic transfer of contaminants within the food chain. While exposures to contaminants within the water column will occur, the significance of this route would, in most cases, make a smaller contribution to overall exposure. These receptors are generally larger and more mobile than the receptors lower in the food chain upon whom they feed. Therefore, when considering the influence of dredging on these receptors the primary (though not only) influence on risk to consumers will be from contamination associated with residuals.

Quantifying exposure to consumers of aquatic life derived from residuals will be a function of the concentrations of contaminants in the residuals, contaminant bioavailability, the duration of the receptors’ exposure to those concentrations, and the size of the area influenced by the deposition of residuals. While the presence of residuals will be most obvious in the immediate dredging project area, there is potential for resuspended sediments to be transported away from the prism or even the boundaries of the site itself. Given that deep sediment layers are commonly more contaminated than surficial layers, the potential for dredging to result in higher surficial contaminant concentrations than before dredging is not only possible, but perhaps even likely in some instances. Quantifying the potential for residual transport and any resulting risk should provide a key input to remedy selection (e.g., dredging versus capping) and the design of an environmental dredging operation (e.g., equipment selection, operational procedures).

The primary challenges to assessing risks to these species, as related to dredging, are the same challenges that plague assessing baseline risks for these receptors. Direct measures of effect caused by sediment-associated contaminants on consumers of aquatic life are difficult to assess. These receptors do not lend themselves to direct toxicity testing, so evidence supporting conclusions about risk to these receptors are most commonly based on inferences drawn from more indirect lines of evidence, including the use of field-collected data (contaminant concentrations in tissue) and modeling (e.g., bioaccumulation modeling). The use of these indirect lines is a significant source of uncertainty in baseline risk estimates for these receptors. This problem is compounded in the case of estimating the contributions dredging will make to increasing or decreasing risks because of the variability and uncertainty introduced by the dredging operation. Baseline risk estimates are made during conditions that closely approximate steady state, for the majority of contaminated sediment sites influenced by legacy industrial activities. Dredging, as well as other active forms of remediation, will change/reset conditions. For many of the compounds of concern at these sites (e.g., PCBs), attaining acceptable risk reduction is expected to take several years to decades because of time lags and slow process rates. These issues emphasize the need to base remedy selection on quantitative predictions about the rates of recovery under various remedial scenarios, including estimates of the uncertainty associated with these predictions. The historical approach of assuming that dredging will achieve the cleanup goal, thus allowing the immediate lifting of fish advisories, cannot be supported, based on the developing body of information on residuals, resuspension, and releases associated with dredging. Reasonable quantification of the range of probable post-dredging exposure to the chemical(s) of concern should be made as part of the remedy evaluation and selection (USEPA 2005). In addition to supporting remedy selection decisions, such predictions also provide the basis for hypotheses that can be tested through pilot-scale demonstrations and monitoring programs.

Key uncertainties and data gaps

The two primary categories of information used in risk assessment are exposure and effects data. While a reasonable argument could be developed to support the importance of both exposure and effects processes as sources of uncertainty in sediment assessment and decision making (e.g., Vorhees et al. (2002)), exposure processes, overall, will be emphasized here. The dynamic nature of the physical processes operating at contaminated sediment sites and the large size of many of these sites are principal sources of uncertainty in exposure assessment. With respect to remedial decision making, risks are managed by taking actions that will reduce exposures. However, the current state of our knowledge with regard to the processes affecting the performance of even the most common remedial options (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 associated with these predictions.

Exposure

Three exposure-dominated uncertainties and data gaps are discussed here: predictions about remedy performance, defining the risk contribution of spatial sub-units of a site, and residuals.

Constraints on the ability to make confident predictions about future performance of remedies introduces significant uncertainty to remedial decision-making. Making such predictions requires temporally defined data for characterizing exposure and effects and the modeling tools to integrate and predict risk. In basing decisions about dredging, as well as the other remedial alternatives, on a comparison of net risk reduction, uncertainty affecting the slope of the curve defining the risk reduction trajectory over time, as well as the uncertainty associated with any given trajectory, can be combined to give an overall estimate of uncertainty in the amount of time required to achieve acceptable risk reduction. Failure to account for this uncertainty for a dredging remedial scenario could result in overly optimistic or pessimistic conclusions about dredging with respect to the other remedial options available.

Most contaminated sediment sites include multiple contaminant sources and spatial subunits, which may correspond to the relative geographic location of the upland sources. The challenge of quantifying the contribution of each of these sources to the risks at a site relates primarily to problems conceptualizing exposure across a range of spatial scales and limitations in our ability to convert that conceptualization into a spatial modeling framework to characterize changes in risk over time. This challenge is more than a legal/economic allocation problem. How risk is spatially discretized will affect conclusions about the nature and magnitude of risk at a site and the development of strategies for remediating that risk. Viewing a site as simply a composition of many small sites, each having their own risk estimate and remedy, will likely lead to decisions that are not optimized to achieve the most overall benefit for the site as a whole or the surrounding watershed.

Dredging residuals can pose both short- and long-term risks. Uncertainty associated with dredging as a remedial technology can be reduced through gaining a better understanding of the processes controlling the generation, transport, and disposition of residuals. Here we emphasize the need for a better understanding of how residuals contribute to exposure and risk. There is relatively little existing experimental data upon which to base conclusions about how a thin (one to a few centimeters) layer of contaminated sediment overlying clean sediment contributes to exposure and risk in the short or long term. Questions concerning the relative bioavailability of contaminants in residuals or how thin caps placed on top of thin residual layers affect either bioavailability or bioaccessibility of contaminants have not been sufficiently examined experimentally. Data for describing the exposure processes relevant to residuals could substantially reduce the uncertainty associated with dredging effectiveness, contribute to more realistic remedy evaluation and selection, and provide for better remedial designs.

Effects

Sources of effects uncertainty that are particularly germane to a dredging scenario concern how to apply published toxicity data or toxicity tests themselves in cases where exposure occurs as a series of pulses. The pulse scenario is most relevant to assessing short-term exposures and risks during active dredging where individual receptors will experience exposures in relatively short pulses (minutes to a few hours). The most available toxicology information for ecological receptors is collected using continuous exposures for periods between about 96 hr (acute data) to a few weeks (chronic). The potential for over-protection in this situation should be recognized, as it can have the consequence of unnecessarily increasing costs associated with additional operational requirements (e.g., silt curtains, restrictions on dredging rates, etc.) that can affect not only the cost efficiency of dredging but the time required to achieve acceptable risk reduction. While not reflected in many current requlatory guidelines (e.g., USEPA Water Quality Criteria), there have been many advances in toxicological modeling of time-varying exposure that may help provide the most realistic assessment of risks from short-term exposures in the water column.

Risk characterization

Enhancing the power of predictive modeling applicable to dredging scenarios, as well as the other remedial options, should also provide for a more complete understanding of all of the processes contributing to risk reduction. There are a lot of processes in motion at a typical contaminated sediment site: ongoing sources of contamination; weather conditions (i.e., rainfall); ongoing human activities (e.g., ship and recreational boat traffic); upstream activities affecting sedimentation processes (e.g., development, farming practices), etc. A key challenge to understanding resuspension, release, and residual conditions, and their contribution to site risks, is distinguishing these dredging and site-related processes from ambient conditions in the encompassing watershed. In other words, how can we determine when changes in risk are the consequence of remediation versus natural or other processes occurring in the watershed? During the monitoring elements of a project the danger is in reacting to changed conditions without a clear understanding of whether the remedy was responsible for the change. One specific example of this relates to determining whether the risk reduction observed during long-term monitoring can be attributed to remedial actions taken at the site or whether they are due to natural processes operating in the watershed. For example, if surficial concentrations post-dredging are at or above pre-dredging concentrations and natural sedimentation and contaminant degradation/sequestration processes (i.e., MNR) are relied upon to reduce risks to acceptable levels, then is the realized risk reduction due to dredging or MNR? Perhaps the clearest example of this occurred at Manistique Harbor, where post-dredging average surficial concentrations (approximately 17 ppm of PCBs) were virtually identical to pre-dredging surficial concentrations (15 ppm), yet, four years later, the average surficial concentrations dropped to 0.74 ppm due to an undefined mixture of enhanced and natural recovery processes. This same question could be asked if capping is combined with dredging to manage exposures from residuals. If backfill/cover or engineered caps are relied upon to reduce post-dredging surface concentrations, then is the realized risk reduction due to dredging or capping? Dredging could make a contribution to risk reduction in these two scenarios if that contribution came from reduced risks associated with the transport of contaminated sediment during an erosion event. However, in projects completed to date, the risks associated with such an event have not been quantified or described in sufficient detail to include such a scenario as an explicit part of a remedy selection process using comparative net risk reduction approach.

Risk monitoring

It is evident from the paucity of existing long-term monitoring data for sediment clean-up sites that more emphasis must be given to this particular aspect of cleanup projects. To be most effective, monitoring should be structured to test specific hypotheses about risk reduction that are developed from the results of predictive modeling. In a sense, remediation projects are large-scale experiments. Data are collected before the remediation to inform how the experiment will be conducted. But the fact of the matter is that no one knows how the experiment will conclude. A well-designed monitoring program can provide the conclusion. Some may object to the notion of viewing multi-million-dollar remediation projects as experiments with an uncertain outcome. The motivation for this objection exposes the need for using adaptive management principles to guide such projects (Linkov et al. 2006a, 2006b).

6 A Path Forward for Risk-Based Management

The two "constants" of sediment remediation projects are that 1) environmental conditions affecting the nature of the problem are dynamic, and 2) uncertainties will affect decision-making and judgments about the effectiveness of decisions. These facts call for the use of adaptive management as a guiding approach for sediment remediation projects (Linkov et al. 2006a, 2006b). The principles of adaptive management provide a structure for implementing an iterative approach to learning, which provides the means for addressing the two constants of sediment remediation projects. Improving understanding of the dredging process, as applied to achieving remediation objectives, will provide a foundation for improving the overall effectiveness of remedial dredging. Given the nature of the problem, 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 multi-disciplinary 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 priority. The result of this collaboration will be an approach that lays out data objectives to assess both risk and engineering outcomes, experimental designs and the associated monitoring requirements for focused studies, and a sound basis for setting expectations for dredging effectiveness.

A critical additional component of future progress in evaluating the effects of resuspension, release, and residuals on dredging effectiveness should include continued evaluation of dredging performance by collecting data allowing for prediction and measurement of residuals in real world projects (pre-dredging prism concentrations and post-dredging average surficial concentrations) as well as additional, focused pilot or research studies of resuspension and releases.

Finally, there is growing recognition that the effectiveness of any remedial technology, including dredging, is most appropriately measured through a comparison of what could be achieved through use of an alternative technology. Comparing predictions of the effectiveness of all potential technologies provides a context for attaching meaning to any particular measure of effectiveness. The importance of this fact is at the heart of recommendations for basing decisions about remedy selection on a comparison of net risk reduction (e.g., USEPA 2005). Such an approach can be integrated with an adaptive management model for sediment projects by scaling remedy implementation. Adaptive management seeks to preserve the opportunity to learn and make adjustments in a management strategy, i.e., a remedy, in a manner that conserves resources. It would be consistent with such a principle to start a remediation project by implementing less invasive and costly remedies that can be more easily modified, or even undone, if the desired risk reduction trajectory is not being met. This logic would lead to giving consideration to MNR before capping and capping before dredging, rather than the reverse.

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14. ABSTRACT

A workshop sponsored by the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency was held at the U.S. Army Engineer Research and Development Center, Waterways Experiment Station, in Vicksburg, MS, in April of 2006. Fifty experts from government, the private sector, and academia participated in the workshop, which focused on four issues (the four Rs) relevant to environmental dredging: (1) sediment resuspension resulting from dredging operations, (2) release of contaminants from bedded and suspended sediments in connection with dredging, (3) residual contaminated sediment produced by and/or remaining after dredging, and (4) the environmental risks that are the target of and associated with dredging.

Goals for the workshop were to: (1) promote consistency in the terms used to define the challenges represented by the four Rs, (2) develop consensus for a conceptual model that relates the relevant processes, (3) identify current resources and needs regarding data and methods/models to better describe and understand the processes, and (4) identify key uncertainties and make recommendations regarding future research to resolve those uncertainties.

This technical report summarizes analysis and synthesis of the results of the workshop.

15. SUBJECT TERMS

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