WESTERN DREDGING ASSOCIATION
(A Non-Profit Professional Organization)

Journal of Dredging Engineering

Volume 6 No. 3, December 2004
Official Journal of the Western Dredging Association

IN THIS ISSUE

AIMS & SCOPE OF THE JOURNAL

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects and case studies.

OPERATIONAL CHARACTERISTICS AND EQUIPMENT SELECTION FACTORS FOR ENVIRONMENTAL DREDGING

Michael R. Palermo,[1] Norman R. Francingues,[2] and Daniel E. Averett[3]

ABSTRACT

Environmental dredging is a critical component for many sediment remediation projects. Mechanical, hydraulic, and specialty dredges have been used for these projects. The major considerations in selecting equipment for environmental dredging include: removal efficiency, resuspension of sediment and contaminant release during the dredging process, residual sediment left in place following dredging, and compatibility with transport/disposal/ and/or treatment options. Selection of the proper equipment type and operational approach for a given site usually requires a balancing of these considerations. Field experience and monitoring data for an increasing number of sites are providing the basis for more informed equipment selection decisions. This paper provides an evaluation of the capabilities and advantages and disadvantages of various equipment types commonly considered for environmental dredging, considering published field experience. A list of specific factors related to removal efficiency, resuspension and release, residual sediment, and compatibility with disposal is provided along with discussion of the relative effectiveness of the various equipment types in addressing each of the factors. This information is being incorporated in newly developed EPA guidance for sediment remediation and environmental dredging.

INTRODUCTION

"Environmental dredging" may be defined as the removal of contaminated sediments from a waterbody for purposes of sediment remediation. There is a range of considerations in selecting environmental dredging as a remediation approach, and the decision to dredge should be based on an unbiased evaluation of all the possible remedy options and their associated risk reduction benefits. The evaluation, design and application of environmental dredging involves many different aspects, and much of the cost and complexity for an environmental dredging remedy are associated with transportation, treatment, and disposal of dredged sediments and associated carrier water rather than the dredging component. However, the effectiveness of the

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[1] Consulting Engineer, Mike Palermo Consulting, 3046 Indiana Ave., Suite R, PMB 204, Vicksburg, MS 39180, 601-831-5412, Email: mike@mikepalermo.com
[2] Senior Consultant, OA Systems Corporation, 100 Redbud Circle, Vicksburg, MS 39180, 601-636-3805, Email: Stormin@canufly.net
[3] Environmental Engineer, U.S. Army Engineer Research and Development Center, Programs Office, Alexandria, VA 22315, 703-428-9120, Email: Daniel.E.Averett@HQ02.usace.army.mil

environmental dredging process itself, particularly the incremental benefits of additional dredge passes, continues to be a major subject of debate for these projects.

Dredging equipment selection is an important consideration in alternative evaluation, design, and implementation phases of an environmental dredging project. In each of these phases, the suitability of equipment must be evaluated and specific equipment must be selected. Although technical guidance of a general nature is available for environmental dredging and for equipment selection (EPA 1994; Herbich 1995; Mohan 1998; EPA 2002a; Palermo and Averett 2003), comprehensive technical guidance on environmental dredging and detailed information for selecting equipment are lacking.

The information described in this paper builds on earlier referenced summaries of equipment capability and selection factors. This paper provides an evaluation of the capabilities and advantages and disadvantages of various equipment types commonly considered for environmental dredging, using published data and best professional judgment. A list of specific factors related to removal efficiency, resuspension and release, residual sediment, and compatibility with disposal is provided along with discussion of the relative effectiveness of the various equipment types in addressing each of the factors. In developing the information in this paper, the authors realized that there were no consistent definitions for the various factors related to environmental dredging equipment suitability. An attempt has therefore been made to define what the factors are and how they relate to selection of equipment.

ENVIRONMENTAL DREDGING EQUIPMENT AND PROCESSES

Factors that affect the selection of the type and size of dredge for a given project include 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, loose rock, or underlying bedrock; 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. Specifically, removal efficiency, resuspension of sediment and contaminant release during the dredging process, residual contaminated sediment left in place following the operation, the need for multiple cuts or cleanup passes, the need to minimize overdredge volumes, and compatibility with transport/disposal/ and/or treatment options must be considered with respect to these factors.

Another critical component of equipment selection is performance standards chosen for an environmental dredging project. Standards for environmental dredging projects may include or be based on some combination of: 1) Removal of contaminated sediment exceeding a specified contaminant concentration, 2) Removal of sediments to a specified elevation within specified areas, 3) Limits on the surficial sediment concentration remaining as residual following dredging, 4) Limits on sediment resuspension generated by the operation, 5) Limits on water column contaminant concentrations, and 6) Limitations on solids content and/or volume throughput for subsequent treatment or disposal (Palermo and Averett 2003). Additional performance standards may be imposed for "quality of life considerations" such as minimizing the duration of the project, minimizing noise or light, or restricting operations to specific times of the day or days of the week. In order for the dredge to meet the performance standards in an efficient manner, the environmental and operational trade-offs should be clearly identified and appropriately balanced taking into account the above factors. Available monitoring data indicate that standards have been generally met for projects with standards set in terms of mass removal or set cut elevations, while success has been mixed for projects with standards set in terms of a low residual surface concentration (Blasland, Bouck and Lee 2001; ReTec 2001; and Cushing and Hammaker 2001). Further, the overall experience base with larger scale projects is limited (Francingues 2001).

The selection of equipment and approaches for environmental dredging cannot be evaluated as a stand-alone component of a sediment remedy. Components to be evaluated when considering an environmental dredging remedy include removal (the environmental dredging component); transport and storage (rehandling); treatment (pretreatment, treatment of decant and/or dewatering effluents and sediment, and potentially separate handling and treatment requirements for different materials such as TSCA versus Non-TSCA); and disposal (liquids and solids) (USEPA 2002a). The environmental dredging component must be compatible with the components subsequent to the removal operation. The treatment and disposal options under consideration, size and capacity of disposal sites, distance from dredging site to treatment or disposal sites, and constraints associated with throughput for transport, storage, rehandling, treatment, or disposal will be major factors in selecting compatible dredging equipment and approaches. In many cases, the inefficiencies experienced at environmental dredging projects result from constraints associated with components of the remedy other than the dredging component.

Although the processes and requirements for environmental dredging are complex, a wide variety of dredging equipment types and designs are available for environmental dredging projects. In developing the information for this paper, a breakdown or categorization of the basic types of dredging equipment most commonly used for environmental dredging in the U.S. was required. Both conventional hydraulic or mechanical dredges used in navigation dredging can be successfully used for environmental projects. Specific modifications to conventional dredges or new designs for environmental dredging have resulted in the term "specialty" dredges. Some of the newer designs have become more commonly available in recent years. The following list of equipment types and definitions was developed based on the available published literature:

- Clamshell – conventional clamshell dredges, wire supported, conventional open clam bucket.

- Enclosed bucket – wire supported, near watertight or sealed bucket as compared to conventional open bucket (recent designs also incorporate a level cut capability as compared to a circular-shaped cut for conventional buckets, e.g. the Cable Arm and Boskalis Horizontal Closing Environmental Grab).

- Articulated Mechanical – backhoe designs, clam-type enclosed buckets, hydraulic closing mechanisms, all supported by articulated fixed-arm (e.g., Ham Visor Grab, Bean Hydraulic Profiling Grab (HPG), Toa High Density Transport, and the Dry Dredge).

- Cutterhead – conventional hydraulic pipeline dredge, with conventional cutterhead.

- Horizontal auger – hydraulic pipeline dredge with horizontal auger dredgehead (e.g., Mudcat).

- Plain Suction – hydraulic pipeline dredge using dredgehead design with no cutting action, plain suction (e.g., cutterhead dredge with no cutter basket mounted, Matchbox dredgehead, articulated Slope Cleaner, Scoop-Dredge BRABO, etc.)

- Pneumatic – air operated submersible pump, pipeline transport, either wire supported or fixed-arm supported (e.g., Japanese Oozer, Italian Pneuma, Dutch "d", Japanese Refresher, etc.)

- Specialty Dredgeheads – other hydraulic pipeline dredges with specialty dredgeheads or pumping systems (e.g., Boskalis Environmental Disc Cutter, Slope Cleaner, Clean Sweep, Water Refresher, Clean Up, Swan 21 System, etc.).

- Diver assisted – hand-held hydraulic suction with pipeline transport.

- Dry Excavation – conventional excavation equipment operating within dewatered containments such as sheet-pile enclosures or cofferdams.

Note that this list is not inclusive of all available dredge types. Dredge types such as hopper dredges, dustpan dredges, bucket-ladder dredges, etc., that were included in earlier evaluations, are not included here since they are primarily used for navigation dredging. Also, within dredge types, specific designs may differ and may have varying capability. In general, the dredge types listed above reflect equipment that is readily available and used for environmental dredging projects in the U.S. The specialty dredge category is the exception in that it embraces a number of dredge types especially designed for environmental work. Most of these specialty designs originated outside the U.S., but several U.S. companies have now formed partnerships allowing for use of specialty equipment from a variety of countries. Only a few specialty dredges have been applied to U.S. projects, so field experience in the U.S. is still limited (Cushing and Hammaker 2001).

Importantly, the equipment used for environmental dredging is usually smaller in size than that commonly used for navigation dredging, because the removal volumes tend to be smaller and dredge depths tend to be shallower. For this reason, the information presented in this paper is generally tailored for mechanical bucket sizes from 2 to 8 cubic meters (about 3 to 10 cubic yards), and hydraulic pump sizes from 15 to 30 cm (about 6 to 12 inches). Of course, larger dredge sizes are available for both mechanical and hydraulic equipment types and can be used for environmental dredging if needed.

EQUIPMENT CAPABILITIES AND SELECTION FACTORS

Table 1 summarizes the information on operational characteristics and equipment selection factors developed for and presented in this paper. The first section of Table 1 contains *quantitative* entries related to specific operational characteristics (both capabilities and limitations) for the dredge types listed and defined above for conditions likely to be encountered for many environmental dredging projects. These operational characteristics reflect what the given dredge type is capable of doing, and are largely a function of the equipment itself. The numbers are not representative of all dredge designs and sizes. Earlier versions of such information were developed for specific projects or specific purposes (Hand et al 1978; Philips and Malek 1984; Palermo and Pankow 1988). These earlier tables included information on dredge types and larger dredge sizes commonly used for navigational dredging. Several literature reviews and summaries of such information have also been developed for environmental dredging (Averett et al 1990; Herbich and Brahme 1991, Herbich 1995, and Herbich 2000). Versions of this information focusing solely on the smaller sizes and types of dredges more commonly used for environmental dredging were included in the EPA Assessment and Remediation of Contaminated Sediments (ARCS) Remediation Guidance Document (EPA 1994) and the Draft EPA Superfund Sediment Guidance (EPA 2002a).

Table 2 provides a summary of reported data on *quantitative* dredge operational characteristics with supporting references. This table includes citations from the readily available literature, but should not be considered comprehensive in that proprietary information or data from specific projects in dredging contractor files and client reports were not available for this review. Also, many of the projects cited in Table 2 were field pilot projects, and may not reflect the efficiencies that may be gained for a full-scale project. Even with these limitations, the information in Table 2 attempts to provide a technical basis for the dredge operational capabilities and limitations shown in Table 1. The quantitative dredge operational characteristics in Table 1 are essentially bracketed by the range of values based on field experience.

The second section of Table 1 contains a matrix of *qualitative* selection factors for each dredge type. These selection factors reflect the potential performance of a given dredge type, but are a function of both the capability of the equipment type and the site and/or sediment conditions. As with the dredge operational characteristics, there were earlier efforts to develop environmental dredging selection factors (Palermo 1991, Mohan and Thomas 1997, Mohan 1998). For example, Mohan (1998) presented a fairly comprehensive overview of remedial dredging and factors that could influence the selection of a remedial dredging alternative.

A review of the open literature (primarily projects in the U.S.) determined that some specifics were documented related to the *quantitative* operational characteristics of the various dredge types in the first section of Table 1, but there was very little information supporting the *qualitative* evaluation of dredge selection factors in the second section of Table 1. Consequently, the technical basis for the *qualitative* entries in the second section of Table 1 presented here was developed based on best professional judgment and interpretation of the readily available data. Each factor in the second section of Table 1 is given a *qualitative* entry of High, Medium or Low, defined as follows:

(High) - indicating the given dredge type is generally suitable or favorable for a given issue or concern,

(Medium) - indicating the given dredge type addresses the issue or concern, but it may not be preferred, and

(Low) - indicating the given dredge type may not be a suitable selection for addressing the issue or concern.

Earlier efforts to develop guidance tables for dredge operational capability and selection factors lacked a consistent definition of the factors involved and lacked adequate explanation of the technical basis for the ratings given. The main goal for this paper was to develop and document such a technical basis for all the entries in Table 1, building on the earlier efforts, and reflecting the most recent information available from the open literature and from recent field experience.

The following subsections provide definitions of each of the operational characteristics and selection factors and the technical basis for each of the associated entries in Table 1. Note that the technical basis for entries in Table 1 are also summarized as footnotes embedded in the table proper to help ensure that the table will not be applied blindly without due consideration of the basis for the entries. The information presented in the subsections below and summarized in Table 1 is intended to help project managers initially assess dredge capabilities, and screen and select equipment types for evaluation at the feasibility study stage or for pilot field testing. Table 1 is NOT intended as a guide for final equipment selection for remedy implementation. There are many site-specific, sediment-specific, and project-specific circumstances that will dictate which equipment is most appropriate for any given situation, and each equipment type can be applied in different ways to adapt to site and sediment conditions. In addition, because new equipment is being continuously developed, project managers will need to consult with experts who are familiar with the latest technologies.

Production Rates

Dredging production refers to the volume of in-situ sediment removed per unit time from the waterway. As compared to navigation dredging, environmental dredging projects are normally characterized by thinner cuts, smaller equipment sizes, and environmental constraints on operations resulting in lower production rates. Consequently efficient production rate is an important performance objective of environmental dredging that is difficult to achieve, and

Table 1. Environmental Dredging Equipment Operational Characteristics and Selection Factors.

ENVIRONMENTAL DREDGING EQUIPMENT OPERATIONAL CHARACTERISTICS AND SELECTION FACTORS Refer to footnotes in parentheses for definitions, explanation, and technical basis (1)										
	Equipment Type (2)									
	Mechanical Dredges (2 to 8 cubic meter buckets)			Hydraulic / Pneumatic Dredges (15 to 30 cm pump sizes)						Dry Excavation
	Conventional Clamshell (Wire) (3)	Enclosed Bucket (Wire) (4)	Articulated Mechanical (Fixed Arm) (5)	Cutterhead (6)	Horizontal Auger (7)	Plain Suction (8)	Pneumatic (9)	Specialty (10)	Diver (11)	Various Mechanical Excavators (12)
OPERATIONAL CHARACTERISTICS (13)										
Operating Production Rate (m^3/ hr) (14)	50 (2 m^3 bucket) 95 (4 m^3 bucket) 145 (6 m^3 bucket) 190 (8 m^3 bucket)			70 (15 cm pump) 145 (20 cm pump) 200 (25 cm pump) 285 (30 cm pump)			Site Specific	Equipment Specific	10	Site Specific
Percent Solids (by weight) (15)	90% In-Situ	80% In-Situ	80% In-Situ	10	10	10	15	Equipment Specific	<5	In-Situ
Vertical Operating Accuracy (cm) (16)	15	15	10	10	10	10	15	10	--	5
Horizontal Operating Accuracy (cm) (17)	10	10	10	10	10	10	10	10	--	5
Maximum Dredging Depth (m) (18)	Stability Limitations	Stability Limitations	15	15	5	15	45	15	30	Stability Limitations
Minimum Dredging Depth (m) (19)	--	--	--	1	0.5	1	5	1	0.5	--

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Table 1 (continued). Environmental Dredging Equipment Operational Characteristics and Selection Factors.

	Mechanical Dredges (2 to 8 cubic meter buckets)			Hydraulic / Pneumatic Dredges (15 to 30 cm pump sizes)						Dry Excavation
	Conventional Clamshell (Wire)[3]	Enclosed Bucket (Wire)[4]	Articulated Mechanical (Fixed Arm)[5]	Cutterhead[6]	Horizontal Auger[7]	Plain Suction[8]	Pneumatic[9]	Specialty[10]	Diver[11]	Various Mechanical Excavators[12]
EQUIPMENT SELECTION FACTORS[20]										
Sediment Resuspension Control[21]	Low	Medium	Medium	Medium	Medium	High	High	High	High	High
Contaminant Release Control[22]	Low	High	High	Medium	Medium	Medium	Medium	Medium	High	High
Residual Sediment/ Cleanup Levels[23]	Low	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	High
Transport by pipeline[24]	Medium	Medium	Medium	High	High	High	High	High	High	Medium
Transport by barge[25]	High	High	High	Medium	Medium	Medium	Medium	Medium	Medium	High
Positioning Control in currents/ wind/ tides[26]	High	High	High	High	Medium	High	High	High	Medium	High
Maneuverability[27]	High	High	High	Low	Low	Low	High	Low	High	High
Portability/ Access[28]	High	High	High	High	High	High	High	Medium	High	High
Availability[29]	High	High	High	High	High	High	Medium	Medium	High	High
Debris/Loose rock/ Vegetation[30]	High	High	High	Low	Low	Low	Low	Low	Low	High
Hardpan/ Rock Bottom[31]	Low	Low	Low	Low	Low	Medium	Medium	Medium	High	High
Flexibility for Varying Conditions[32]	High	High	Medium	High	Medium	Low	Low	Low	Low	High
Thin Lift / Residual Removal[33]	Low	Medium	Medium	Medium	High	High	High	High	High	High

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Table 1 (continued). Environmental Dredging Equipment Operational Characteristics and Selection Factors.

Footnotes:

(1) This table provides general information to help project managers initially assess dredge capabilities, and screen and select equipment types for evaluation at the feasibility study stage or for pilot field testing. This table is NOT intended as a guide for final equipment selection for remedy implementation. There are many site-specific, sediment-specific, and project-specific circumstances that will dictate which equipment is most appropriate for any given situation, and each equipment type can be applied in different ways to adapt to site and sediment conditions. In addition, because new equipment is being continuously developed, project managers will need to consult with experts who are familiar with the latest technologies. For additional information on development and technical basis for the entries in this table refer to: *Palermo, et al. (2004). Operational Characteristics and Equipment Selection Factors for Environmental Dredging. Journal of Dredging Engineering, Western Dredging Association, Vol 5, No. 4.*

(2) Equipment types shown here are considered the most commonly used for environmental dredging in the U.S. Other dredge types are available. Equipment used for environmental dredging is usually smaller in size than that commonly used for navigation dredging. Information presented here is tailored for mechanical bucket sizes from 3 to 10 cubic yards (about 2 to 8 cubic meters), and hydraulic/pneumatic pump sizes from 6 to 12 inches (about 15 to 30 cm). Larger sizes are available for many equipment types.

(3) Clamshell – conventional clamshell dredges, wire supported, conventional open clam bucket.

(4) Enclosed bucket – wire supported, near watertight or sealed bucket usually incorporating a level cut capability.

(5) Articulated Mechanical – backhoe designs, clam-type enclosed buckets, hydraulic closing mechanisms, all supported by articulated fixed-arm

(6) Cutterhead – conventional hydraulic pipeline dredge, with conventional cutterhead.

(7) Horizontal auger – hydraulic pipeline dredge with horizontal auger dredgehead.

(8) Plain Suction – hydraulic pipeline dredge using dredgehead design with no cutting action.

(9) Pneumatic – air operated submersible pump, pipeline transport, either wire supported or fixed-arm supported.

(10) Specialty Dredgeheads – other hydraulic pipeline dredges with specialty dredgeheads or pumping systems

(11) Diver assisted – hand-held hydraulic suction with pipeline transport.

(12) Dry Excavation – conventional excavation equipment operating within dewatered containments such as sheet-pile enclosures or cofferdams.

(13) OPERATIONAL CHARACTERISTICS are shown as quantitative entries, reflecting capabilities and limitations of dredge types, and are solely a function of the equipment itself.

(14) Production rate - in-situ volume of sediment removed per unit time. Rates shown are calculated production cuts as opposed to “cleanup passes” and are for active periods of operation under average conditions. Rates for several bucket or pump sizes are shown for comparison. For mechanical dredges, the rates were calculated assuming 80% bucket fill with a bucket cycle time of 2 minutes. For hydraulic dredges, the rates were calculated assuming in-situ sediment 35% solids by weight, 10% solids by weight for slurry, and pump discharge velocity of 15 feet/sec. The rate shown for diver-assisted assumes a maximum pump size of 15 cm and roughly 50% efficiency of diver effort while working. Production rate for dry excavation is would be largely dictated by the time required to isolate and dewater the areas targeted for excavation. A variety of factors may influence the effective operating time per day, week, or season, and should be considered in calculating times required for removal.

(15) Percent solids by weight – ratio of weight of dry solids to total weight of the dredged material as removed, expressed as a percentage. Percent solids for mechanical dredging is a function of the in-situ percent solids and the effective bucket fill (expressed as a percentage of the bucket capacity filled by in-situ sediment as opposed to free water), and near in-situ percent solids is possible for production cuts. A wide range of percent solids for hydraulic dredges is reported, but 10% solids can be expected for production cuts for most environmental dredging projects.

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Table 1 (continued). Environmental Dredging Equipment Operational Characteristics and Selection Factors.

(16) Vertical operating accuracy - the ability to position the dredgehead at a desired depth or elevation for the cut and maintain or repeat that vertical position during the dredging operation. Although positioning instrumentation is accurate to within a few centimeters, the design of the dredge and the linkages between the dredgehead and the positioning system will affect the accuracy attainable in positioning the dredgehead. A vertical accuracy of cut of about 15 cm (one-half foot) is considered attainable for most project conditions. Fixed arm equipment holds some advantage over wire-supported in maintaining vertical operating accuracy. The accuracies achievable for sediment characterization should be considered in setting performance standards for environmental dredging operating accuracy (both vertical and horizontal).

(17) Horizontal operating accuracy - the ability to position and operate the dredgehead at a desired location or within a desired surface area. Considerations are similar to those for vertical accuracy.

(18) Maximum dredging depth - physical limitation to reach below a given depth. Wire-supported buckets or pumps can be deployed at substantial depths, so the maximum digging depth is limited by stability of the excavation. Reach of fixed arm supported buckets or hydraulic dredges is limited by the length of the arm or ladder. Conventional backhoe equipment is limited to about 15 meters reach. Smaller hydraulic dredges are usually designed for a maximum dredging depth of about 15 meters. Hydraulic dredges also have a limiting depth of removal of about 50 feet due to the limitation of atmospheric pressure, but this limitation can be overcome by addition of a submerged pump on the ladder. The table entries should NOT be considered as hard and fast limits. Larger dredge sizes and designs are available for deeper depths.

(19) Minimum dredging depth - constraints on draft limitations of some floating dredges or potential loss of pump prime for hydraulic dredges. Such limitations can be managed if the dredge "digs its way into the area". For smaller dredges, these limitations are at approximately the 1-meter water depth. Pneumatic dredges require a minimum water depth of about 5 meters for efficient pump operation.

(20) SELECTION FACTORS are shown as qualitative entries, reflecting the potential performance of a given dredge type, and are a function of both the capability of the equipment type and the site and/or sediment conditions. Entries defined as follows:

(High) - indicating the given dredge type is generally suitable or favorable for a given issue or concern,
(Medium) - indicating the given dredge type addresses the issue or concern, but it may not be preferred, and
(Low) - indicating the given dredge type may not be a suitable selection for addressing this issue or concern.

(21) Sediment Resuspension - potential of a given dredge type in minimizing sediment resuspension. Clamshell (Low) - Circular-shaped cutting action, cratered bottom subject to sloughing, open bucket design subject to washout and spillage, scows and workboats working in shallow areas. Enclosed Bucket (Medium) - Seal around the lips of the bucket and an enclosed top when in the shut position, level cut design minimizes sloughing. Articulated Mechanical (Medium) - Less resuspension as compared to conventional clamshell dredges. Cutterhead/ Horizontal Auger (Medium) - Conventional cutterhead dredges and horizontal augers result in less resuspension as compared to conventional clamshell dredges. May be fitted with hoods or shrouds to partially control resuspension. Plain Suction/ Pneumatic (Medium) - No mechanical action to dislodge the material. Specialty (High) - Although designs vary, many of the so-called specialty dredges have features specifically intended to reduce resuspension. Diver (High) - Precision of diver assisted hydraulic dredging, the smaller size of the dredgeheads used, and inherently slow speed of operation. Dry Excavation (High) - Completely isolates the excavation process from the water column.

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Table 1 (continued). Environmental Dredging Equipment Operational Characteristics and Selection Factors.

(22) Contaminant Release Control - the inherent ability to control sediment resuspension and dissolved and volatile releases for the given equipment type and associated operation. Clamshell (Low) – can be operated such that the excavation and water column exposure of the bucket is within a silt curtain containment or enclosure, however, high suspended solids within the silt curtain may be released when the curtain is moved. Enclosed bucket/ Articulated Mechanical (High) – can be operated such that the excavation and water column exposure of the bucket is within a silt curtain enclosure with relatively small footprint. Enclosed buckets act as a control to greatly reduce resuspension within the enclosures and potential for release. Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads/ (Medium) – capable of transporting the material directly by pipeline, minimizing exposure to the water column and to volatilization. Can be operated within enclosures, but the footprint of such enclosures would necessarily be larger than that for mechanical dredges. Diver assisted (High) – scale of diver-assisted dredging would seldom require contaminant release controls. Dry Excavation (High) – Dewatering of the dredging area effectively eliminates dissolved releases. Sediment surface exposed to the atmosphere has lower volatile emission rates as compared to the same surface ponded with elevated suspended sediment concentrations.

(23) Residual sediment/ Cleanup Levels – efficiency of the dredge in removing material without leaving a residual, and potentially meeting a cleanup criterion. Clamshell (Low) – high potential to leave residual sediment because of the circular-shaped cutting action and the tendency to leave a cratered bottom subject to sloughing. Enclosed bucket/ Articulated Mechanical/ Cutterhead/ Horizontal auger/ Plain Suction/ Pneumatic/ Specialty Dredgeheads (Medium) – all dredges with active dredgeheads and/or movement in contact with the bottom sediment will leave some residual sediment. The control offered by the articulated arm provides an advantage for removal of thin residual layers. Diver assisted (High) – hand-held action of diver-assisted work has a low potential for generating residual sediment. Dry Excavation (High) – any fallback of sediment excavated under dry conditions can be readily observed and managed.

(24) Transport by Pipeline - compatibility of the dredge with subsequent transport by pipeline. Clamshell/ Enclosed bucket/ Articulated Mechanical (Medium) – All mechanical dredges remove material at near in-situ density, and additional reslurry and rehandling equipment must be employed to allow for pipeline transport. Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads/ Diver Assisted (High) – All hydraulic and pneumatic dredges are designed for pipeline transport. Dry Excavation (Medium) – Additional reslurry and rehandling equipment must be employed to allow for pipeline transport.

(25) Transport by barge - compatibility of the dredge with subsequent transport by barge. Clamshell/ Enclosed bucket/ Articulated Mechanical (High) – material excavated with mechanical dredges is close to in-situ density and may be directly placed in barges for transport. Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads/ Diver Assisted (Medium) – barge transport of hydraulically dredged material is inefficient. Although pneumatic and some specialty dredges are capable of removing soft sediments at high water content, intermittent operation for change-out of barges will significantly reduce efficiency. Dry Excavation (High) – material excavated in the dry may be placed directly in barges using conveyers or front-end loaders.

(26) Positioning Control in currents/wind/tides - ability of the dredge to hold a desired position of the dredgehead horizontally with current, wind, or vertically with fluctuating tides. Clamshell/ Enclosed bucket/ Articulated Mechanical (High) – operate with spuds or jack-up piles and are inherently stable against movement by normal winds and currents. Cutterhead/ Plain suction/ Specialty Dredgeheads (High) – equipped with spuds and use "walking spud" method of operation inherently stable against movement by normal winds and current. Horizontal auger (Medium) – free floating and operate using an anchor and cable system, subject to movement with longer anchor sets. Pneumatic (High) – operate from spudded barges or platforms and are inherently stable against movement by normal winds and currents. Diver assisted (Medium) – ability of divers to maintain a desired position will be hampered by currents. Dry Excavation (High) – not affected by wind and currents.

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Table 1 (continued). Environmental Dredging Equipment Operational Characteristics and Selection Factors.

(27) Maneuverability - ability of the dredge to operate effectively in close proximity or around utilities and other infrastructure, narrow channel widths, surface and submerged obstructions, and overhead restrictions. Clamshell/ Enclosed bucket/ Articulated Mechanical/ Pneumatic (High) – buckets are wire supported or fixed-arm articulated and may be operated close in to infrastructure and within tightly restricted areas. Cutterhead/ Plain suction/ Horizontal auger/ Specialty Dredgeheads (Low) – swinging action of the walking spud method of operation for hydraulic pipeline dredges and the need for long anchor and cable setup for horizontal auger dredges limits their ability to operate near infrastructure or within tightly restricted areas. Diver assisted (High) – can be conducted close to infrastructure and within tightly restricted areas. Dry Excavation (High) – containments for dry excavation can be designed for areas near infrastructure and tightly restricted areas may be completely contained.

(28) Portability/Access - ability of the dredge to pass under bridges, through narrow channels, or to be transported by truck and easily launched to the site. Clamshell/ Enclosed bucket/ Articulated Mechanical/ Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Diver assisted/ Dry Excavation (High) – dredge types considered here are the smaller size and are generally truck transportable. Specialty Dredgeheads (Medium) – some specialty dredge designs are too large for truck transport.

(29) Availability - This factor refers to the potential availability of dredges types to contractors and the potential physical presence of the equipment in the U.S. Clamshell/ Enclosed bucket/ Articulated Mechanical/ Cutterhead/ Plain suction/ Horizontal auger/ Diver assisted/ Dry Excavation (High) – Most dredge types are readily available. Pneumatic/ Specialty Dredgeheads (Medium) – Some specialty dredges are only available through one contractor, or may be subject to restrictions under the Jones Act.

(30) Debris/Loose Rock/Vegetation - susceptibility of a given dredge type to clogging by debris and subsequent loss of operational efficiency. Clamshell/ Enclosed bucket/ Articulated Mechanical (High) – mechanical dredges can effectively remove sediments containing debris, although leakage may result. Mechanical equipment is the only approach for debris-removal passes. Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads (Low) – subject to clogging by debris and are incapable of removing larger pieces of loose rock and larger debris. Loose rock and large debris can also cause inefficient sediment removal. Diver assisted (Low) – presence of logs and large debris may present dangerous conditions for diver-assisted dredging. Although divers can remove sediment from around large debris or rocks, this type of operation would be inefficient. Dry Excavation (High) – dry excavation allows use of conventional excavation equipment. Leakage from buckets caused by debris is not a consideration for dry excavation.

(31) Hardpan/ Rock Bottom - ability of a dredge type to efficiently remove a sediment layer overlying hardpan or rock bottom without leaving excessive residual sediment. Clamshell/ Enclosed bucket/ Articulated Mechanical/Cutterhead/ Horizontal auger (Low) – closing action of buckets and cutting action of dredgeheads result in problems maintaining a desired vertical cutting position and would tend to leave behind excessive residual sediment. Power associated with articulated mechanical has advantage in removing hard materials. Plain suction/ Pneumatic/ Specialty Dredges (Medium) – lack an active closing or cutting action and can operate over an uneven hard surface, although removal efficiency may be low. Diver assisted (High) – may be the most effective approach for precise cleanup of a hard face, since the divers can feel the surface and adjust the excavation accordingly. Dry Excavation (High) – allows the visual location of pockets of residual remaining on an uneven hard surface.

Continued Next Page

Table 1 (concluded). Environmental Dredging Equipment Operational Characteristics and Selection Factors.

(32) Flexibility for Varying Conditions - flexibility of a given dredge type in adapting to differing conditions, such as sediment stiffness, variable cut thicknesses, and the overall ability to take thick cuts. Clamshell/ Enclosed bucket (High) – buckets are capable of taking thin cuts or thicker cuts in proportion to the bucket size, and bucket sizes can be easily switched. Articulated Mechanical (Medium) – ability to change bucket sizes for articulated mechanical is limited. Cutterhead (High) – capable of taking variable cut thicknesses by varying the burial depth of the cutter. Different cutterhead sizes or designs can be used to adapt to changing cut thicknesses or sediment stiffness. Horizontal auger (Medium) – designed for a set maximum cut thickness, and attempts to remove thick cuts may result in plowing actions with excessive resuspension and residual. Plain suction/ Pneumatic (Low) – no cutting action limits ability to take thicker cuts or remove stiffer materials. Specialty Dredgeheads (Low) – specialty dredges are designed for a specific application and have limited flexibility. Diver assisted (Low) – removal is limited to thin cuts. Dry Excavation (High) – allows use of a full range of conventional excavation equipment.

(33) Thin lift/ residual removal - ability of a given dredge type to removal thin layers of contaminated material without excessive overdredging. Clamshell (Low) – circular shaped cut not suited to efficient removal of thin layers. Enclosed bucket/ Articulated Mechanical (Medium) – level cutting action is capable of removing thin layers, but the buckets would only be partially filled, resulting in inefficient production and higher handling and treatment costs. Cutterhead/ Horizontal Auger (Medium) – capable of removing thin layers, but the percent solids is reduced under these conditions. Plain suction/ Pneumatic (High) –well suited for removal of thin lifts, especially loose material such as residual sediment. Specialty Dredgeheads (High) – some specialty dredges are designed specifically for removal of thin lifts. Diver assisted (High) – precision of diver-assisted dredging is well suited for removal of thin layers, especially residuals. Dry Excavation (High) – allows for a precise control of cut thickness, amenable to removal of thin layers.

Table 2. Summary of Reported Data on Operational Characteristics for Environmental Dredging.

Operational Characteristic or Factor	*Mechanical Dredges*			*Hydraulic Dredges – Pnuematic Dredges*						**Dry Exca-vation**
	Conventional Clamshell (Wire Supported)	**Enclosed Bucket (Wire Supported)**	**Articulated Mechanical (Fixed Arm)**	**Cutter- head**	**Horizontal Auger**	**Plain Suction**	**Pneumatic**	**Specialty Dredges**	**Diver Assisted**	**Mechanical Excavate**
Production Rate (m^3/hr)										
Herbich (1995)					15.3 to 61(1)					
Herbich (1995)				12.3	31.3 (2)	18.7(3)				
Hornsby (1995)	8									
Cushing and Hammaker (2001)	31	31								
Wang, Hotchkiss, Scudder (2000)		32 to 64								
Cushing (2002)				19.1 to 38.2						
Hayes and Wu (2001)				28-56(4)						
Pelletier (1995)							25 to 45(5)			
Herbich (1995)							240 to 300(6)	85 to 103		
Herbich (2000)									15 to 35(7)	
Mohan (1998)									12 to 36(8)	

Table 2 (continued). Summary of Reported Data on Operational Characteristics for Environmental Dredging.

Operational Characteristic or Factor	*Mechanical Dredges*			*Hydraulic Dredges – Pnuematic Dredges*						Dry Exca-vation
	Conventional Clamshell (Wire Supported)	Enclosed Bucket (Wire Supported)	Articulated Mechanical (Fixed Arm)	Cutter- head	Horizontal Auger	Plain Suction	Pneumatic	Specialty Dredges	Diver Assisted	Mechanical Excavate
Pound (2000)									48	
Bennett and Hill (1994)								2 to 7[9]		
Percent Solids (by wt)										
Herbich (1995)		44 to 48[10]			8 to 22[11]		40 to 50[12]			
Mohan (1998)									2 to 4[13]	
Pelletier (1995)							17 to 31[14] 20 to 40[15]			
Appel (2001)								15 to 20[16]		
VanRaalte (1986)								70[17]		
Vertical Accuracy (cm)										
Scott el al (2002)	20									10[18]
Blanchard and Priore (2002)		2.5								
Herbich (2000)					8[19] 3[20]					
DeRugeris and Nilson (2000)					15					

Table 2 (concluded). Summary of Reported Data on Operational Characteristics for Environmental Dredging.

Operational Characteristic or Factor	*Mechanical Dredges*			*Hydraulic Dredges – Pnuematic Dredges*						Dry Excavation
	Conventional Clamshell (Wire Supported)	Enclosed Bucket (Wire Supported)	Articulated Mechanical (Fixed Arm)	Cutter- head	Horizontal Auger	Plain Suction	Pneumatic	Specialty Dredges	Diver Assisted	Mechanical Excavate
Seagren 2002						5.1				
Easterline et al 2002		5.1								
Horizontal Accuracy (cm)										
DeRugeris and Nilsen (2000)				20	20(21)					
Maximum Digging Depth (m)										
Herbich (1995, 2000)	9 to 12	9 to 12		12	5 to 8	26(22)	60(23) 18(24)	21(25) 18 to 35(26) 31(27)		

(1) Marathon Battery Custom auger, (2) Mudcat New Bedford Pilot Study, (3) Mudcat New Bedford Pilot Study, (4) Calumet, Acushnet, Lavaca Bay, (5) Pneuma 150 Collingwood Harbor, (6) Pneuma 450 Gibraltar Lake, (7) Manistique, (8) LTV Steel, (9) Vacuum Clam, (10) Cablearm - HamiltonHarbor, (11) Mudcat Welland River, (12) Pneuma 450 Gibraltar Lake, (13) Manistique, (14) Pneuma, (15) Collingwood Harbor, (16) ICH Dredging Wheel, (17) Disk Cutter, (18) Mallee 2002, (19) Bayou Bonfouca p. 18.23, (20) Marathon Battery, (21) Lake Capri, NY, (22) Matchbox, (23) Pneuma, (24) Oozer, (25) Cleanup, (26) Refresher, (27) Wide Sweeper

production often competes with other requirements such as resuspension control and minimization of residuals.

Production can be considered and defined in several ways. For purposes of this paper, the operating production rate is defined as the production rate during periods of continuous operation while removing full production cuts. Overall or sustained production rate is defined as the production rate across the full duration of the project. Sustained production rates are difficult to estimate because these rates are driven by both production and "cleanup" passes, constraints on allowable times for dredging, and possible disposal-related constraints.

Techniques used to calculate production rates for environmental dredging have been adapted from those used in estimating conventional dredging projects. However, these estimation techniques must consider constraints related to resuspension and release of contaminants and the rate of transport, treatment, or disposal. If a high production rate is a critical dredge selection factor, use of multiple dredges may be needed to meet a production standard instead of using a single dredge.

Dredges may be operated in a way to minimize resuspension and release. Reducing swing speed for hydraulic dredging or increasing cycle time for bucket dredges may slightly reduce the rate of resuspension but will prolong the time required for removal. Unfortunately, slower operations may not achieve efficient production with lower overall resuspension and release. Use of skilled operators is a key consideration in this regard (Francingues 2001).

A major factor in overall production is the potential lost time required to meet environmental or other constraints on the operation. Environmental dredging projects are more likely to have such constraints than navigation dredging projects. Constraints of this nature may include limitations on sediment resuspension, contaminant release or residual, requirements for moving in and out of enclosures and/or moving such enclosures, monitoring requirements to verify residual sediment concentrations or water column concentrations prior to movement of enclosures, and limitations on dredging during certain times of the day or night, days of the week, or seasons of the year due to adjacent homeowners, other waterway uses, etc.

Another key consideration regarding production is the throughput rate for any necessary rehandling, pre-treatment, treatment, and disposal. Experience with many projects indicates that the dredging production rate can be severely constrained by these processes, and not by the dredging process itself (Maher and Nichols 1995). Increased storage volume for sediment removal as a pre-treatment/ disposal step or multiple and redundant units for various processes may offset this constraint.

Many factors affect the operating production rate for hydraulic dredges. These include dredge size, dredge design, pump horsepower, dredging depth, length of pipeline, elevation of the discharge point, the possible addition of a submerged ladder pump, in-situ sediment density, stiffness of the material, the thickness of the cut, and other minor factors. So, hydraulic production is tied to both the inherent capability of the equipment, site and operating conditions, and the properties of the material being dredged. Further, the operating production rate will change with changing sediment or operating conditions. The overall or sustained production is tied to the production rate and the effective dredging time. Reported overall production rates vary greatly across projects and hydraulic dredge types. For example, sustained production rates for three 10- and 12- inch cutterheads for environmental dredging ranged from 28 to 56 cubic meters per hour (Hayes and Wu 2001) and 19 to 38 cubic meters per hour (Cushing and Hammaker 2001). Sediment remediation projects would normally be dredged by smaller equipment, so the entries in Table 1 are developed for 6- to 12-inch hydraulic dredges.

Production for mechanical dredges is a function of the bucket size (expressed as a volume), the effective bucket fill (expressed as a percentage of the bucket capacity filled by in-situ sediment as opposed to free water), the effective cycle time per bucket load, and the effective dredging time. Bucket sizes for environmental projects have typically ranged from 3 to 10 cubic yards (approximately 2 to 8 cubic meters), which is at the lower range of available bucket sizes.

Cycle time is usually defined as the total time required to complete the process of closing the bucket to excavate a bucket load of sediment, raise the bucket through the water column, place the material into the transport barge or other conveyance, and swing back and lower the bucket to the bottom and reposition for the next bucket load. For navigation projects, the cycle times are on the order of one minute. However, cycle times may be longer (2-8 minutes) for remediation projects, because greater care is needed to precisely position the bucket for each bucket load, and there may be requirements related to minimizing resuspension and rinsing out/off the bucket between cuts. The effective dredging time for mechanical dredges also depends on the logistics of changing out barges and may even depend on the number of transport barges used for the project.

Published sustained dredging rates for mechanical dredges vary greatly depending on the size of the bucket, cycle time, bucket fill, and amount of debris encountered (see Table 2). An average production rate of 31 cubic meters per hour from daily logs at Saginaw River over 209 dredging days was achieved using two Cable Arm buckets (6 and 16 cubic yard buckets) and 4 conventional clamshell buckets (4, 5, 8, and 10 cubic yard buckets) (Cushing and Hammaker 2001). Cycles times of 4-8 minutes with production of 32-64 cubic meters per hour were reported for a 9 cubic yard environmental bucket operating on the East Waterway project (Wang, Hotchkiss, and Scudder 2000). The production for the newer enclosed bucket designs should be similar to conventional buckets of the same size.

Diver assisted dredging may be required for some remediation situations, such as removal under piers and around piling, from hard rock bottoms, etc. Data are available from several projects to support estimates of possible production. For example, hard-hat divers were used to remove sediments from around intakes at a water supply reservoir in Westchester County, New York in water depths of 80 feet. In this case, a modified portable dredge was outfitted with an 18-inch steel diameter manifold with 4-inch nipples and 100 ft. suction hose attached to each nipple with a 12-inch by 4-inch funnel shaped attachment put on end of each hose. Reported production with this arrangement was about 48 cubic meters per hour (Pound 2000).

Planning level estimates for operating production rates for both mechanical and hydraulic dredges are shown in Table 1. The values shown in Table 1 are for production cuts as opposed to "cleanup passes" and are for periods of continuous operation under average conditions. The numbers therefore reflect what the dredge type and size is capable of removing while actually operating for a full production cut. The numbers also assume conditions for soft, fine-grained sediments, representative of most environmental dredging projects.

For hydraulic dredging, a planning-level estimate of operating production rate can be determined as the product of pump size, pump discharge velocity, and the ratio of slurry solids concentration to in-situ sediment solids concentration (both by weight). The rates for hydraulic dredges shown in Table 1 were calculated for 15, 20, 25, and 30 cm pump sizes, using 35% solids by weight in-situ, 10% solids by weight for slurry, and pump discharge velocity of 15 feet/sec. The rate shown for diver-assisted assumes a maximum pump size of 15 cm and roughly 50% efficiency of diver effort.

For mechanical dredging, a planning-level estimate of operating production rate can be determined as the product of bucket volume, cycle time and percent bucket fill. The rates for mechanical dredges shown in Table 1 were calculated for 2, 4, 6, and 8 cubic meter buckets, using 80% bucket fill and a bucket cycle time of 2 minutes.

Production data for dry excavation is highly site and project specific. The effective production would be largely dictated by the time required to isolate and dewater the areas targeted for excavation.

It is important to note that the calculations of operating production rates in Table 1 are based on simplifying assumptions and should be used for planning level estimates only. A more rigorous estimation of production is needed for project design and implementation phases. Further, it is important to note that the operating production rates in Table 1 do not reflect sustained or overall production rates, accounting for constraints on effective dredging time or constraints related to treatment or disposal throughput rates.

Percent Solids by Weight

Percent solids by weight is defined as the ratio of weight of dry solids to total weight of the dredged material as removed, expressed as a percentage. This is a convenient way to describe the density of removed material, especially for hydraulic dredging. The percent solids in the material as it is removed and transported by the dredge will have a major impact on the production rate and the compatibility of the dredging operation with subsequent handling, treatment, and disposal of the material. Normally, a higher solids content delivered by the dredge translates to lower costs for handling, treating, and disposal of water and sediment. Most environmental dredging projects involve predominantly fine-grained sediments, and the in-situ sediments often have high water content. So, there is a substantial volume of water in the removed sediments, even with a dredging process capable of removal at near in-situ water content.

Physical characteristics of the sediment (density, particle size distribution, cohesiveness, etc.) influence the solids content achievable by a hydraulic dredge. Conventional hydraulic dredges add a volume of water equivalent to about 4 times the volume of in-situ sediment removed. For navigation dredging, solids contents of 10 to 15% solids by weight are routinely achieved. The available data for environmental dredging indicates lower solids content for many projects with a wide range of percent solids for hydraulic dredges reported, but 10% solids can be expected for production cuts for most environmental dredging projects. In recent years, newer dredgehead and pump designs have been developed for hydraulic systems that are capable of removing material at higher percent solids as compared to conventional pipeline dredges (Herbich 1995). In some cases, removal at near in-situ concentrations has been reported for sediments with relatively high in-situ water contents. For example, Van Raalte (1986) reported an average of 70% in situ material (about 30% excess water) with the Disc Cutter for maintenance of "polder canals" in The Netherlands.

Percent solids for mechanical dredging is a function of the in-situ percent solids and the effective bucket fill (expressed as a percentage of the bucket capacity filled by in-situ sediment as opposed to free water). Mechanical dredges can remove sediment with minimal addition of water if a full cut is possible. A common rule of thumb for navigation mechanical dredging is an addition of 10% water by volume, reflecting a condition equivalent to the bucket filled to 90% of its volume with in-situ sediment, and 10% with excess water. For environmental dredging, the solids content may be reduced, since partial or overlapping cuts may be required and the depth of cut must be carefully controlled, so a higher percentage of excess water can be expected. For example, a 39% bulking for clamshell dredging was reported at a site in Baltimore's inner harbor (Synder et al 1995), and estimates for production for dredging in the East Waterway in Commencement Bay assumed a bucket filled to 70% of capacity (Wang, Hotchkiss, and Scudder 2000).

Vertical Operating Accuracy

In the context of this paper, vertical operating accuracy refers to the ability to position the dredgehead at a desired depth or elevation for the cut and maintain or repeat that vertical position during the dredging operation. Strictly speaking, the term accuracy refers to how close a measurement is to the actual value being measured, while precision refers to the ability to repeat a measurement. Both accuracy and precision are important in the context of environmental dredging, for the key to a successful environmental dredging project is the removal of the "target layer" without excessively removing clean material. Removal of excessive clean material will normally lead to higher costs for treatment and disposal. So, the ability to accurately and precisely position the dredgehead, both horizontally and vertically, is critical.

The cut line in the sediment is established by the precise location of the dredgehead. The development of electronic positioning technologies such as Differential Global Positioning Systems (DGPS) has greatly enabled dredging operators to precisely remove targeted material. DGPS accuracies of 7 cm horizontal and 12 cm vertical are attainable. With Kinematic Differential Global Positioning Systems (KDGPS), horizontal accuracy is 1-2 cm, while vertical accuracy is about 1.5 times horizontal or about 2-3 cm (Lilllycrop, Clausner, and Rosati 2002). But these accuracies are related to the capability of the positioning devices themselves, and can vary greatly between sites. The design of the dredge and the linkages between the dredgehead and the positioning system will affect the operating accuracy attainable in positioning the dredgehead and vertically maintaining the desired cutline as dredging progresses. Transponders may be mounted at critical points on the dredge (such as at the top of a crane boom) or directly on the dredgehead to improve accuracy of the dredging operation. Sensors to provide real-time feedback on the actual cut achieved are also possible. Depending on site conditions, size and type of dredge, and positioning instrumentation, the dredgehead and cut elevation can vary within a vertical accuracy of 5-30 cm. Assuming a state of the art positioning system, vertical accuracies of 10 cm for fixed arm dredgeheads should be consistently attainable. For wire-supported buckets, vertical accuracies are strongly influenced by variations in sediment properties, but vertical accuracies of 15 cm should be attainable with proper operator training.

The vertical and horizontal positioning accuracy related to the sediment characterization data should be considered in setting performance standards for environmental dredging operating accuracy (both vertical and horizontal). The benefits of accurate dredging 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 a known elevation datum is also an important consideration. In some cases, the attainable accuracy in locating the cut is greater than the accuracy of the sediment characterization data (Palermo and Averett 2003).

Horizontal Operating Accuracy

Horizontal operating accuracy refers to the ability to position and operate the dredgehead at a desired location or within a desired surface area. Positioning systems and displays now allow the operator to "see" and record specific locations of each bucket cut or each arc cut with a hydraulic dredge. The goal is to excavate all the area targeted for removal; therefore, some overlap of the horizontal extent of sediment removal is often practiced. However, excessive overlapping of cuts can increase the excess water removed by the dredge and may result in reduced production and higher water treatment costs. Another factor related to horizontal accuracy is the ability of the dredge to maintain its position in wind or currents. This is described below as a separate selection factor. Depending on site conditions, size and type of dredge, and positioning instrumentation, the horizontal position of the dredgehead can vary within an accuracy of about 3 to 20 cm (DeRugeris and Nilson 2000).

The considerations for expected horizontal operating accuracies are similar to those for the vertical accuracy, although horizontal accuracy would not normally be affected by varying sediment properties. Assuming a state of the art positioning system, horizontal operating accuracies of 10 cm should be consistently attainable. Considering operating accuracies of 10 to 15 cm in the vertical and 10 cm in the horizontal, an environmental dredging operation supported by state-of-the-art positioning systems can accurately remove the mass of contaminated sediment from a waterbody under most project conditions. However, the accuracy of removing contaminated inventory by dredging to a target cutline is limited by positioning instrumentation accuracy, operational factors as described above, and the accuracy of the sediment characterization data.

Maximum Dredging Depth

The operating characteristic for maximum dredging depth refers to the physical limitations of equipment to reach below a given depth. Some dredges have a physical limitation on their ability to reach below a given depth, related to the length of the dredging arm or ladder. For example, the limiting reach of conventional backhoe equipment is about 50 feet (about 15 meters). Hydraulic dredges have a limiting depth of removal of about 50 feet due to the limitation of atmospheric pressure, but this limitation can be overcome by addition of a submerged pump on the ladder. Reach of fixed arm supported buckets or hydraulic dredges is limited by the length of the arm or ladder. Wire-supported buckets or pumps can be deployed at substantial depths, so the maximum digging depth is usually limited by stability of the excavation. Summary data on dredging digging depth limitations (Herbich 1995; Herbich 2000) shows a wide variation across dredge types. The entries for this operational characteristic in Table 1 are for equipment types and smaller equipment sizes commonly considered for environmental dredging. None of the entries should be interpreted as hard and fast limits, since larger dredge sizes and designs are available for deeper depths.

Minimum Dredging Depth

Conversely, the draft limitations of some floating dredges limit their ability to work in very shallow water (less than a meter). This limitation can be managed if the dredge "digs its way into the area", or by increasing the flotation of the dredge platform or barge relative to the weight of the dredge plant. Also, for hydraulic equipment, excessively shallow water can cause the pump to loose prime or require use of a small dredgehead. Minimum draft may also be an important factor for the auxiliary vessels that service or reposition the dredge, since the propeller wash will resuspend the bottom sediment in shallow areas. Shallow water was documented as a problem with New Bedford (< 6ft) and at Marathon Battery with mud flats and marsh. (Cushing 1998).

Sediment Resuspension Control

Sediment resuspension is defined for purposes of this paper as that portion of the sediment dislodged or loosened by the dredging operation, not picked up by the dredging process, and that subsequently becomes dispersed in the water column and transported by current as a suspended solids plume (Palermo and Averett 2003). The selection factor for sediment resuspension control refers to the inherent potential of a given dredge type to minimize sediment resuspension. The available data on the magnitude of the resuspension "source strength" (the mass of sediment resuspended per unit time) for various dredges are based on field measurements of suspended solids at points near an operating dredge (although there is no rigorous protocol for such measurements). Other sources of resuspension related to use of a particular dredge type, such as propeller wash from work boats or grounding of barges should also be considered.

There are data for sediment resuspension at a number of sites and for a number of different dredge types. The most informative data regarding performance of different dredge types have been developed in field studies that compared the resuspension behavior of multiple dredge types operating at the same site and dredging the same sediment (Hayes 1986a and b). Also, the available resuspension data have been summarized and interpreted over the years by several investigators (Herbich and Brahme 1991; Herbich 2000; Hayes and Wu 2001). The available data show that dredge type and method of operation both influence the magnitude of resuspension "source strength" for given sediment and site conditions. For mechanical dredges, the use of enclosed buckets has shown some advantages over conventional open clamshells. For hydraulic dredges, conventional cutterheads have shown some advantage over horizontal augers.

The ratings and associated technical basis for each dredge type for sediment resuspension control are as follows:

- Clamshell (Low) – Resuspension due to sloughing, leakage and spillage from open buckets has potential to generate high levels of suspended sediment. Conventional clamshell buckets use a circular-shaped cutting action, leaving a cratered bottom subject to sloughing. The open bucket design is subject to washout and spillage during the raising and swinging portions of the dredging cycle. The operation and movement of scows and workboats would also resuspend material when working in shallow areas.
- Enclosed bucket (Medium) – Enclosed clamshell buckets are designed with a seal around the lips of the bucket and an enclosed top when in the shut position. Newer designs also result in a level cut which minimizes sloughing.
- Articulated Mechanical (Medium) – Grab buckets for articulated mechanical dredges are designed with seals around the lips of the bucket, an enclosed top when the bucket is in the shut position, and have a level cutting action. The articulated design may also provide better control and consistency for vertical positioning as compared to wire-supported buckets, which may reduce resuspension.
- Cutterhead (Medium) – Available data show conventional cutterhead dredges generate less sediment resuspension than conventional clamshell dredges.

- Horizontal Auger (Medium) – Available data show auger dredges generate less resuspension than conventional clamshell dredges, but higher resuspension as compared to cutters due to the higher rotation speed of the augers.
- Plain suction (High) – Plain suction dredges have no mechanical action at the dredgehead to dislodge sediment, so resuspension potential is solely due to the advance of the dredgehead through the sediment.
- Pneumatic (High) – Pneumatic dredges have no mechanical action to dislodge the material, acting essentially in the same manner as a plain suction dredge with respect to resuspension.
- Specialty Dredgeheads (High) – Although designs vary, many of the so-called specialty dredges have features specifically intended to reduce resuspension.
- Diver assisted (High) – The precision of diver assisted hydraulic dredging, the smaller size of the dredgeheads used, and the inherent speed of the operation all contribute to low potential for sediment resuspension.
- Dry Excavation (High) – This approach completely isolates the excavation process from the water column.

Contaminant Release Control

The selection factor for contaminant release control refers to the inherent ability to control sediment resuspension and dissolved and volatile releases for the given equipment type and associated operation. Resuspension of sediment during dredging will result in release of contaminants to the dissolved phase in the water column by release of porewater and by desorption from resuspended sediment particles. The resuspension due to operation and movement of scows and workboats in shallow water areas is another consideration, but is generally not amenable to control. Depending on the contaminant, subsequent releases to the air through volatilization may also be a concern (Cushing 1998). Volatile releases from the material in the barge may also be an issue for some sites. Volatile releases may also be an issue at the disposal or rehandling/treatment site, but the surface of a disposal or rehandling basin is not generally amenable to controls. Potential for contaminant releases at the dredging site is directly related to the degree of sediment resuspension (as described above), but contaminant release control is considered as a separate equipment selection factor focused on the ability to control releases, rather than the inherent potential of a given dredge type to minimize sediment resuspension.

A distinction should be made between engineered controls and operational controls for environmental dredging. Operational controls may be defined as changes in operation of the equipment or operational approach for the project that result in reduced resuspension and release. Examples of operational controls might include a general reduction in the rate of removal (essentially slowing the operation), limiting operations to specific hydrodynamic conditions (such as flowrate or tidal cycle), optimizing specific operations (such as ladder swing speed, cutter rotation speed, depth of cut, or speed of advance of the dredge), optimizing the sequence of dredging (upstream to downstream units or with respect to number of vertical cuts). Engineered controls for environmental dredging may be defined as designed controls or containments deployed around or in conjunction with the dredge plant. Examples of engineered controls might include installation of dredgehead shrouds, silt curtains, sheet pile enclosures, surface membranes or coatings to minimize volatilization, or other containment types.

Application of controls is potentially expensive and can significantly reduce overall production rates and efficiency. Therefore, controls should be applied only when conditions clearly indicate a need, and should not be set as a requirement for a project solely because they CAN be applied. An engineered control such as a silt curtain does not reduce turbidity or sediment resuspension, rather it merely confines the resuspended sediment, and may allow concentrations of both suspended solids and dissolved contaminants to increase to high values within the enclosure, only to be released when the curtain is moved. There is little data to support reductions in resuspension and release resulting from application of operational controls related to rates of operation. With appropriate feedback, experienced dredge operators can find the optimal rate and method of operation for a given set of conditions. For hydraulic dredging, resuspension is generally minimized at the same point that production is optimized. If the rate of operation is slowed or accelerated, the resuspension and release may be increased.

The ratings and associated technical basis for contaminant release control are as follows:

- Clamshell (Low) – Conventional clamshells can be operated such that the excavation and water column exposure of the bucket is within a silt curtain containment or enclosure, however, high suspended solids within the silt curtain may be released when the curtain is moved.
- Enclosed bucket/ Articulated Mechanical (High) – Enclosed buckets can be operated such that the excavation and water column exposure of the bucket is within a silt curtain enclosure with relatively small footprint. The enclosed buckets act as a control to greatly reduce resuspension within the enclosures and potential for release.
- Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads/ (Medium) – Cutterhead and auger dredges have been fitted with hoods or shrouds in an attempt to partially control the spread of resuspended sediments, but there is no definitive data to support their effectiveness. All hydraulic and pneumatic dredges are capable of transporting the material directly by pipeline to subsequent disposal or treatment minimizing exposure to the entire water column and exposure of excavated material to volatilization at the dredging site. Hydraulic dredges can be operated within silt curtain or sheet pile enclosures, but the footprint of such enclosures would necessarily be larger than that for mechanical dredges.
- Diver assisted (High) – The scale of diver-assisted dredging would seldom require contaminant release controls.
- Dry Excavation (High) – Dewatering of the dredging area effectively eliminates dissolved releases. A sediment surface exposed to the atmosphere has lower volatile emission rates as compared to the same surface ponded with elevated suspended sediment concentrations.

Residual Sediment/ Clean Up Criteria

Residual sediment is defined as that portion of the sediment that is dislodged but not picked up by the dredging process, and that quickly falls to the bottom at the point of dredging without being dispersed to the water column (Palermo and Averett 2003). Resuspended plumes caused by dredging or other processes may be dispersed, may settle to the bottom, and may also contribute to residual sediment. The term "spill or spillage" is sometimes used to describe that portion of the material that is directly left behind by the dredge. This selection factor refers to how efficient the dredge is in removing material without leaving a residual, and therefore how efficient the dredge type may be in meeting a cleanup criterion.

All dredges leave some residual sediment, and it has become clear with field experience that residual sediment can be a major factor driving cost and effectiveness of an environmental dredging project. Residual sediment thicknesses for environmental dredging projects have ranged from a few inches up to a foot, while measured residual contaminant concentrations have widely varied, ranging from less than 1% to near 100% of the pre-dredge concentrations (surficial concentrations were actually higher after dredging for a few projects) (Herrenkohl et al 2003). Residual concentrations have been predicted for some projects based on an average concentration of the pre-dredging sediment profile (Herrenkohl et al 2003, Reible at al 2003, and Service Environmental 2002), and such predictions compared favorably with post-dredging sampling at the New Bedford Harbor site (Herrenkohl et al 2003). Unfortunately, there is little quality data on the magnitude and nature of residual and no commonly accepted methods to predict or monitor the thickness or concentration of residual for a given dredge type operating at a given site (Palermo and Averett 2003).

The ratings and associated technical basis for residual sediment/ clean up criteria are as follows:

- Clamshell (Low) – Conventional clamshell dredges have a high potential to leave residual sediment because of the circular-shaped cutting action and the tendency to leave a cratered bottom subject to sloughing.
- Enclosed bucket/ Articulated Mechanical/ Cutterhead/ Horizontal auger/ Plain Suction/ Pneumatic/ Specialty Dredgeheads (Medium) – All dredges with active dredgeheads and/or movement in contact with the bottom sediment will leave some residual sediment. The control offered by the articulated arm provides an advantage for removal of thin residual layers.
- Diver assisted (High) – The hand-held action of diver-assisted work has a low potential for generating residual sediment.
- Dry Excavation (High) – Any fallback of sediment excavated under dry conditions can be readily observed and managed.

Transport by Pipeline

Distance to the treatment/disposal location and the optimal condition for the material arriving at that location will greatly influence the selected method of transport. The selection factor for transport by pipeline refers to the compatibility of the dredge with subsequent transport by pipeline. And, this selection factor and the companion selection factor for transport by barge are closely related to the operational characteristic of percent solids as described above.

Hydraulic pipeline dredges are designed to pump material directly to a disposal or treatment site for distances up to several miles, and even over longer distances if booster pumps are used. The addition of excess water by the hydraulic dredging process (as described above) allows for easy hydraulic transport. But, excess water released from a disposal facility may require treatment. Also, if the material must be in a dewatered condition prior to disposal or treatment, active dewatering would usually be needed as pre-treatment, and the excess water would likely require treatment prior to discharge.

Pipeline transport can be used in conjunction with mechanical dredging, but additional equipment is required. Mechanical dredging removes the sediment at close to the in situ conditions as described above, but material at this water content is generally too stiff to pump via pipeline without addition of water. High solids content pumps can be used or water can be added to slurry the material. Some of the newer concepts and designs involve 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).

The ratings and associated technical basis for transport by pipeline are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical (Medium) – All mechanical dredges remove material at near in-situ density, and additional reslurry and rehandling equipment must be employed to allow for pipeline transport.
- Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads/ Diver Assisted (High) – All hydraulic and pneumatic dredges are designed for pipeline transport.
- Dry Excavation (Medium) – Additional reslurry and rehandling equipment must be employed to allow for pipeline transport.

Transport by Barge

This selection factor refers to the compatibility of the dredge with subsequent transport by barge and is practically the mirror image of that for transport by pipeline. A barge transport operation ideally involves use of several barges, one being filled while others are being transported and emptied, so that the dredge may operate on a close-to-continuous basis with minimal downtime. Since many environmental dredging projects involve removal of material in relatively shallow water, smaller shallow-draft barges (on the order of 500 to 1500 cubic meters) would normally be used as compared to the larger barge sizes commonly used for navigation dredging (up to 4500 cubic meters).

Efficient use of barges requires the material to be loaded in as dense a condition as possible. For this reason, mechanical dredging is ideally matched with barge transport. Hydraulic pipeline dredges can be used with barge transport, but such an operation is an inefficient use of equipment capability. The flowrate generated by hydraulic dredging would quickly fill a small barge with low-density slurry, and once the slurry is transported for offloading, the requirements for dewatering and water treatment would be similar to that for direct pipeline transport.

The ratings and associated technical basis for transport by barge are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical (High) – Material excavated with mechanical dredges is close to in-situ density and may be directly placed in barges for transport.
- Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads/ Diver Assisted (Medium) – Barge transport of hydraulically dredged material is inefficient. Although pneumatic and some specialty dredges are capable of removing soft sediments at high water content, intermittent operation for change-out of barges will significantly reduce efficiency.
- Dry Excavation (High) – Material excavated in the dry may be placed directly in barges using conveyers or front-end loaders.

Positioning control

This selection factor refers to the ability of the dredge to hold a desired position of the dredgehead horizontally with current, wind, or vertically with fluctuating tides. All the dredge types listed in Table 1 operate with a spud arrangement with the exception of the horizontal auger dredge that is free-floating and uses a cable and anchor system. Spuds are essentially vertical piles that can be set in the bottom material to provide reaction force for the excavating action of mechanical dredges, or a pivot for the swinging action of hydraulic pipeline dredges. Some of the dredge types may also use jack-up piles, an even more stable arrangement. Of course, divers are free standing and subject to currents. Positioning control is not a factor for dry excavation.

The ratings and associated technical basis for positioning control are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical (High) – Mechanical dredges operate with spuds or jack-up piles and are inherently stable against movement by normal winds and currents.
- Cutterhead/ Plain suction/ Specialty Dredgeheads (High) – Hydraulic dredges equipped with spuds and using a "walking spud" method of operation are inherently stable against movement by normal winds and current.
- Horizontal auger (Medium) – Horizontal auger dredges are free floating and operate using an anchor and cable system. The auger dredge is subject to movement in winds and currents with longer anchor sets.
- Pneumatic (High) – Pneumatic dredges operate from spudded barges or platforms and are inherently stable against movement by normal winds and currents.

- Diver assisted (Medium) – The ability of divers to maintain a desired position will be hampered by currents.
- Dry Excavation (High) – Dry excavation is not affected by wind and currents. The containment must be designed for normal tidal or river stage fluctuation.

Maneuverability

Maneuverability refers to the ability of the dredge to operate effectively in close proximity or around utilities and other infrastructure, narrow channel widths, surface and submerged obstructions, overhead restrictions, such as bridges, and other site access restrictions that may limit the type and size of equipment that can be used. Contaminated sediments may be located next to piers, stabilized shorelines, under bridges, etc. The presence of buried utilities, pipelines, and other infrastructure may also require buffer zones for clearance that may limit the ability of the dredge to gain access to all the areas requiring excavation. The mechanical dredges generally have the ability to operate closer to infrastructure and within tighter areas than the hydraulic dredge types.

The ratings and associated technical basis for maneuverability are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical/ Pneumatic (High) – Because the buckets are wire supported or fixed-arm articulated, mechanical dredges may be operated close in to infrastructure such as bridges or piers, and within tightly restricted areas such as narrow slips or channels.
- Cutterhead/ Plain suction/ Horizontal auger/ Specialty Dredgeheads (Low) – The swinging action of the walking spud method of operation for hydraulic pipeline dredges and the need for long anchor and cable setup for horizontal auger dredges limits their ability to operate near infrastructure or within tightly restricted areas.
- Diver assisted (High) – Diver assisted work can be conducted close to infrastructure and within tightly restricted areas.
- Dry Excavation (High) – Containments for dry excavation can be designed for areas near infrastructure and tightly restricted areas may be completely contained.

Portability/Access

This selection factor refers to the ability of the dredge to pass under bridges, through narrow channels, or to be transported by truck and easily launched to the site. Since this paper focuses only on small dredges, the ability to pass under bridges or through narrow channels would not normally be of concern. But the ability for truck transport and easy launching is a consideration for some small dredges.

The ratings and associated technical basis for portability/ access are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical/ Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Diver assisted/ Dry Excavation (High) – The dredge types considered here are the smaller size and are generally truck transportable.
- Specialty Dredgeheads (Medium) – Some specialty dredge designs are too large for truck transport.

Availability

This factor refers to the potential availability of dredges types to contractors and the potential physical presence of the equipment in the U.S. All the dredge types described in this paper are available to contractors to perform environmental dredging work. The one exception is the full range of the specialty dredges. Since these dredges were designed and are widely available only in countries outside the U.S., there may be constraints on availability for U.S. projects. The Jones Act restricts use of dredges on foreign-made vessels, but the use of a foreign-made dredgehead on a U.S. vessel is not restricted. Several U.S. companies have formed partnerships allowing for use of specialty equipment from a variety of countries, but the availability of a specific specialty dredge through only one contractor presents a significant constraint on competitive bidding.

The ratings and associated technical basis for availability are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical/ Cutterhead/ Plain suction/ Horizontal auger/ Diver assisted/ Dry Excavation (High) – Most dredge types are readily available.
- Pneumatic/ Specialty Dredgeheads (Medium) – Some specialty dredges are only available through one contractor, or may be subject to restrictions under the Jones Act.

Debris/Loose Rock/Vegetation

Debris is commonly present in nearshore sediments, especially in areas adjacent to piers, etc. The debris may be composed of almost anything, but pieces of piling, logs, vegetation, cable, welding rods, shopping carts, etc., are common. Some projects also involve presence of loose rock (cobble size to boulder size). Such debris tends to clog hydraulic dredgeheads, causing downtime and loss of production (in fact large debris is essentially left behind by small hydraulic dredges). Debris can prevent mechanical buckets from fully closing, causing increased sediment resuspension and contaminant release. This factor refers to the ability of the dredge type to effectively remove sediment containing debris or loose rock without excessive resuspension or excessive downtime to remove clogs, etc. In general, mechanical dredges are well suited to remove debris (as in a debris-removal pass) or to remove sediment with small debris present, even though presence of debris may result in some bucket leakage. The smaller hydraulic dredges can cut through some small debris, and small rocks and debris can pass through the pumps, but these dredges cannot remove larger loose rock or large debris such as logs or pilings.

The ratings and associated technical basis for debris/ loose rock/ and vegetation are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical (High) – Mechanical dredges can effectively remove sediments containing debris, although leakage may result. Mechanical equipment is the only approach for debris-removal passes.
- Cutterhead/ Plain suction/ Horizontal auger/ Pneumatic/ Specialty Dredgeheads (Low) – The hydraulic or pneumatic dredges are subject to clogging by debris and are incapable of removing larger pieces of loose rock and larger debris. Loose rock and large debris can also cause inefficient sediment removal.
- Diver assisted (Low) – Presence of logs and large debris may present dangerous conditions for diver-assisted dredging. Although divers can remove sediment from around large debris or rocks, this type of operation would be inefficient.
- Dry Excavation (High) – Dewatering of areas for dry excavation allow use of conventional excavation equipment. Leakage from buckets caused by debris is not a consideration for dry excavation.

Hardpan/ Rock Bottom

The presence of a rock bottom or hardpan with overlying contaminated sediments presents a most difficult condition for environmental dredging. No dredge type is ideally suited for efficient operation in such conditions. This factor refers to the ability of a dredge type to efficiently remove a sediment layer overlying hardpan or rock bottom without leaving excessive residual sediment. Rock bottom or hardpan interfaces would normally be uneven and may also contain loose rock from natural processes or from blasting if the project is in proximity to navigation channels, etc. The uneven hard surface prevents any dredgehead from maintaining a level cutting action. Dredgeheads with moving cutting components (e.g. cutterheads or augers) would tend to "bounce" off the hard surface during operation, leaving behind excessive residual sediments. Mechanical buckets would be prevented from level cutting action and would also tend to leave behind excessive residuals at the hard surface. Plain suction, including some of the specialty dredges that operate with essentially a plain suction removal action, may provide some advantage. But even the advance action of these dredge types over an uneven hard surface may be impeded and leave excessive residuals. Use of one equipment type for removal of most of the sediment mass, followed by another equipment type for residual at the hard surface may be the best approach for these conditions. An exception is a specialty dredge (Slope Cleaner) that has been designed specifically for removal of soft sediments accumulating between riprap linings along channels in The Netherlands.

The ratings and associated technical basis for hardpan/rock bottom are as follows:

- Clamshell/ Enclosed bucket/ Articulated Mechanical/Cutterhead/ Horizontal auger (Low) – The closing action of mechanical buckets and the cutting action of hydraulic pipeline dredgeheads would result in problems maintaining a desired vertical cutting position and would tend to leave behind excessive residual sediment. Power associated with articulated mechanical has advantage in removing hard materials.

- Plain suction/ Pneumatic/ Specialty Dredges (Medium) – Plain suction dredges and some pneumatic and specialty dredges lack an active closing or cutting action and can operate over an uneven hard surface, although removal efficiency may be low.
- Diver assisted (High) – Diver assisted dredging may be the most effective approach for precise cleanup of a hard face, since the divers can feel the surface and adjust the excavation accordingly.
- Dry Excavation (High) – Dry excavation allows the visual location of pockets of residual remaining on an uneven hard surface.

Flexibility for Varying Conditions

For some projects, the thickness of sediment to be removed or the sediment and site conditions may vary considerably. This selection factor refers to the flexibility of a given dredge type in adapting to differing conditions, such as sediment stiffness, variable cut thicknesses, and the overall ability to take thick cuts.

The ratings and associated technical basis for flexibility for varying conditions are as follows:

- Clamshell/ Enclosed bucket (High) – Conventional clamshells and enclosed buckets are capable of taking thin cuts or thicker cuts in proportion to the bucket size. Also, different bucket sizes can be easily switched with these dredge types to adapt to varying conditions between areas to be dredged.
- Articulated Mechanical (Medium) – Grab buckets for articulated mechanical dredges are capable of taking thin cuts or thicker cuts in proportion to the bucket size. The ability to change bucket sizes for articulated mechanical is limited.
- Cutterhead (High) – Cutterhead dredges are capable of taking variable cut thicknesses by varying the burial depth of the cutter. Also, different cutterhead sizes or designs can be used to adapt to changing cut thicknesses or sediment stiffness.
- Horizontal auger (Medium) – Augers are designed for a set maximum cut thickness, and attempts to remove thick cuts may result in plowing actions with excessive resuspension and residual.
- Plain suction (Low) – Plain suction dredges remove material without any cutting action and are limited in their ability to take thicker cuts or remove stiffer materials.
- Pneumatic (Low) – Pneumatic dredges remove material without any cutting action and are limited in their ability to take thicker cuts or remove stiffer materials.
- Specialty Dredgeheads (Low) – Most specialty dredges are designed for a specific application and have limited flexibility.
- Diver assisted (Low) – Diver assisted removal is limited to thin cuts.
- Dry Excavation (High) – Dry excavation allows use of a full range of conventional excavation equipment.

Thin lift/ residual removal

Contaminated sediments are often present in thin lifts, which requires the dredge to remove thin cuts. Also, all environmental dredging projects, regardless of the initial thickness of material, may require removal of thin layers of residual sediment once a full cut has been completed. This selection factor refers to the ability of a given dredge type to removal thin layers of contaminated material without excessive overdredging.

The ratings and associated technical basis for thin lift/ residual removal are as follows:

- Clamshell (Low) – The circular shaped cut of a conventional clamshell is not suited to efficient removal of thin layers.
- Enclosed bucket/ Articulated Mechanical (Medium) – Enclosed buckets with level cutting action are capable of removing thin layers, but the buckets would only be partially filled, resulting in inefficient production and higher handling and treatment costs.
- Cutterhead (Medium) – Cutterheads are capable of removing thin layers, but the percent solids is reduced under these conditions.
- Horizontal auger (Medium) – Augers are capable of removing thin layers, but the percent solids is reduced under these conditions.
- Plain suction (High) – The action of a plain suction dredge is well suited for removal of thin lifts, especially loose material such as residual sediment.
- Pneumatic (High) – Pneumatic dredges use a plain suction and are well suited for removal of thin lifts, especially loose material such as residual sediment.
- Specialty Dredgeheads (High) – Some specialty dredges are designed specifically for removal of thin lifts.
- Diver assisted (High) – The precision of diver-assisted dredging is well suited for removal of thin layers, especially residuals.
- Dry Excavation (High) – Dry excavation allows for a precise control of cut thickness, amenable to removal of thin layers.

DISCUSSION AND SUMMARY

Table 1 summaries the information on operational characteristics and equipment selection factors for environmental dredging developed and presented in this paper. The intention is to provide general information to help project managers make an initial assessment of dredge capabilities. There are many site-specific circumstances that will dictate which equipment will work for any given situation. Additionally, because new equipment is being continuously developed, project managers will need to consult with experts who are familiar with the latest technological developments in order to make an informed selection.

The key information presented in this paper is summarized as follows:

- The development and presentation of information on environmental dredging equipment selection factors has evolved over the past 25 or more years. The information in this paper provides definitions and a technical basis for the various operational characteristics and selection factors presented.

- Selection of equipment for environmental dredging must be considered in the context of the entire project. The dredging operation must be compatible with and fully integrated with the materials handling, transport, treatment, and ultimate disposal of the dredged material.

- Performance standards are a major driver in selection of equipment and operational approach for a given environmental dredging project. Project managers should develop performance standards to meet the project requirements, and, to the extent possible, resolve potential conflicts between standards (e.g. resuspension or quality of life standards vs. production standards).

- A range of equipment types is suitable for environmental dredging, but there is no one equipment type or design that is best suited for all projects. Each dredge type has both advantages and disadvantages with respect to the operational characteristics and selection factors. For many projects, multiple dredge types may be used to optimize operations, e.g. one dredge for production cuts and another dredge for thin cuts and/or residual passes.

- A number of factors must be considered in evaluating and selecting equipment for environmental dredging. The *quantitative* capabilities and limitations of equipment commonly available in the U.S for environmental dredging related to removal precision, production rates, dredging depths, etc., vary among equipment types and designs (see the first section of Table 1).

- The available equipment types and designs also vary with respect to relative effectiveness in addressing factors related to removal efficiency, resuspension and release, residual sediment, and compatibility with transport and disposal. The data related to the equipment selection factors that are a function of site and sediment conditions (those in the second section of Table 1) is *qualitative*. And the wide variation in site and sediment conditions does not presently allow for quantitative expression of these selection factors.

- Selection of equipment should be based on a project specific, site specific and sediment specific evaluation of all the pertinent factors. Selection of the best equipment type and operational approach for a given site usually requires a balancing of these considerations.

- The quantitative operational characteristics and qualitative selection factors presented in this paper are appropriate for screening and selecting equipment types for evaluation at the feasibility study stage or for pilot field-testing. Qualified individuals with field experience should undertake final selection of equipment for environmental dredging projects. Final selection of equipment for project implementation should normally be left to the contractor.

- Environmental dredging operations are highly complex, and the available data for drawing general conclusions, such as those contained in this paper, are very limited. Additional data collection is therefore crucial to further enhancing our understanding of dredging as a remedial tool for contaminated sediments.

ACKNOWLEDGEMENT

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. Permission to publish this material was granted by the Chief of Engineers. This journal paper is a revised and expanded version of an earlier conference paper published in the proceedings of the 23rd Annual Meeting of the Western Dredging Association (WEDA XXIII) held in Chicago, IL, June 10th to 13th, 2003 (Palermo et al, 2003). A special session on Environmental Dredging was held at that meeting to solicit input and comments on the conference paper from an expert panel of consultants and contractors with environmental dredging experience and the larger group of session attendees. Additional input was incorporated through a review of the revised paper by the expert panel and through the peer-review process for publication in the WEDA *Journal of Dredging Engineering*. Appreciation is expressed to the WEDA XXIII expert panel for their contributions and input. Panel members included:

Ancil Taylor - Bean Environmental
Mike Crystal - Sevenson Environmental Services, Inc.
Philip Spadaro - Blasland, Bouck and Lee
Don Hayes - University of Utah
Greg Hartman - Dalton, Olmsted, & Fuglevand, Inc.
Eric Seagren - Seagren Corporation

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