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USACE TECHNICAL GUIDELINES FOR PREDICTING THE 3RS OF ENVIRONMENTAL DREDGING

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ABSTRACT

A critical component of the evaluation of environmental dredging as a contaminated sediment remediation alternative is the prediction of the 3Rs: Resuspension, Release and Residuals. Sediment resuspension by dredging operations promotes contaminant release and impacts the short-term effectiveness of the remedy as well as the ability to protect the environment and comply with Applicable or Relevant and Appropriate Requirements. Sediment resuspension also contributes to the contaminated residuals from dredging. Residuals impact the reduction of toxicity and both short- and long-term effectiveness.

The USACE Technical Guidelines for Environmental Dredging of Contaminated Sediments (Palermo et al. 2008) provides state-of-the-art prediction methods for the 3Rs. The guidelines present the key parameters that influence the magnitude of sediment resuspension and summarize the findings from past dredging projects for a variety of equipment. The guidelines provide a method to adjust resuspension estimates for different site and sediment properties. Sediment properties are strongly correlated with resuspension. Contaminant release is driven by the resuspension, plume dispersion, particle flocculation and settling, and the kinetics of contaminant partitioning. These processes are considered in the acquisition of non-equilibrium partitioning data from the dredging elutriate test and in its use in fate and transport models. The guidelines provide a method to estimate the quantity of generated dredging residuals based on past studies, equipment selection and site conditions and a predictive technique to estimate contaminant concentration in the residuals based on the sediment profile (contaminant concentration and density) and work plan. Estimates of the 3Rs provide the basis for determination of the need for control measures, short-term risk from removal operations, and potential remediation effectiveness/feasibility.

Keywords: Remediation, contaminated sediments, resuspension, contaminant release, residuals

INTRODUCTION

All dredging operations resuspend sediment, release contaminants, and generate residuals (see Figure 1). Resuspension is the dislodgement and dispersal of sediment into the water column where the finer sediment particles and flocs are subject to transport and dispersion by currents. Resuspension of sediment will also result in some short-term release of contaminants to the dissolved phase in the water column by release of pore water and by desorption from suspended sediment particles. Since contaminants normally associated with sediments tend to remain tightly bound to fine-grained sediment particles, control of sediment resuspension will also help in control of contaminant release. The vast majority of resuspended sediments settle close to the dredge within one hour, and only a small fraction takes longer to resettle (Wright 1978; Van Oostrum and Vroege 1994; Grimwood 1983). However, fine particles and flocs with critical settling velocities below the ambient localized turbulence-induced velocities are subject to transport for hours and perhaps days before settling, posing a potentially significant release of contaminants over a large area. Contaminants are also released and subjected to transport with dissolved organic constituents, colloidal organics, and oil. Once the contaminants are in the dissolved phase, or in the air, the released contaminants are subject to far-field transport.

Generated residuals are defined as sediment dislodged, but not removed, by dredging which falls back, spills, sloughs, or settles in or near the dredging footprint and forms a new sediment layer (Figure 1). Undisturbed residuals can result from poor site characterization or sample spacing during characterization, core compression during sampling, and dredging that did not achieve the required elevation or poor bucket positioning due to operator error or insufficient positioning system accuracy. Residuals contribute to the short-term release of contaminants by release of pore water during settling and consolidation and to the long-term release by molecular diffusion, bioturbation and erosion of the exposed residual sediment layer.

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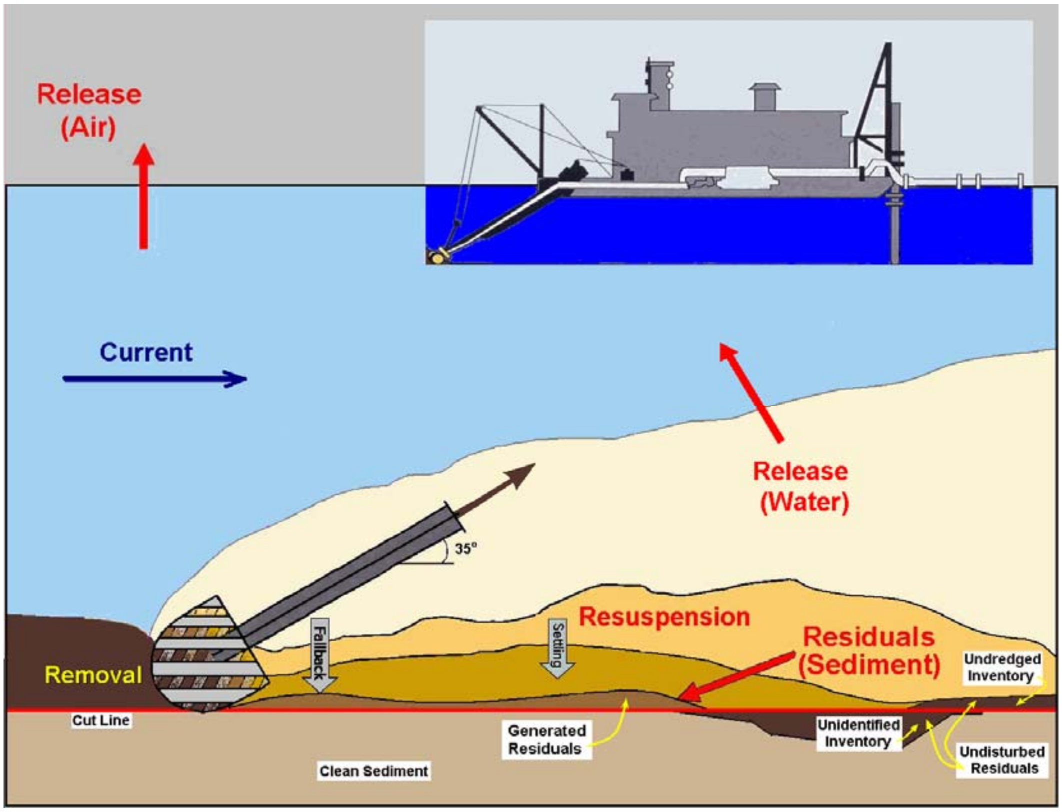

Figure 1. Conceptual illustration of environmental dredging and processes.

This paper presents methods for the prediction and evaluation of the resuspension of sediment due to dredging, contaminant release by dredging, and generated residuals of dredging. Considerable field measurements of resuspension and residuals have been made, but these empirical observations have limited predictive value if site and sediment properties are different at a different location. The actual operation of the dredge by the operator can have significant impacts on residuals and resuspension. Issues such as bucket overfilling, overpenetration, bucket speed when contacting bottom, and bucket speed when lifting bucket off bottom can all significantly impacts resuspension and residuals for mechanical dredging. Cutterhead speed, swing speed, and bank height all impacts resuspension and residuals by hydraulic dredges. Support equipment such as tug boats can also be a significant source of resuspension. Nevertheless, these field observations provide the basis for prediction of resuspension and residuals. A variety of sediment resuspension and contaminant release models based on field observations and laboratory tests are available for dredging operations, but, until recently, the process of sediment resuspension has received much more attention than the associated contaminant releases. Field measurements of contaminant release are very limited; therefore, predictive methods for contaminant release to the water column and air are more theoretically based than empirical. However, contaminant release is strongly dependent on both resuspension and generated residuals predictions, and risk is dependent on contaminant release and residuals.

Resuspension and generated residuals prediction methodologies serve as source strength inputs for fate and transport models to predict solids behavior, contaminant release and contaminant concentrations/exposure for risk calculations. This paper focuses on resuspension and residuals models because they are unique to dredging operations and are in their infancy, while both simple screening level and comprehensive fate and transport models for water quality prediction and toxicity are well developed.

SEDIMENT RESUSPENSION

Resuspension will occur in every dredging project, but the degree of resuspension is a function of a number of factors that includes (Hayes et al. in preparation):

- Sediment properties such as in situ dry bulk density (solids concentration, solids content or water content), organic content, particle-size distribution, and mineralogy
- Site conditions such as water depth, currents, waves, and presence of hardpan or bedrock
- Nature and extent of impediments, such as debris, loose cobbles, boulders and obstructions
- Operational considerations such as the thickness of dredge cuts, dredging equipment type, method of operation, and skill of the operator

The sensitivity of these factors is unknown, but is expected to account for the large differences in the field observations.

Suspended sediment data for specific dredging operations have been published, and a few methods for estimating release have been developed. However, the available data do not cover a sufficient range of sediment, environmental, and operational conditions to serve as a predictive base for distinctly different dredging operations. Predictive techniques developed by Nakai (1978), Collins (1995), and Hayes et al. (2000) either suffer from limited empirical data sets, apply to only a relatively narrow set of conditions, or require information seldom known early in the project when these estimates are needed most. Therefore, the best predictive approach currently available is to rely on past field measurements as a baseline to develop an equipment-specific characteristic resuspension factor that can be adjusted for site-specific sediment properties, site conditions, impediments and operations. The resuspension factor is defined as the fraction of the fine-grained material in the dredged sediment that is dispersed in the water column.

Characteristic Resuspension Factors

Resuspension data from environmental dredging projects is minimal. However, navigational dredging has been studied much more extensively and, because resuspension is driven by the same processes, it is relevant to the environmental dredging experience. Sediment resuspension data have been collected from a variety of navigation dredging operations and provide useful insight into resuspension rates relating to the dredgehead (Nakai 1978, Pennekamp et al. 1996, Hayes et al. 2000). Nakai (1978) monitored ten cutterhead navigation maintenance dredging operations. The estimated resuspension factors ranged from 0.02% to 3.93%. The mean resuspension factor for these operations was about 1.2%, while the median was about 0.5%. Hayes and Wu (2001) and Hayes and et al. (2000) showed resuspension factors for five cutterhead navigation maintenance dredging operations. The average resuspension factors ranged from 0.003% to 0.13% for the five sites, and the maximum observed resuspension factor of the nearly 400 observations was 0.51%.

Nakai (1978) monitored seven mechanical clamshell and bucket navigation maintenance dredging operations, but only three or four of the seven operations were likely without overflow from the barge. The mean resuspension factor without overflow was about 0.2% to 0.6%, while with overflow the mean was about 8.6% to 10.9%. Hayes and Wu (2001) computed resuspension factors for five mechanical clamshell navigation maintenance dredging operations. The resuspension factors ranged from 0.2% to 0.9% and had a mean of 0.45%. Pennekamp et al. (1996) monitored twelve mechanical navigation maintenance dredging operations that varied greatly in equipment type, which included open clamshells with and without silt curtains, watertight clamshells with and without silt curtains, excavators with and without silt curtains, and bucket dredges. The resuspension factors ranged from 0.3% to 1% for open clamshells, from 0.3% to 2% for watertight clamshells, from 0.6% to 5% for excavators, and from 0.3% to 2% for bucket dredges. The mean resuspension factor was about 1.5%, and the median was 1.1%. The mean value for the seven clamshell dredges was 1%, and the median was 1.1%. The backhoe excavators had resuspension factors that were equal to two to three times those of the clamshell dredges.

The range in resuspension factors shows that there is no such thing as a typical resuspension factor. However, based on these data sets, Hayes et al. (in prep.) estimates that the conservative characteristic resuspension factor for cutterhead dredges is about 0.5% of fine silt and clay fraction of the sediment, and the conservative characteristic resuspension factor for mechanical dredges with open or watertight buckets without overflow is about 1%. [The coarse-grained fraction (sands and gravels) is assumed to settle back quickly near the dredge and is not able to be transported from the site as a suspended load.] More modern environmental clamshell dredges would be expected to perform better than the watertight clamshell dredges reported in the literature by Pennekamp et al. (1996); the use of precision dredging navigation systems that can reduce overpenetration and bucket overfilling and therefore reduce resuspension. Therefore, the conservative characteristic resuspension factor for mechanical dredges with environmental buckets without overflow is about 0.5%. These characteristic resuspension factors reflect the central tendency (average and median) of the empirical data and represent resuspension for characteristic site, sediment and operating parameters. Actual resuspension would deviate from the characteristic resuspension as actual site, sediment and operating parameters deviate from characteristic conditions. Adjustments to the characteristic resuspension factors for actual conditions are given below.

Since these data were collected primarily from navigation maintenance dredging where limited quantities of debris were present, the characteristic resuspension factors should be increased by a factor of two or three for environmental dredging sites when significant quantities of debris are encountered. Additional resuspension will occur from supporting activities such as debris removal, barge/pipe/silt curtain tending, barge/dredge transport (tug operations), and crew operations, which should be included in the overall estimate of resuspension. However, these activities are limited and infrequent when compared with the dredging.

Adjustments to Characteristic Resuspension Factors

Prediction of a representative resuspension factor for a specific project requires adjustment of the characteristic resuspension factors given above for project specific conditions. The magnitudes of these required adjustments are unknown, but the range in the results for the reported field data provides a basis for bounding the adjustments. Maximum resuspension factors tend to be equal to 3 to 5 times the average or median resuspension factor for a given type of equipment. Minimum resuspension factors tend to be equal to only 5 to 10% of the average or median resuspension factor for cutterhead dredges and 30 to 40% of the average or median resuspension factor for mechanical dredges.

The resuspension factor should increase with the liquidity of the sediment. Liquidity is a geotechnical property of the sediment and is related to the water content and Atterberg limits (plasticity and nature of a fine-grained soil) of the sediment as follows:

$$LI = (W - PL) / (LL - PL) \quad \text{or} \quad LI = (W - PL) / PI \qquad (1)$$

where:

LI = liquidity index
W = water content, percent
PL = plastic limit, percent
LL = liquid limit, percent
PI = plastic index, percent

Very soupy sediments resuspend more easily. Liquidity may have the single largest effect on resuspension. Liquidity incorporates numerous sediment properties. Liquidity increases with a decrease in the density of the sediment or an increase in the water content, porosity or void ratio of the sediment. Liquidity also increases with the grain size for fine-grained sediments or a decrease in clay content. Silts are more liquid than clays at the same water content. Sands are neither liquid nor plastic because liquidity and plasticity are only measures of fine-grained materials. Liquidity increases with a decrease in the plasticity or plasticity index of the sediment.

Increases in currents and wave energy should increase the resuspension factors. Stronger currents are able to disperse dislodged sediments in the water column. The impacts should be greater for mechanical dredging, particularly with open buckets, which expose the sediments during vertical transport of the dredged material through the water column. Similarly, increases in water depth would increase resuspension for mechanical dredges. The effects are greater for sediments with higher liquidity.

Increases in impediments to dredging such as debris, cobbles, boulders, hardpan, bedrock and rock outcroppings increases resuspension. Of these impediments, debris poses the most problem to resuspension because it can prevent closure or seal of the clamshell, causing significant leakage or loss of dredged material to the water column. Debris can also disrupt the capture of sediment by cutterhead dredges and increase dispersion of the dislodged sediments. Additionally, debris is often removed in a separate removal operation that can resuspend nearly as much sediment as the dredging operation as well as increasing the liquidity of the material for subsequent dredging.

Operations can also affect resuspension. Low production rates and shallow cuts for hydraulic dredges can increase resuspension (increase the fraction of fines lost, but not necessarily the concentration of suspended sediment). Similarly, high production rates can increase resuspension when currents are high because more sediment can be dislodged than captured by the dredge head. Operations also affect resuspension for mechanical dredges. High bucket drop speeds can erode the sediment bed and increase resuspension. Overfilling the bucket or excessive cut depth can cause spillage from the bucket or release of sediment from bucket vents during penetration, leading to an increase in resuspension. Barge transport over the site can contribute to resuspension that can be controlled by equipment selection and site management.

Nakai TGU Method

The oldest and most commonly referenced method to predict dredging-induced resuspension loss rates was published by Nakai in 1978. Referred to as the TGU method (Turbidity Generation Unit), it is a readily implemented predictive tool for open clamshell dredges, cutterhead dredges, and hopper dredges. Nakai (1978) measured TSS downstream of a dredging operation; his measurements are summarized above. After measuring the TSS downstream, Nakai used a simple relationship to infer what the resuspension losses were at the dredge. This inference required knowledge of the settling velocities, particle distribution, turbulent velocities in the water column, shear stress distributions in the water column, and critical shear stress for settling. These items were not measured at the sites and are largely unknown at dredging sites. Nakai assumed that all particles above 5 microns settled to develop his table of TGU values. Recent measurements of particle/floc sizes in turbidity plumes from dredging operations showed large quantities of material above 5 microns, typically up to 20 to 30 microns. As such, the TGU values in his table are greatly overestimated because the multiplier (the ratio of materials released to material settled assumed to be the ratio of mass smaller than 74 microns to the mass smaller than 5 microns) used to obtain the TGU values is considerably larger than the ratio of mass smaller than 74 microns to the mass smaller than 20 microns, particularly for sediments with low clay fractions. In addition to the overestimated TGU values, the number of sediments, pieces of equipment, and lack of key site, sediment, and operations descriptors limit the utility of the method and its application.

Collins (1995) Resuspension Correlations for Open Clamshells

Collins (1995) developed a model to estimate dredging-induced sediment resuspension rates at the point of dredging. These rates were a function of the dredge, operational characteristics, and sediment properties based on empirical observations. TSS concentrations at the point of dredging were not directly available; therefore, TSS concentrations at the source of the resuspension were calculated for clamshell buckets by plotting measured TSS concentrations at various depths and distances from the dredge and then extrapolating to the concentration at dredging location. A mathematical model for the source concentration was developed based on the parameters of settling velocity, bucket size, channel depth, and cycle time. The source volume having the initial TSS concentration was defined as the apparent bucket footprint multiplied by the channel depth.

The model assumes that sediment is resuspended in the source volume of the water column during the fraction of the dredging cycle when the bucket is ascending from the channel bottom towards the water surface. When the bucket surfaces, the concentration throughout the cylinder is assumed uniform. This concentration of sediments is then progressively expelled, at an assumed linear rate, from the source volume as the bucket descends back through the water column toward the channel bottom. When the bucket reaches the channel bottom, it is assumed that the entire mass of suspended sediments in the column has been emptied. The contribution of sediments to the near-field volume from this source volume is averaged over the duration of the entire dredging cycle, although in reality sediment is contributed only in certain phases of dredging for clamshell bucket dredges.

Hayes et al. (2000) Cutterhead Correlation Method

Hayes et al. (2000) developed a dimensional and non-dimensional model for estimating the resuspension factor of sediment due to cutterhead dredging operations. The fundamental basis for both models followed Hayes' (1986b) hypothesis that the majority of sediment resuspended during cutterhead dredging operations was due to the stripping of fine-grained sediment that adhered to the cutter blades following sediment cutting. Field data from the cutterhead dredging operations on the James River, VA, Savannah River, GA, Calumet River, IL, and Acushnet River, MA (New Bedford Harbor) were used to develop the empirical source strength models.

The field data from these sites yielded 106 observations of the parameters used to develop the source models, namely

- rate of sediment suspended by the cutter that will be transported away from the dredge
- rate of in situ sediment cut by the dredge
- rate of sediment removal by the dredge swing speed of cutter tip
- tangential speed of cutter blades
- intake suction velocity at cutter blades
- total surface area of cutter blades exposed to washing
- total surface area of the cutter

Hayes et al. (2000) stated that the following factors should be considered when employing the dimensional and non-dimensional models:

- The models are most applicable to scenarios similar to those used in their development.
- The models should only be applied to dredges within the range of operating characteristics found in the four field sites.
- If applied outside the range of operating characteristics for which the models were derived, very high (conservative) estimates can result.
- The models have not been validated against independently collected field data.

USACE DREDGE Model

The DREDGE model (Hayes and Je 2000) is a steady-state screening level model for modeling resuspension and contaminant release. DREDGE couples resuspension source models with a Gaussian dispersion model (Kuo and Lukens 1985, Kuo and Hayes 1991) and Stokian settling model in a uniform flow field. DREDGE estimates the mass rate at which bottom sediments become suspended into the water column as the result of hydraulic and mechanical dredging operations and computes the resulting suspended sediment and contaminant concentrations. DREDGE allows the user to select from and apply either the predictive methods for resuspension described or their own estimate from empirical observations. The Nakai (1978) TGU method, Collins (1995) and Hayes et al. (2000) correlation methods, and Hayes et al. (in prep) resuspension factor method are incorporated as source strength models and each can be examined to aid the user when selecting their own estimate of the resuspension. These are combined with information about site conditions to simulate the size and extent of the resulting suspended sediment plume under steady-state conditions. DREDGE also estimates total and dissolved contaminant concentrations in the water column based upon sediment contaminant concentrations and equilibrium partitioning theory.

Hayes and Je (2000) developed the DREDGE model for the U.S. Army Corps of Engineers (USACE) to assist users in making a priori assessments of environmental impacts from proposed navigational dredging operations. DREDGE is a module of the Automated Dredging and Disposal Alternatives Modeling System (ADDAMS) distributed by the Environmental Laboratory of the U.S. Army Engineer Research and Development Center. ADDAMS (Schroeder et al. 2004) consists of approximately 20 modules to assist in design and evaluation of various aspects of dredging and dredged material disposal operations.

EPA ARCS Guidance

The EPA Great Lakes National Program Office (GLNPO) Assessment and Remediation of Contaminated Sediments (ARCS) Program published guidance on "Estimating Contaminant Losses from Components of Remediation Alternatives for Contaminated Sediments" (U.S. EPA 1996). The guidance provides observations of resuspension losses and TSS concentrations for a large variety of dredges. These observations and descriptions of dredging equipment can assist in developing estimates of resuspension factors for other dredging equipment. In addition, the guidance provides information for estimating losses by other components of dredging operations such as transport by pipelines, and barges. In addition, the observations of TSS concentrations provide a basis to check the predictions of resuspension and its fate and transport for consistency.

Fate and Transport Models

A thorough discussion on the use and selection of models to evaluate remedial alternatives is given in the *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (U.S. EPA 2005). A wide range of simpler empirical models and more robust computer models can be applied to model the fate of resuspended sediment and associated sediments. Simple models that aggregate processes or consider only some portion of a problem can provide significant insights and should be applied routinely at sediment sites, even complex sites. These models are particularly useful in modeling the source, the dredging zone and the near field. The models can help identify appropriate monitoring locations, impact areas for residuals formation by settling of resuspended sediment, and potential accumulation of residuals. The DREDGE model described above is such a model.

Often a complex fate and transport model is developed for a site to understand more fully the potential future risks of a site and to verify a site conceptual model. Comprehensive technical reviews of available models have been conducted for the EPA's ORD National Exposure Research Laboratory (Imhoff et al. 2003). When available, these models can be quite useful in predicting the fate of resuspended sediment particles in the far field. Complex processes such as flocculation, settling, and erosion in unsteady flow regimes are best modeled using more advanced fate and transport models. However, if a complex fate and transport model is not developed, simple modeling can be used to develop a better understanding of the resuspension and release processes by incorporating unsteady features and variable parameter descriptions. The USACE PTM (Particle Tracking Model) is an example of model that can address unsteady flow regimes, handle a number of particle sizes and settling rates, and allow erosion of settled particles (MacDonald et al. 2006). Whether and when to use a model and what models to use are site-specific decisions, and modeling experts should be consulted (U.S. EPA 2005).

Resuspension Controls

Resuspension controls such as silt curtains do not affect the resuspension source strength in terms of the resuspension factor. However, controls may affect production rates, and the resuspension rate in terms of kg/sec may change. Controls are likely to alter the transport of resuspended solids and perhaps settling rates. Confining the resuspended sediments in a small area may increase flocculation and settling rates. Additionally, silt curtains can slow currents in the dredging zone and cause release and transport of solids to occur only near the bottom of the water column. When controls are employed, the input to the source and transport models should incorporate the effects of the controls. Silt curtains can also cause an increase in resuspension and residuals by providing a false sense of security to dredge operators who may increase dredge speed or pay less attention to other best management practices (BMPs) because they are operating within a contained area.

RESIDUALS

One of the more significant limitations currently associated with assessing 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; however, it should be noted that many projects were completed using standard navigation equipment and did not benefit from positioning systems such as RTK GPS. This is to be expected due to the inherent limitations of even the most modern dredging equipment, and the distribution of contamination found in many sites – where typically higher concentrations exist at deeper unexposed 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). In many situations, these complicating factors can make the sediment removal process and achievement of risk-based remediation goals particularly difficult as well as costly.

The descriptions of residuals processes, factors affecting residuals, and considerations for prediction of residuals described in this paper were primarily adapted from Palermo and Patmont (2007), Patmont and Palermo (2007), and Bridges et al. (2008). Residuals are contaminated sediment found at the post-dredge 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, and 2) generated residuals. Undisturbed residuals are contaminated sediments found at the post-dredge sediment surface that have been uncovered by dredging but not fully removed. Generated residuals are contaminated post-dredge surface sediments that are dislodged or suspended by the dredging operation and are subsequently redeposited on the bottom of the water body.

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 manage such materials actively. 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 (U.S. EPA 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 action level requirements.

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

- Contaminant (COCs) concentrations (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 (esp. 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?), and
- Mobility and fate (e.g., what is likely to happen in the future?).

Projects with performance standards related to residual contaminant concentrations normally have provisions for multiple passes of the dredge to achieve the objectives. A common approach for multiple passes is to focus on mass removal of contaminated sediment with the initial passes of the dredge, followed by passes used for "cleanup". Removing the bulk of the material in several passes that do not exceed three to five feet in any one pass tend to limit sloughage from adjacent undredged areas.

Residuals Characteristics

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 generally falls back to the bottom relatively close to the point of dredging and may have characteristics similar to undisturbed residuals. Resuspended sediment, which has settled to the bottom after it has been transported as a plume, may have very different characteristics from the undisturbed sediment. Generally, undisturbed residuals remain below the dredge cut elevation at a higher dry bulk density than generated residuals; their dry bulk density would 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 and at relatively low dry bulk density if deposited from suspension or from fluid mud layers. Generated residuals may also exhibit a less fluid-like, but still soft unconsolidated layer resulting from resettlement and fluidized mud flows, along with sloughing (i.e., shallow slope failures) of dredge cut slopes. Finally, generated layers of residuals may be underlain by more consolidated undisturbed residuals.

Field results to date for completed environmental dredging pilot projects and full-scale projects (Patmont and Palermo 2007) suggest there are common geotechnical and geochemical characteristics of residuals, as follows:

- Physical and geotechnical characteristics
  - Generated residuals (excluding sloughed materials) are more prone to resuspension immediately after dredging.
  - At some sites, there is a potential for downslope migration of fluid mud portions of the generated residuals.
  - 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 layers of residuals (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 discernible (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 discernible 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 contaminant concentrations in the top 10 cm of the sediment profile.

- Geochemical characteristics
  - Existing data suggest that the average concentration of COCs in generated residuals can be reasonably approximated based on the weighted average sediment concentration in the final production cut profile (the concentration of the final production cut would in turn be influenced by the previous dredge passes necessary to remove the entire sediment column dredged) (Patmont and Palermo 2007). If clean-up passes are used, the remaining generated residuals can be reasonably approximated based on the mass-weighted average sediment concentration in the final clean-up cut profile.
  - 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).

Factors Affecting Dredging Residuals

Similar to resuspension releases discussed above, the extent of residual contamination is dependent on a number of factors including:

- Type and size of dredging equipment
- Operation of the dredging equipment
- Amount of contaminated sediment resuspended by the dredging operation
- Extent of controls on dispersion of resuspended sediment (e.g., silt curtains, sheet piling)
- Relationship of surface and sub-surface contaminant concentrations in the area to be dredged
- Contaminant concentrations in surrounding un-dredged areas
- Characteristics of sediment being dredged, including grain size, water content, and organic content

- Characteristics of underlying sediment or bedrock (e.g., whether over-dredging is feasible)
- Site conditions including depth and currents
- Extent of debris, obstructions or confined operating area (e.g., which may limit effectiveness of dredge operation)
- Skill of operators

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, utility crossing which are left in place.
- Incomplete characterization of the horizontal and vertical extent of contaminants and/or over-reliance on the ability of geostatistical models to adequately represent the distribution of contaminants,
- Inappropriate selection of a target dredge cut design elevation,
- Inaccuracies in meeting targeted dredging elevations, or horizontal bucket placement resulting in missed material, and
- Development of dredge plans that intentionally do not target complete removal of contaminated sediments (e.g., due to engineering limitations).

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), including preventing complete closure of the bucket,
- Sediment that sloughs into the dredge cut from adjacent undredged areas,
- Sediment moved by slope failures caused by the process of dredging or innate slope instability,
- Sediments resuspended by the dredgehead that quickly resettle,
- Sediments resuspended by dredging or other dredging-related activities including prop wash that resettle within or adjacent to the dredging footprint, and
- Bucket overpenetration and overfilling

Predicting Dredging Residuals

It is logical that the quantity and quality of post-dredging residuals are related to dredging equipment, dredging methods, sediment characteristics and physical site conditions. However, currently there is no commonly accepted method to accurately predict post-dredging contaminant concentrations in generated residuals immediately following completion of the dredging (Palermo and Averett 2003).

Patmont (2006) compiled data on residuals from twelve environmental dredging projects completed between 1999 and 2005, using a variety of equipment. He found that the residuals contained 5 to 9% of contaminant mass removed for the eight projects containing PCBs. The other four sites having more mobile contaminants had residuals ranging from 2 to 4% of the contaminant mass removed. These masses of residuals are much larger than the observed masses of resuspension, indicating that fallback, slumping, sloughing and spillage are major sources of residuals.

Given the field observations, Hayes and Patmont (2004) and Desrosiers et al. (2005) recommend estimating the residual contaminant concentration to be equal to the depth-averaged contaminant concentration of the sediment removed in the last pass. The sediment concentration of the last pass would be influenced by the residuals volume and concentration from prior dredge passes. The residuals volume from the previous pass would be 5 to 20% of the volume of the previous pass, depending on equipment type, sediment properties, water depth, and other site conditions. The volume would be expected to be greater with more liquid sediments or more steeply sloped sediments where slumping, sloughing and spillage would be greater, or when conventional navigation equipment and less precise positioning systems are used. The percentage is also likely to be greater with thin cuts when using non-level bottom cutting equipment. Hayes and Patmont (2004) caution that these values and procedures have a high degree of uncertainty, but no other predictive techniques are available.

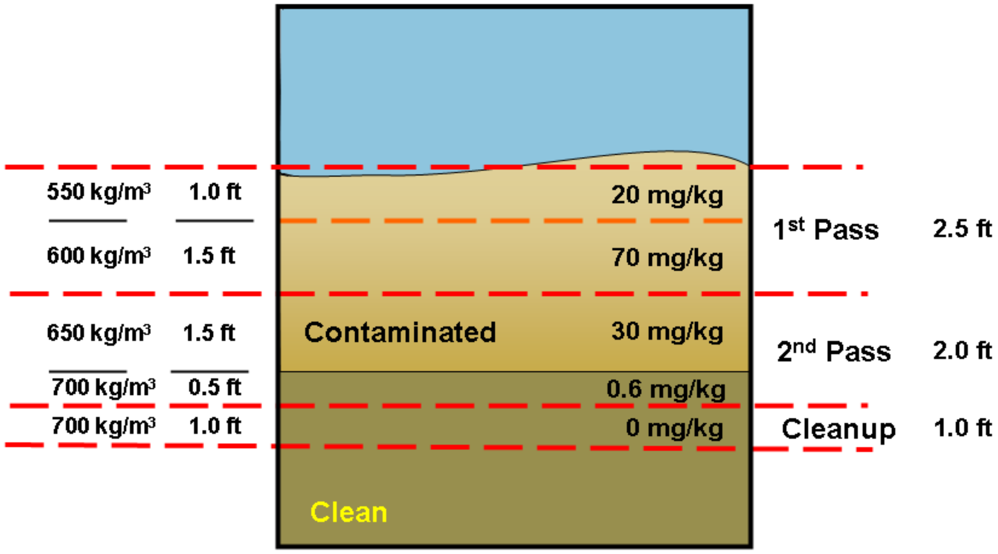

Figure 2. Example dredging work plan.

Example Calculation of Generated Residuals

This example is based on multiple dredging passes as illustrated in Figure 2 where one full production passes is performed, followed by a partial production pass with overdredging and a cleanup pass. The first pass is 2.5 ft thick and is composed of two layers of sediment. The first layer is 1 ft thick and has a bulk dry density of 550 kg/cu m and a contaminant concentration of 20 mg/kg. The second layer is 1.5 ft thick and has a bulk dry density of 600 kg/cu m and a contaminant concentration of 70 mg/kg. The second pass will consist of residuals from the first pass, 1.5 ft of additional contaminated sediment, and 0.5 ft of overdredging. The additional contaminated sediment has a dry bulk density of 650 kg/cu m and a contaminant concentration of 30 mg/kg and 0.5 ft of overdredging has a dry bulk density of 700 kg/cu m and a contaminant concentration of 0.6 mg/kg. The cleanup pass will consist of residuals from the second pass plus 1 ft of sediment with a dry bulk density of 700 kg/cu m and a contaminant concentration of 0 mg/kg. The sediment removal is being performed using a 12-inch cutterhead dredge with an articulated ladder where 10% of the dry mass of the sediment in each pass is left as residuals in a spillage layer. The example calculations follow:

First Production Pass Residuals Layer:

Mass: 10% x [(1.0 ft x 550 kg/cu m) + (1.5 ft x 600 kg/cu m)] x 1 unit area = 145 kg-ft-unit area /cu m

Contaminant Mass: 10% x [(1.0 ft x 550 kg/cu m x 20 mg/kg) + (1.5 ft x 600 kg/cu m x 70 mg/kg)] x 1 unit area = 7400 mg-ft-unit area /cu m

Residuals Contaminant Concentration: 7400 mg-ft-unit area /cu m ÷ 145 kg-ft-unit area /cu m = 51.03 mg/kg

Second Production Pass Sediment:

Mass: [(1.5 ft x 650 kg/cu m) + (0.5 ft x 700 kg/cu m)] x 1 unit area = 1325 kg-ft-unit area /cu m

Contaminant Mass: [(1.5 ft x 650 kg/cu m x 30 mg/kg) + (0.5 ft x 700 kg/cu m x 0.6 mg/kg)] x 1 unit area = 29,460 mg-ft-unit area /cu m

Second Production Pass Composite (residuals plus sediment):

Mass: 145 kg-ft-unit area /cu m + 1325 kg-ft-unit area /cu m = 1470 kg-ft-unit area /cu m

Contaminant Mass: 7400 mg-ft-unit area /cu m + 29,460 mg-ft-unit area /cu m = 36,860 mg-ft-unit area /cu m

Second Production Pass Residuals Layer:

Mass: 10% x 1470 kg-ft-unit area /cu m = 147 kg-ft-unit area /cu m

Contaminant Mass: 10% x 36,860 mg-ft-unit area /cu m = 3686 mg-ft-unit area /cu m

Residuals Contaminant Concentration: 3686 mg-ft-unit area /cu m ÷ 147 kg-ft-unit area /cu m = 25.07 mg/kg

Cleanup Pass Sediment:

Mass: 1 ft x 700 kg/cu m x 1 unit area = 700 kg-ft-unit area /cu m

Contaminant Mass: 1 ft x 700 kg /cu m x 0 mg/kg x 1 unit area = 0 mg-ft-unit area /cu m

Cleanup Pass Composite (residuals plus sediment):

Mass: 147 kg-ft-unit area /cu m + 700 kg-ft-unit area /cu m = 847 kg-ft-unit area /cu m

Contaminant Mass: 3686 mg-ft-unit area /cu m + 0 mg-ft-unit area /cu m = 3686 mg-ft-unit area /cu m

Cleanup Pass Residuals Layer:

Mass: 10% x 847 kg-ft-unit area /cu m = 84.7 kg-ft-unit area /cu m

Contaminant Mass: 10% x 3686 mg-ft-unit area /cu m = 368.6 mg-ft-unit area /cu m

Residuals Contaminant Concentration: 368.6 mg-ft-unit area /cu m ÷ 84.7 kg-ft-unit area /cu m = **4.35 mg/kg**

Residuals Thickness (assuming a density of 450 kg/cu m): 84.7 kg-ft-unit area /cu m ÷ 450 kg/cu m ÷ 1 unit area = **0.19 ft or 5.7 cm**

CONTAMINANT RELEASE

Contaminant releases associated with dredging can occur in particulate, dissolved, or volatile fractions, with each characterized by a different transport and/or exposure pathway. Particulate-associated contaminants are released as resuspension of fine-grained and organic particulates as discussed above. Some resuspended fine particles have low settling velocities and can remain suspended in the water column for hours or days, and the suspended 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 release of contaminants to the dissolved phase in the water column by release of contaminants in the sediment pore water and by desorption of contaminants from suspended sediment particles. Once in the dissolved phase, released contaminants are subject to far-field transport and can increase the contaminant exposure and resulting risk. This release pathway can be a particularly significant pathway to consider given the bioavailability of dissolved contaminants. While the exposures and risks associated with dissolved 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 length of the dredging operation and a range of other physical and chemical factors. These dissolved contaminants will interact with background solids and materials outside the dredging zone, undergo abiotic and biotic reactions, be dispersed and incorporated in the local ecosystem, and/or be transported away.

Releases to the air through volatilization may also be a concern. Releases to air are a function of the dissolved contaminant concentration at the surface of the water column. In addition, floating oils are sometimes released to the water column during the dredging process, providing another avenue for facilitating contaminant transport. Fortunately, contaminants normally associated with sediments tend to remain tightly bound to fine-grained and organic particles; therefore, control of sediment resuspension will also help in control of contaminant release.

Releases can be quite difficult to quantify because particulate and dissolved releases of contaminants vary widely temporally and spatially due to the nature of dredging operations. To measure the variability of contaminant concentrations temporally and spatially is both difficult and expensive. Therefore, very little data are available on contaminant releases and contaminant release processes/sources. Consequently, predictions of contaminant releases are largely theoretical or based on laboratory measurements such as the dredging elutriate test (DRET) (DiGiano et al. 1995) described below. However, even the DRET is largely unverified and protocols for application of the test results are unsettled.

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. Typically, samples are taken at distances of 300 to 1,000 feet from the dredge head, which correspond to travel times of 10 to 30 minutes.

The location of the sampling often corresponds with 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. The sampling has not been designed to quantify release processes, which would require more frequent sampling across a grid in proximity to the sources.

Contaminant losses also occur from residuals both during and following dredging operations. Contaminant losses from residuals result from densification/ consolidation of the residuals layer, expelling pore water with dissolved contaminants from the forming and consolidating residuals layer. Residuals may have very low solids concentrations when initially formed and, potentially, may continuously release large quantities of contaminated water during the dredging operation, perhaps corresponding to a meter of water across the dredging footprint. These releases of water from the residuals layer formation may be largely indistinguishable from the resuspension losses. The residuals may also be eroded during the dredging operations and release contaminated particulates and pore water. Contaminant losses from residuals may exceed the losses from resuspension. Following the dredging operations, dissolved contaminants will continue to be released from the residuals by molecular diffusion and bioturbation, and particulate-associated contaminants will be released by erosion. Residuals provide the same sources of risk as the original sediment bed, but the magnitude of the risk will depend on the bioavailable contaminant concentration and thickness of the residuals.

Particulate Contaminant Releases from Resuspension

These two sections on contaminant releases were adapted from "Estimating Contaminant Losses from Components of Remediation Alternatives for Contaminated Sediments," prepared for the Assessment and Remediation of Contaminated Sediments (ARCS) Program, Great Lakes National Program Office (GLNPO) (U.S. EPA 1996). Consideration of the dredge program and schedule is important in predicting (modeling) the release effects of the dredging operations. The time frame over which the entire project will be implemented and the spatial dredge plan should be factored into the evaluation of short-term exposure.

Resuspension of particulates is a function of dredge type and operation and sediment properties. Sediment properties are a site-specific concern that cannot be definitively quantified without reference to a specific dredging project. In general, finer, less cohesive sediments have the greatest potential for resuspension.

Contaminants associated with resuspended particulates are primarily metals and other elemental species and organic contaminants. Elemental species of concern may be in geochemical phases with slow release properties or in geochemical phases that readily accept and release elemental species. Organic contaminants are usually bound in the organic fraction of the sediment through reversible sorption reactions. Contaminant species may also be dissolved in the pore water adjacent to the sediment particles; but for most contaminants, the dissolved fraction is much smaller than the particulate fraction.

The mass release of a contaminant during dredging is defined by

$$m = f_r \ \rho_s \ A \ D \ C_s \qquad (2)$$

where:

m = contaminant mass released (mg)
f_r = fraction of sediment resuspended during dredging (dimensionless)
ρ_s = in situ bulk density of the sediment (kg/m^3)
V = volume of sediment being dredged (m^3)
C_s = contaminant concentration in sediment (dry wt) (mg/kg)

Equation 2 is useful as a definition, but it is not as a predictive equation because the fraction of sediment resuspended is difficult to estimate and mass release is more conveniently expressed on a rate basis. To obtain the rate of mass release, the volume of sediment being dredged is replaced with the production rate (cubic meters per second) and m becomes R_D, the mass of contaminant released per unit time (milligrams per second). Alternatively, if an average water column resuspended solid concentration is known over some volume, the rate of contaminant resuspension, R_D, is given by

$$R_D = C_p\, Q_d\, C_s \qquad (3)$$

where:

R_D	=	rate of particulate-associated contaminant release (mg/sec)
C_p	=	suspended solids concentration averaged over a characteristic volume at point of dredging (kg/L)
Q_d	=	volumetric flow of water through averaging volume (L/sec)

The contaminant release rate defined in Equation 3 is based on the total contaminant concentration initially in the in situ sediment and, therefore, includes both particulate and dissolved contaminant fractions. Estimation of the total contaminant release or the release rate per unit time by resuspension of the sediment is thus reduced to estimation of the fraction of particles that are resuspended.

Dissolved Contaminant Releases from Resuspension

Resuspension of sediment solids during dredging can also affect water quality through the release of contaminants in dissolved form. Before resuspension, contaminant distribution between sediment solids and sediment pore water is probably at equilibrium. Dredging exposes sediments to major shifts in liquids/solids ratio and oxidation-reduction potential (redox). Because the sediment solids are removed from the equilibrium conditions previously existing, there is a potential for change in the distribution of contaminant between solid and aqueous phases. Initially upon resuspension, the bulk of the contaminants are sorbed to particulate matter. As the resuspended particulate concentration is diluted by mixing with dredging site water, release of sorbed contaminants to adjacent waters results in a continuous increase in the fraction of contaminants that are dissolved.

It should be noted that the total release of contaminants at the point of dredging is estimated by the equations of the previous section. The dissolved release calculated by the methods of this section largely occurs after the mixing and dilution of the resuspended sediments with the ambient waters. The fraction of the contaminant associated with the particulate phase continues to change as dilution reduces the particle concentration. The majority of the dilution occurs in less than an hour in many systems. However, it may take days for the particles contaminated with hydrophobic organics to achieve a new pseudo-equilibrium with the water column, which is often longer than the settling time for the particles.

In this section, equilibrium partitioning is discussed as a predictive technique for dissolved organic contaminants. Equilibrium partitioning is a conservative approach that may over-predict dissolved contaminant releases by a factor of 2 or 3 and perhaps up to an order of magnitude for some contaminants. Equilibrium partitioning approaches are more appropriate in the far field than in the dredging zone and near field where dilution is occurring rapidly and rapid, pronounced changes in redox of the sediment particles make equilibrium approaches unreliable and uncertain.

The most accurate predictive indicator of dissolved contaminant release during dredging would be a fully developed and verified laboratory test that reproduces the mixing and dilution processes that are observed in the water column after resuspension of contaminated sediments. Such a test would indicate sediment-specific effects on desorption rate and contaminant tendency to desorb. The test would be especially important for elemental species, such as heavy metals, that undergo complex reactions that are not easily predicted by mathematical models. The test would also be important for strongly sorbed hydrophobic organic species that may desorb slowly due to mass transfer resistances. The dredging elutriate test, discussed below, was developed to serve this goal (DiGiano et al. 1995).

In the absence of specific information to the contrary, it seems appropriate to use equilibrium partitioning to establish an upper bound on dissolved organic concentrations at the point of dredging. However, equilibrium partitioning is usually a very conservative assumption. DiGiano, Miller, and Yoon (1993) found that an equilibrium partitioning model did a *good* job of predicting the soluble PCB concentrations. Estimates of the partitioning (distribution) coefficient derived from DRET results for the sediment may provide better predictions. At low contaminant concentrations, equilibrium partitioning between sediment and water can usually be represented by a linear isotherm, that is, $C_{sorb} = K_d\, C_w$, where K_d is a distribution coefficient assumed independent of concentration. Here, C_w is the water phase concentration and C_{sorb} is the concentration of the contaminant sorbed to the solid phase. The sorbed concentration in the solid phase is usually assumed to be approximately equal to the bulk sediment contaminant concentration C_s, so that, $C_{sorb} \approx C_s$ for hydrophobic contaminants.

Using local equilibrium partitioning, the dissolved concentration is given by

$$C_w = \frac{C_s C_p}{K_d C_p + 1} \tag{4}$$

where:

C_w = dissolved phase contaminant concentration (mg/L)
C_s = bulk contaminant concentration in sediment (mg/kg)
C_p = suspended solids concentration averaged over a characteristic volume at point of dredging (kg/L)
K_d = contaminant-specific equilibrium distribution coefficient (L/kg)

The distribution coefficient in Equation 4 can be determined in batch equilibrium tests, estimated using empirical relationships from the literature, or computed from DRET results.

The release rate for dissolved contaminants is the product of the dissolved contaminant concentration averaged over the volume dislodged by the dredge and the volumetric flow through the averaging volume. The dissolved contaminant release rate for a cutterhead dredge is thus given by

$$R_{d,ch} = C_w\, V_t\, \alpha\, H_{ch}\, \beta L_{ch} \tag{5}$$

where Vt is the swing speed of the cutterhead in mm/sec and $\alpha\, H_{ch}\, \beta L_{ch}$ is the effective cross-sectional area of the advancing cutterhead. H_{ch} is the height of the cutterhead in meters and L_{ch} is the length of the cutterhead in meters. α and β account for the fact that the sweep area is typically larger than the cutterhead and are estimated as $\alpha = 1.75$ and $\beta = 1.25$.

Similarly, the dissolved contaminant release rate for a clamshell bucket dredge is given by

$$R_{d,b} = \gamma\, \rho_w \left(L_{bc}\right)^2 \frac{h_b}{\tau_{cb}} C_w \tag{6}$$

where:

γ = Bohlen sweep area correction factor (ranges from 2 to 4)
ρ_w = density of water (kg/m^3)
L_{bc} = average length and width of the bucket (m)
h_b = water depth (m)
τ_{cb} = bucket cycle time (sec)

Several limitations apply to Equations 5 and 6. First, there are little field data for verification of these equations. Second, the equations are not applicable to estimation of dissolved metals releases unless developed from DRET results. In addition, the linear partitioning used in Equations 5 and 6 assumes dissolved phase concentrations much lower than the water solubility limit. Deviations from linear partitioning might be expected when dissolved phase concentrations approach 50 percent of the solubility limit.

The total contaminant release for cutterhead hydraulic and bucket dredges is provided by Equations 5 and 6. Although dissolved losses at the point of dredging represent a small fraction of the total loss for strongly sorbing chemicals, some estimation of dissolved losses may be needed for transport models used to assess impacts and risks and to compare the no-action alternative to dredging and treatment/disposal alternatives. Finally, Equations 5 and 6 predict dissolved concentrations at the point of dredging (the source), not downstream dissolved concentrations. Fate and transport models should be used to predict downstream dissolved concentrations.

Although hydrophobic organic species often partition in the simple manner discussed previously, the release of metals is much more complex. During the development of the standard elutriate test (SET), there was little correlation observed between sediment bulk metal concentration and the dissolved metal concentration at disposal sites or in the standard elutriate. In most cases, dissolved metal concentrations in site water prior to and during disposal operations were about the same (Jones and Lee 1978). In some cases, dissolved metal concentrations were higher in site water prior to disposal operation than after disposal operations (Jones and Lee 1978). These results can often be explained in terms of the aqueous environmental chemistry of iron. Many sediments contain a large reservoir of reactive ferrous iron that readily reacts with oxygen in site water to form amorphorous iron oxyhydroxides. Iron oxyhydroxides tend to floc and scavenge metals. Thus, an adaptation of the SET such as DRET is probably required to get reliable estimates of soluble metal releases during dredging.

Dissolved Contaminant Releases from Residuals

In addition to resuspension as the primary source of contaminants, there are a number of contaminant release sources that may be worthy of consideration for some site conditions, sediment properties, equipment types, and contaminant classes. These additional release sources include:

- release of dissolved contaminants and dispersed solids from densification of 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, and
- Non-Aqueous Phase Liquid (NAPL) exposure.

With the exception of NAPL exposure, these additional release sources have potential to be significant where the contaminants have low partitioning characteristics or where the areal extent of the residuals is large in comparison to the dredging zone. The releases from densification are more important when thick, extensive layers of fluff, fluid mud and residuals are created. Their creation would be both equipment and sediment dependent. Release by molecular diffusion from the residuals increases with porosity of the sediment and the areal extent of the cut face and residuals.

Release predictions computed by the methods given above using DRET data from a test run on a 5 g/L or a 10 g/L suspension of sediment likely incorporates these additional releases. DRET results from tests run on 0.5 g/L or 1 g/L suspensions likely only provide information on releases from resuspension. Care should be taken in selecting the suspension concentration for a DRET to account for the predicted resuspension factor and residual mass. Additional information on the DRET is provided below. In the absence of DRET results, prediction of these additional releases is difficult and very uncertain due to a lack of information on the formation of layers of residuals, the initial solids concentrations of components (spillage, sloughing, settling, etc.) forming the residuals layer and their relative contribution in mass of the layer. If little densification of the layer components occurs, then the release could be estimated by molecular diffusion and pore water advection.

DRET Test

DiGiano, Miller, and Yoon (1995) proposed an adaptation of the standard elutriate test, a dredging elutriate test (DRET), for the purpose of predicting dissolved contaminant releases. The DRET has been verified for only PCBs and at only one site. Therefore, the DRET requires further verification before the test should be unconditionally applied; however, the DRET is the only test available to develop sediment- and operation-specific contaminant release characteristics. The SET was developed during the DMRP to predict contaminant release during open-water disposal operations (Jones and Lee 1978). In the SET, water and sediment are mixed in a proportion of 4:1, mixed for 30 min and allowed to settle for 1 hr. The modifications suggested by DiGiano, Miller, and Yoon (1995) were designed to achieve a more realistic solids/water ratio (0.5 to 10 g/L) consistent with conditions for resuspended sediment due to dredging. DiGiano, Miller, and Yoon (1993) employed an aerated mixing time of 1 to 6 hr and a settling time of 1 hr (0.5 to 24 hr were also investigated). The solids concentration and mixing time should be selected to be representative of the predicted resuspension and dredging operation, respectively.

Typical fine-grained sediment concentrations dispersed by dredge-induced resuspension in the water column are about 0.3 to 2 g TSS/L at a distance of 1 to 3 meters from the dredgehead or bucket. TSS concentrations of 5 to 10 g/L tend to limit dispersion due to density differences with the water column. Typical concentrations, adjusted for the fine-grained fraction of the sediment, should be selected when estimating releases by resuspension alone. When estimating releases by resuspension and residuals, a higher concentration of sediment should be used in the test to account for release of water during densification of the residuals that entrained a large volume of water. The fraction of the residuals mass formed by spillage, density flows and settling should be included in the DRET.

The DRET results provide an estimate of contaminant concentrations near the dredgehead or bucket. In addition, the DRET results can provide an estimate of the non-equilibrium partitioning (distribution) coefficient for estimating short-term dissolved releases. The partitioning coefficient can be computed from the DRET results as follows

$$K_d = \frac{(C_s\ C_{test}) - C_w}{C_w\ C_{test}} \tag{7}$$

where:

- C_w = aqueous phase (dissolved) contaminant concentration (mg/L)
- C_s = bulk (total) contaminant concentration in sediment (mg/kg)
- C_{test} = solids concentration in the test (kg/L)
- K_d = contaminant-specific, non-equilibrium distribution coefficient (L/kg)

The DRET was evaluated by comparison to field dredging studies conducted in New Bedford Harbor, Massachusetts. The DRET was found to be a reasonable indicator of the soluble and total (soluble plus unsettled particulate) PCB concentrations released during cutterhead or matchbox suction dredging, but the DRET underpredicted PCB concentrations when a horizontal auger dredge head was used. The New Bedford Harbor studies involved highly contaminated sediment at an estuarine location. Extrapolation of the New Bedford Harbor results to freshwater sites with one to two orders of magnitude lower contamination levels is not technically defensible at this time. Where feasible, additional testing/verification of DRET should be performed and the DRET results should not be used as the sole basis of evaluation and design.

Contaminant Volatilization to Air

Another potential route of contaminant release during dredging or excavation is volatilization of contaminants, either near the dredge or excavation site or in a holding facility like a confined disposal facility (CDF) (Chiarenzeli et al. 1998). At sites with high concentrations of volatile contaminants, dredging or excavation might present special challenges for monitoring and operational controls if volatile contaminants pose a potential risk to workers and the nearby community.

The EPA GLNPO ARCS Program published guidance on "Estimating Contaminant Losses from Components of Remediation Alternatives for Contaminated Sediments" (U.S. EPA 1996), which provides methods to compute volatilization from water bodies, barges, tanks, and disposal facilities, both ponded and dewatered based on theoretical chemodynamic models developed by Thibodeaux (1989). These computational approaches have been incorporated into volatilization screening methodology of the Evaluation of Dredged Material Proposed for Disposal at Island, Nearshore, or Upland Confined Disposal Facilities — Testing Manual (better known as the Upland Testing Manual) (USACE 2003).

After computing contaminant flux by volatilization, the dispersion of contaminants in the air can be modeled using commonly available air dispersion models to calculate exposure concentrations required to estimate air borne risks. Numerous air dispersion models are available ranging from steady-state, area source, Gaussian models for simple terrains such as EPA's SCREEN3 (U.S. EPA 1995c) to more complex 3D models such as EPA's AERMOD (U.S. EPA 2004b).

Volatilization Flux Test

Predictions of volatilization flux can be improved using a laboratory test to measure volatilization from dilute suspensions of contaminated sediment and from exposed sediment samples. The test yields volatilization constants specific to the sediment (partitioning constants including Henry's constant). Guidance on the conduct of volatilization flux tests is found in the Upland Testing Manual (USACE 2003).

Table of Contents

Fate and Transport Models

A wide range of simpler empirical models and more robust computer models can be applied to model the fate of contaminants and associated particulates. Fate and transport models for contaminants are particularly useful to illustrate how contaminant concentrations will vary spatially at a site; to predict contaminant fate and transport over long periods of time (e.g., decades) or during episodic, high-energy events (e.g., tropical storm or low-frequency flood event); and to predict future contaminant concentrations in sediment, water and biota for evaluating relative differences among the proposed remedial alternatives, including capping of residuals (U.S. EPA 2005). Simple models that aggregate processes or consider only some portion of a problem can provide significant insights and should be applied routinely at sediment sites, even complex sites. These models are particularly useful in modeling resuspension and release at the source, and the dispersion and settling in the dredging zone and the near field. The USACE DREDGE (Hayes and Je 2000) and RECOVERY (Ruiz et al. 2001) models are good examples of screening level models that aggregate and integrate processes. Simple mass balance and equilibrium partitioning models of the residuals and sediment can help define the contaminant mass release from pore water, and areal extent and volume of the source. While useful, these screening level approaches need to be further developed to greater predictive accuracy.

Often a complex fate and transport model is developed for a site in order to more fully understand the potential future risks of a site and to verify a site conceptual model. These models can be quite useful in predicting the fate of contaminants in the far field. Comprehensive technical reviews of available models have been conducted for the EPA's ORD National Exposure Research Laboratory (Imhoff et al. 2003). Complex processes such as non-equilibrium partitioning, particle interactions with the sediment bed, and biogeochemical transformations in unsteady flow regimes are best modeled using more complex fate and transport models. However, if a project-specific complex fate and transport model is never developed, simple modeling can be used to develop a better understanding of the resuspension and release processes by incorporating unsteady features and variable parameter descriptions. As described by EPA (U.S. EPA 2005), whether and when to use a model and what models to use are site-specific decisions and modeling experts should be consulted.

SUMMARY OF PREDICTIVE METHODS FOR RESUSPENSION, RESIDUALS AND RELEASE

This paper presented methods for prediction and evaluation of the resuspension of sediment due to dredging, contaminant release from dredging, and residuals of dredging. The predictive methods presented in this chapter are empirically based on limited data sets of actual field measurements. Much of the data were collected for conventional navigation dredging projects; nevertheless, all environmental dredging operations also resuspend sediment, generate residuals and release contaminants, although newer equipment and methods can provide improvements over results achieved with conventional navigation equipment. Considerable field measurements of resuspension and residuals have been made, but these empirical observations have limited predictive value for other locations without a comparison of site and sediment properties. Nevertheless, these field observations provide the basis for prediction of resuspension and residuals. Field measurements of contaminant release are very limited; therefore, predictive methods for contaminant release to the water column and air are based on the laboratory tests and theoretical models. Full-scale pilot studies using the anticipated equipment and operation can be particularly useful for developing site-specific information and estimates and to verify predictions of the magnitude and characteristics of these processes. Resuspension, residuals and release prediction methodologies serve as source strength inputs for fate and transport models to predict solids behavior, contaminant release and contaminant concentrations/exposure for risk calculations.

ACKNOWLEDGEMENTS

This paper summarizes results of studies conducted by the U.S. Army Corps of Engineers, Center for Contaminated Sediments, at the U.S. Army Engineer Research and Development Center, Waterways Experiment Station, for the U.S. Environmental Protection Agency. Permission to publish this material was granted by the Chief of Engineers.

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