# ENVIRONMENTAL DREDGING – A STATE OF THE ART REVIEW

Michael R. Palermo, U.S. Army Engineer Research and Development Center, Waterways Experiment Station, Vicksburg, MS, USA.
Daniel E. Averett, U.S. Army Engineer Research and Development Center, Programs Office, Alexandria, VA, USA.

ABSTRACT

Sediment removal or "environmental dredging" is a commonly selected alternative for remediation of contaminated sediments. Environmental dredging using several equipment types and approaches, followed by treatment and disposal of the contaminated material, has been accomplished at a number of sites. This option is also currently being considered for some of the largest and most controversial contaminated sediment projects in the U.S. This paper reviews technical considerations for environmental dredging and summarizes the state of the art with respect to equipment selection and operational practice.

RESUME

L'enlèvement des sédiments ou le "dragage environnemental" est une alternative communément choisie pour la restauration des sédiments contaminés. Le dragage environnemental en utilisant divers types d'équipements et approches, suivit du traitement et de la disposition du matériel contaminé a été utilisé sur de nombreux sites. Cette option est aussi couramment considérée pour quelques-uns des projets les plus grands et les plus controversés de sédiments contaminés aux États-Unis. Cet article résume sommairement les considérations technologiques pour le dragage environnemental et l'état de l'art concernant le choix de l'équipement et de la pratique opérationnelle..

## 1. INTRODUCTION

Many sediment remediation projects require the removal of contaminated sediments from a waterbody prior to treatment or disposal. The term "environmental dredging" has come into common use for describing this process. Although dredging has been conducted for centuries to maintain navigation depths in harbors and waterways, the concept of environmental dredging is a relatively new one. In this paper, the state of the art for environmental dredging is summarized, based on field experience and published information from projects executed to date in the U.S.

Much of the publicly available information on environmental dredging based on cleanup experience has been developed within the past 10 years. The U.S. Environmental Protection Agency (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 published additional general information in 2002 (USEPA 2002a). 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, and NAS 2000). But to date, detailed information for selecting equipment, designing operational strategies, and predicting effectiveness has been largely site-specific; and, comprehensive technical guidance on environmental dredging is lacking.

## 2. ENVIRONMENTAL DREDGING PROCESSES

The major considerations for environmental dredging include the following:

- Objectives, goals, and performance standards for the project,
- Equipment availability and selection,
- Removal rate and precision of removal,
- Resuspension of sediment during the dredging process,
- Release of dissolved contaminants to water or volatilization of contaminants to air due to resuspension,
- Residual contaminated sediment left in place following the dredging operation, and
- Transport of the dredged material for subsequent treatment or disposal.

Each of these aspects must be appropriately evaluated in selecting environmental dredging as a remedy component, in determining the optimal equipment and operational approach, and in determining the potential effectiveness of environmental dredging. And, some of these processes must be considered for environmental dredging in a manner different than for navigation dredging. Further, these processes are interrelated.

## 3. OBJECTIVES, GOALS AND STANDARDS

All decisions for a sediment remediation project should be risk-based (USEPA 2002b), and environmental dredging should be considered as part of a comparative risk assessment of all practicable alternatives. Remedial action objectives for a project should be based on reduction in risk (e.g., reduction in cancer risk to fishers). Remediation goals (e.g. reduction in fish tissue concentrations) are then developed to support the objectives. Cleanup levels (in terms of contaminant concentrations in the sediment) may then be established to meet the goals. The objectives, goals, and cleanup levels should all be based on the need to achieve risk reduction at the site (USEPA 2002a and 2002b). A successful environmental dredging project should modify the exposure component of the risk model through removal of the contaminated sediment and reduction in sediment concentrations such that the cleanup level is met. Performance standards are needed to measure success.

Performance standards (what the environmental dredging process is required to do) versus operational efficiency (what the process can efficiently do for the given project conditions) is a major issue. The success of an environmental dredging project can be defined as the degree to which the project objectives and performance standards are met. Conversely, the way in which performance standards are set is a major factor in determining the efficiency and potential for success of the project.

Performance standards for environmental dredging may include or be based on some combination of the following:

- Mass removal of contaminated sediment exceeding a specified contaminant concentration,
- Removal of sediments to a specified elevation within specified areas,
- Limits on the surficial sediment concentration remaining as residual following dredging,
- Limits on sediment resuspension generated by the operation,
- Limits on contaminant releases, and
- Limitations on solids content and/or volume throughput for subsequent treatment or disposal.

Recent studies of completed projects (MCSS Database 2001; ReTec 2001; and Cushing and Hammaker 2001) found that the performance standards varied considerably, with many focused solely on achieving mass sediment removal or removal to a specified cut line elevation. Others included standards related to a residual sediment concentration. The field experience to date indicates that projects with standards set in terms of mass removal or set cut elevations have been largely successful in meeting those standards. Success has been mixed for projects with standards set in terms of a low residual surface concentration. Further, the overall experience base with larger scale projects is limited (Francingues 2001). The limitations of the environmental dredging process should therefore be considered carefully in selecting removal as a remedy or remedy component for a given project and in developing performance standards.

Performance standards for resuspension and release are related to the short-term effectiveness of an environmental dredging remedy. Since the areas requiring environmental dredging are contaminated and risk to human health and/or the environment already exists at the site, project managers should consider that some short-term impacts resulting from environmental dredging may be required to reap the long-term benefits of the remedy. This is consistent with USEPA's newly issued Sediment Management Principles (USEPA 2002b).

Standards for mass removal and residual are related to long-term effectiveness of the remedy. These standards must be attainable in an operationally efficient manner. Standards requiring an unlimited number of passes of the dredge to achieve a very low residual concentration are inefficient and costly. Project managers should consider limiting the number of required passes and providing an option for placement of a residual cap of clean material to achieve a residual standard. This brings more certainty into the process of cost estimating and bidding.

## 4. EQUIPMENT AVAILABILITY AND SELECTION

Most dredges remove sediment using mechanical or hydraulic processes. Dredges used for navigation dredging, commonly called "conventional" dredges, can be successfully used for environmental projects; but, a number of newer dredge designs, including dredges specifically designed for environmental dredging, are now available. These "specialty" dredges can provide benefits with respect to reductions in resuspension and release, and operational efficiency for removal and transportation, depending on the sediment and project conditions and the performance standards.

The type and size of dredge selected for a particular project depends on a number of factors, including: volume to be dredged; site conditions such as water depth and current and wave climate; physical and chemical characteristics of the sediment; presence of debris, vegetation, or loose rock; physical site constraints such as bridges or waterway widths; distance to the disposal site; treatment and disposal methods; availability and cost of equipment; and the performance standards for the operation. Because the dredge must be capable of meeting the performance standards in an efficient manner, all these factors should be considered, and the environmental and operational trade-offs should be clearly identified and appropriately balanced (Palermo, Francingues and Averett 2003).

Environmental dredging projects are now almost exclusively conducted with smaller conventional equipment sizes and newer designs. U.S. dredge designers, manufacturers, and dredging contractors are making significant contributions, and many international dredging companies have now formed partnerships with U.S. companies, allowing for use of specialty equipment from a variety of countries. However, field experience in the U.S. with specialty dredges is still limited (Cushing and Hammaker 2001).

5. REMOVAL PRECISION AND PRODUCTION

Production and precision will both determine the efficiency of the removal process for an environmental dredging project. Production refers to the rate of removal of sediment from the waterway, usually measured in in-situ volume of sediment removed per unit time. For many environmental dredging projects, the thickness of sediment requiring removal is not large, and smaller equipment sizes with lower production rates as compared to large navigation projects are commonly used. However, removal of the contaminated sediments in a reasonable time is usually one performance objective for an environmental dredging project, so an efficient production rate is important.

The production requirements for environmental dredging for a given set of project conditions can be evaluated in the same general manner as for conventional navigation dredging, and methods commonly used for calculation of production rates for navigation dredging can be adapted for environmental projects. However, production must be evaluated in the context of constraints related to resuspension and release and on constraints on the rate of transport, treatment, or disposal. Multiple dredges may be needed to meet a production standard if other factors limit the size or production of a single dredge.

The method of operation of a given dredge is also a consideration in achieving efficient production while minimizing resuspension and release. For example, slower operation may slightly reduce the rate of resuspension but will prolong the time required for removal. So, slower operation does not necessarily result in lower overall resuspension and release. Use of skilled operators is a key consideration in this regard (Francingues 2001).

Precision refers to the ability of the equipment to remove the sediment intended for removal without excessively removing clean material. Excessive removal of clean material should be minimized, since that volume of sediment must also be managed, usually at relatively high cost. So, the ability to precisely locate the dredge plant, specifically the dredgehead (that part of the equipment in direct contact with the sediment during dredging), both horizontally and vertically, is critical. Precise location of the dredgehead establishes the cut line in the sediment. The precision of locating a dredge or dredgehead has been greatly improved in recent years with improvements in electronic positioning technology, e. g., Differential Global Positioning Systems (DGPS). Transponders may be located at critical points on the dredge (such as at the top of a crane boom) or directly on the dredgehead to improve accuracy.

The current conventional wisdom on precision positioning is that, depending on site conditions, and size and type of dredge, the dredgehead and cut elevation can be set within an accuracy of several inches (Palermo, Francingues, and Averett 2003). Considering this level of precision, environmental dredging can accurately remove the mass of contaminated sediment from a waterbody under most project conditions.

However, dredge positioning accuracy does not necessary translate to the same precision for the dredge cut itself, and the sediment removed does not necessarily correspond exactly with that lying above the cut line. The mechanical forces of the dredging process cause mixing of sediments below the cut line and the dredging process cannot remove all the sediment that is cut (residual is discussed further in Section 8).

It is also important to note that the benefits of accurate positioning are realized only when there is a corresponding level of accuracy in the sediment and site characterization data. A site investigation with accurate horizontal and vertical control on data locations is essential. Referencing data locations to elevation is also an important consideration. In some cases, the ability to accurately locate the cut has outstripped the accuracy of the sediment data.

6. RESUSPENSION DUE TO DREDGING

All dredges will resuspend some sediment. And when sediment is resuspended, the particles are subject to transport and dispersion by currents. Although the contaminants normally of concern in sediments tend to be tightly bound to sediment particles, the resuspension of sediment will also result in some release of dissolved contaminants in the water column and volatilization of contaminants to the air. A variety of models and laboratory tests are available for evaluation of sediment resuspension and contaminant release due to dredging operations, but, until recently, the process of sediment resuspension has received much more attention than the associated contaminant releases.

It is important to distinguish between that portion of the sediment that is cut and dislodged by the dredgehead and left as residual and that portion that is dislodged and becomes resuspended to the water column. A portion of the sediment that is dislodged but not picked up by the dredging process may remain as cohesive chunks and will quickly fall to the bottom at the point of dredging without being dispersed. This material is commonly called “spill” or “fallback”. An example of fallback is the chunks of sediment falling from an overfilled open bucket or from the outside of the bucket before the load is placed in a barge. Such material will contribute to a residual layer at the dredging area.

A portion of the dislodged sediment not picked up by the dredging process will become dispersed in the water column and will be transported by current as a suspended solids plume. This portion is the resuspended sediment. The available data on the magnitude of the resuspension “source strength”, or the mass of sediment resuspended per unit time, are based on field measurements of suspended solids at points near an operating dredge. However, there is no common standard for such measurements, and a more rigorous and consistent definition of resuspension and the methods for data collection are needed so that data among projects may be compared and predictive capability improved (Burt and Clausner 2002).

Fortunately, the mass of sediment resuspended by dredging is small compared to the mass of sediment removed. Based on a recent analysis of field studies and available predictive models, the mass of sediment resuspended is generally limited to less than one percent of the mass dredged (Hayes and Wu 2001).

Much of this resuspended material will settle out within a distance of a few hundred meters of the dredging operation, and may contribute to a residual layer, in some cases outside the dredging area. Because the particles will resettle within a short distance, sediment resuspension is a near-field process, and can be more easily managed as compared to dissolved or volatilized contaminants.

The magnitude of resuspension due to dredging should be placed in context with other sediment resuspension events or sources. For example, the overflow from a barge will generate a large amount of sediment resuspension (consequently, overflow would not normally be allowed for an environmental dredging project). Boat traffic, movement of silt curtains, and other activities ancillary to the dredging can also be a source of resuspension and should be carefully managed. Storms or vessel traffic will occur on a recurring basis and cannot be controlled. In most cases the resuspension due to dredging is small in comparison to that generated by even a high-frequency storm event. But, the potential for contaminant release due to dredging resuspension may differ from other sources, if sediments from deep layers with high contaminant concentrations are resuspended by dredging.

Resuspension can be minimized by proper equipment selection, modifying equipment, modifying the operation of the equipment, or by containment of re-suspended sediment using barriers or silt curtains. Equipment selection is sometimes limited by availability, but operational controls can be considered for a wide range of equipment types. Containment of re-suspended sediment by barriers, such as silt curtains or screens, is most effective in relatively quiescent waters. Operational constraints imposed by the presence of a barrier or curtain may increase costs and reduce production, and depending on the conditions, be of marginal effectiveness. Also, residual and resuspended sediment may build up within the contained area, and may cause problems when the barrier is removed.

## 7. RELEASE OF CONTAMINANTS

Resuspension of sediment will also result in release of contaminants to the dissolved phase in the water column by release of porewater and by desorption from suspended sediment particles. Depending on the contaminant, subsequent releases to the air through volatilization may also be a concern. Also, floating oils are sometimes released to the water column during the dredging process, providing another avenue for contaminant transport. Fortunately, contaminants normally associated with sediments tend to remain tightly bound to fine-grained sediment particles, so control of sediment resuspension will also help in control of contaminant release. However, once in the dissolved phase, or in air, released contaminants are subject to far-field transport. So, releases to the dissolved phase or to air result in different exposures and risks than suspended sediment particles, and should be appropriately evaluated.

The field data collected to date in both demonstration projects and full-scale cleanups indicate that environmental dredging can be effective in removing contaminated sediment without excessive resuspension and contaminant release. However, these studies for the most part did not address residual sediment.

## 8. RESIDUAL SEDIMENT

All dredges will leave some residual, regardless of the precision of the cut. The mechanical action of the cut will plow and mix sediment with underlying sediment, dislodged sediment not picked up by the dredge will quickly settle to the bottom at the point of dredging, and resuspended sediment transported as a plume will settle to the bottom at some distance. It has become clear with field experience that residual sediment is a major issue, directly affecting cost and effectiveness of environmental dredging. Several projects have experienced residual concentrations in surface sediments exceeding cleanup levels after many passes of the dredge.

Unfortunately, there is no commonly accepted method to predict the degree of residual sediment resulting from a given dredge type removing a given sediment type under given site conditions. Residual will vary depending on dredge design, method of operation, sediment type, contaminant concentrations, site hydrodynamics and conditions, presence of debris or loose rock, and other factors. Quality data on residual thicknesses and concentrations are available for only a few projects. And, the basis for monitoring residual has varied considerably across projects. In most cases, the measurement of a residual concentration is based on analysis of a specified surficial sediment thickness collected by coring. The ability of a core sampler to capture a fluffy thin veneer of residual sediment and the method of handling the core sample can greatly affect the monitoring results. Monitoring data for residuals collected in a consistent manner and across a range of project conditions is needed to allow for a better predictive capability and better decisions on future projects.

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 first passes of the dredge, followed by passes used for "cleanup". A cleanup pass is more likely to result in lower residual if conditions allow for removal of a minimal overdredge thickness of cleaner material below the limits of contamination as part of the cleanup pass (contamination lying directly on bedrock is problematic in this regard). There is generally diminishing operational efficiency with multiple cleanup passes, since they will require taking a higher proportion of underlying clean sediment. In some cases, use of a different dredge for the cleanup pass as compared with the mass removal pass may be warranted. As mentioned above, placement of a thin residual cap is another method of achieving cleanup levels, and this option is being considered for several projects.

## 9. TRANSPORT FOR DISPOSAL OR TREATMENT

Although much attention has been focused on resuspension, release, and residual for environmental dredging projects, a major consideration in selection of equipment and operational approach is the method for transporting the sediment and the compatibility of that method with subsequent treatment and/or disposal requirements. Treatment and disposal of the dredged material accounts for a major proportion of the total cost of remediation projects. Typically, there is a "process train" for dredging, transport, rehandling, pre-treatment, treatment, and ultimate disposal. The environmental dredging process must be compatible with the initial transport, rehandling, and pre-treatment steps. Depending on the equipment selected for dredging and the approach to rehandling and transporting sediment, the dredging process will result in a given throughput rate and solids content of the dredged sediment. For some equipment types, transportation could be viewed essentially as a separate process (e.g. the transportation by barges filled with mechanical dredges). In other cases, the transportation process is inherent to the removal process, as in the case of hydraulic dredging with pipeline transport directly to the next process step. But there are many other combinations.

Transportation methods must be considered in light of the distance to the treatment/disposal location, and the optimal condition for the material arriving at that location. In general, mechanical dredging methods remove the sediment with resulting water contents close to the in situ conditions. Hydraulic dredging for navigation typically adds about four volumes of excess water for every volume of in situ sediment removed. Even more water may be entrained during environmental dredging due to constraints on cutting depth, contaminant releases, or other operational parameters. Each of these options holds advantages and disadvantages for subsequent sediment transport, treatment, and disposal. Dewatering of the sediment prior to disposal is a requirement in many cases, and mechanical dredging has advantages in this regard. But for treatment or disposal sites located inland, mechanical dredging would require double or triple handling of the material. Hydraulically dredged material can be pumped directly to the site, but the dewatering process will produce a large volume of water requiring treatment.

Several recent equipment innovations can mitigate the problems related to rehandling and/or excess water production and subsequent treatment requirements. These include newer pump designs for increased solids concentrations, use of dual pipelines for hydraulic re-slurry of mechanically dredged material from barges, (one for transport to the treatment/disposal site, with another for return of excess water for subsequent re-use), and the use of hybrid dredging and transport combinations (e.g., mechanical dredging with dual pipelines for reslurry directly from the dredging site).

The dredging method that may result in the least resuspension, release or residual may not result in a production or density of dredged material most suitable for efficient or economic treatment or disposal. Usually, a balancing of considerations is needed between the potential for increased resuspension, release, and residual and the overall benefits of a given method as related to treatment or disposal.

## 10. CONCLUSIONS

The "state of the art" on environmental dredging, based on the publicly available information and project experience in the U.S. to date can be summarized as follows:

- Project managers should carefully consider the principle of risk reduction and the capabilities and limitations of the environmental dredging process in selecting a dredging remedy and in setting performance standards. In this way, an efficient balance between operational efficiency and control of resuspension, release, and residual can be achieved.

- A wide range of mechanical and hydraulic dredging equipment is available and generally suitable for environmental dredging projects.

- Mass sediment removal or removal to a specified elevation are achievable for environmental dredging. Production rates can be evaluated using the same general methods now commonly used for navigation dredging.

- Precision removal of contaminated sediment without excessively removing clean material is critical for effective environmental dredging. Positioning technology now allows a dredging cut line to be set within an accuracy of several inches. Appropriately detailed site and sediment data are essential for realizing benefits of dredging accuracy. Data locations for both physical and chemical sediment parameters should be precisely located both horizontally and vertically.

- All dredges resuspend some sediment, but removal can be achieved at an efficient rate with minimal resuspension rates. Field data indicates the mass of sediment resuspended is generally less than 1% of the mass dredged. Operational and engineering control measures can be applied to further reduce the impacts of sediment resuspension.

- Sediment resuspension results in release of dissolved contaminants to the water column and release to the air through volatilization. Such releases are subject to far field transport and the resulting exposures and risks should be appropriately evaluated.

- All dredges will leave behind some residual, but the magnitude of residual is difficult to predict. Residual sediment is a major issue, directly affecting cost and effectiveness of environmental dredging. A removal pass of the dredge, followed by a cleanup pass with minimal overdredging can result in lower residual concentrations; but, multiple cleanup passes generally have diminishing efficiency. Placement of a residual cap of clean material should also be considered as an option to achieve a residual standard.

- The dredging method and the transportation of dredged sediment to the disposal site may be considered as separate processes; but, they must be compatible with subsequent rehandling, pre-treatment and ultimate treatment and disposal.

- Detailed information on environmental dredging is largely site-specific, and only general guidance for project managers is presently available. Comprehensive technical guidance on equipment selection, design of operational strategies, and methods for prediction of effectiveness is needed. The USACE and USEPA are presently developing such guidance.

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