MANAGING DEBRIS FOR ENVIRONMENTAL DREDGING PROJECTS

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ABSTRACT

Debris is an important factor in the investigation and project planning phases for environmental dredging projects. An understanding of the characteristics and extent of debris within the dredging footprint is essential to understand potential project cost; identify appropriate means, methods, and required equipment to remove and manage debris; provide environmental protectiveness during construction; and ensure remedy performance after construction. The urgency of effectively investigating and addressing debris issues increases as surface and buried debris volume increases, especially if concentrated debris pockets or zones exist, or if the types and sizes of the debris present specific challenges. Available technical guidelines and resources detail methods for identifying debris, but do not provide definitive guidance for managing debris and minimizing their impact on the 5Rs (Removal, Resuspension, Release, Residuals, and Risk) of environmental dredging. This paper synthesizes available resources on debris considerations, from characterization through remedy construction, to provide a common basis for identifying and evaluating debris issues for environmental dredging projects. The goal is to advance the state of practice for environmental dredging regarding debris-related issues including identification, classification, management, and disposal.

Keywords: Contaminated sediment, sediment remediation, navigation dredging, sediment removal, sediment management, multibeam bathymetry, side-scan sonar, post-dredging residuals.

INTRODUCTION

Defining Debris

Merriam-Webster[6] lists the essential meaning of debris as "the remains of something broken down or destroyed" or "things (such as broken pieces and old objects) that are lying where they fell or that have been left somewhere because they are not wanted." U.S. Army Corps of Engineers (USACE) (2015) described debris as "…large rocks, timbers, trees, trash, and other discarded materials…" and while both may be appropriate, the latter meaning is more appropriate in this context. Experience has shown that debris in waterways and water bodies includes a myriad of items, some uniquely local and others more common. The wide variety of items leads to an even wider variety of shapes, weights, and densities. Consider the differences in gathering 8-foot (2.4-meter) long timber, trees, shopping carts, concrete blocks, wire rope,

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[6] https://www.merriam-webster.com/dictionary/debris, accessed on 26 January 2022.

steel barrels, and 10 feet (3 meters) long steel pipes, for example, embedded in soft sediment, possibly even covered by several feet of sediment. Even abandoned vehicles have been found at some sites.

With that in mind, the authors propose this definition of debris in the context of dredging projects:

> "Non-sediment material(s) of limited intrinsic value scattered or clustered within the sediment matrix, either buried or on its surface, having characteristics such as being sufficiently large and strong as to potentially impact dredging operations intended to remove sediment and/or impact the managing activities of the dredged materials. Debris can range in size from very small objects to large obstructions that require special equipment to remove. Items may range in composition from organic to inorganic materials. Debris typically excludes non-sediment granular materials such as saw dust and spilled raw materials."

Materials such as unexploded ordnance (UXO) and historical artifacts or other items of cultural or archaeological significance are excluded from this definition and are beyond the scope of this paper. Debris is a concern for any dredging project; however, routine dredging that occurs in navigation channels lessens the time during which debris can accumulate. In contrast, environmental dredging projects, especially those at legacy-contaminated sediment sites, often occur in areas that have not been dredged in many years. Further, many environmental dredging sites are in urban or industrial areas with increased debris potential from a variety of sources. Debris in river and lake systems often includes trees and other wood debris transported by floods. Vegetation and root mat can also interfere with dredging and become entrained in the dredge material as debris. Among the challenges presented by debris, it is common for debris to be found buried well below the mudline, complicating identification, characterization, and removal.

Accumulated debris occurring in concentrated debris pockets or zones (also referred to as "dense debris") can be a major issue for environmental dredging projects. This extends beyond the challenges of dredging sediment containing occasional debris. Debris removal operations to address dense debris may require specialized equipment and support vessels. Debris removal operations may increase sediment disturbance, which may warrant supplementary best management practices (BMPs) to protect water quality and control residuals. Finally, the debris itself may be contaminated and require special handling and disposal. Unexpected quantities of debris can impact the project's cost and schedule. Although localized areas of dense debris sometimes exist, especially near public access points, debris is usually scattered throughout the sediment of waterbodies. Widespread distribution further complicates finding debris during the investigation and planning stages. The range of materials dimensions, densities, and weight associated with the debris exacerbates these complications.

Improvements in debris management strategies are needed to mitigate cost increases during construction, reduce project delays, and avoid impacts to environmental protection.

DEBRIS CONSIDERATIONS FOR ENVIRONMENTAL DREDGING

Types of Debris and Key Characteristics

A focused debris characterization system could facilitate improved debris management by providing common terminology that becomes adopted by practitioners. Debris could be described based on a variety of characteristics that relate to how debris affects dredging and sediment handling. For purposes of this paper, a matrix was developed listing commonly encountered debris items and categorizing them by the characteristics most likely to affect dredging (the debris matrix exceeds page requirements for the conference; however, it is available at the following link: http://thedredgingprofessor.com/debris-matrix-table. Key characteristics include the following:

- ***Size***—Physical dimensions of debris determine dredgability and handling needs. Long objects (i.e., pipes, pilings, board, etc.) can prevent bucket closure for mechanical dredging and stop rotating cutters. Wide items such as concrete slab and sheet metal can prevent bucket or cutterhead penetration, occluding access to targeted sediments beneath.
- ***Embeddedness—***Large objects may require removal prior to dredging. As such, their embeddedness in sediment is a key factor in how they affect operations. Pilings, relic seawalls, and abandoned pipelines or cables all present special challenges.
- ***Material Hardness and Density***—Materials such as rotted wood may be soft enough that buckets or cutterheads can shear even large debris into smaller, dredgable pieces ("debris items"). Alternatively, harder debris can cause problems even if debris items are small by preventing bucket penetration, jamming hydraulic screens, causing wear in transport pipes, and jamming pumps. Material that is light or buoyant can become dislodged and pose an obstacle during dredging or add to logistics necessary to manage the floating debris. Concentrated debris pockets or zones may be of such weight that it requires separate equipment for removal or specialized demolition techniques.
- ***Debris Distribution***—Concentrated debris pockets or zones ("dense debris"), as compared to widely distributed debris throughout the removal volume, may have differing logistics for removal. Debris impacts may or may not be similar. For example, significant quantities of medium-sized debris distributed throughout the depths of dredging may be removable by environmental or conventional mechanical dredge buckets (with potentially similar effects on resuspension rates, residuals generation, and dredging production rate), whereas concentrated pockets of medium-sized debris may require supplementary operations for removal. The latter may have some differing considerations for effects on resuspension rates, residuals generation, and dredging production rate.
- ***Environmental Concerns***—Some debris may be a source of chemical release or contain chemicals that require special handling or disposal. This may include creosoted pilings and rail ties, wood that has absorbed chemicals from surrounding sediments, cars or appliances containing oils and hydraulic fluids, and slag or coke containing metals or altered pH. While some of these can sometimes be managed using the same methods as for sediment, others may require special considerations based on the regulatory framework.

Using these characteristics, debris can be classified into common types. Size categories are nominally classified as large, medium, and small. In this effort, large debris is defined as greater than 6 feet in any one dimension, which is larger than the throat of many environmental buckets and sufficient to occlude materials from hydraulic removal. Medium debris is defined as debris between 2 and 6 feet in its largest dimension, and small debris less than 2 feet in all dimensions. The selection of 2 and 6 feet as nominal divisions is based on experience associated with debris management; however, these lengths should not be considered as precise or absolute. They are best described as guidelines.

Common debris materials that differ in hardness and density include: wood; stone and related conglomerates, including rock, concrete, slag, asphalt, or brick; metal (typically iron or steel); machinery, including appliances, cars, vessels, etc.; and other miscellaneous materials such as plastic or foam.

Debris Impacts on Dredging Operations

Debris can significantly impact the effectiveness, implementability, and cost of environmental dredging projects. It can interfere with dredge operations by impeding penetration, movement, and sediment capture, often requiring multiple removal attempts targeting the same sediment. Multiple dredging attempts reduce efficiency and the remolded sediment structure exacerbates impacts associated with the 5Rs of environmental dredging. Figure 1 illustrates the mechanisms of resuspension, release, and residuals as components of the 5Rs given the action of a single mechanical dredging bucket's interaction with the sediment bed. It becomes evident that additional interaction of the bucket and debris, whether dislodging additional sediment or preventing bucket closure, will be contributing to these mechanisms for each bucket cycle involving debris.

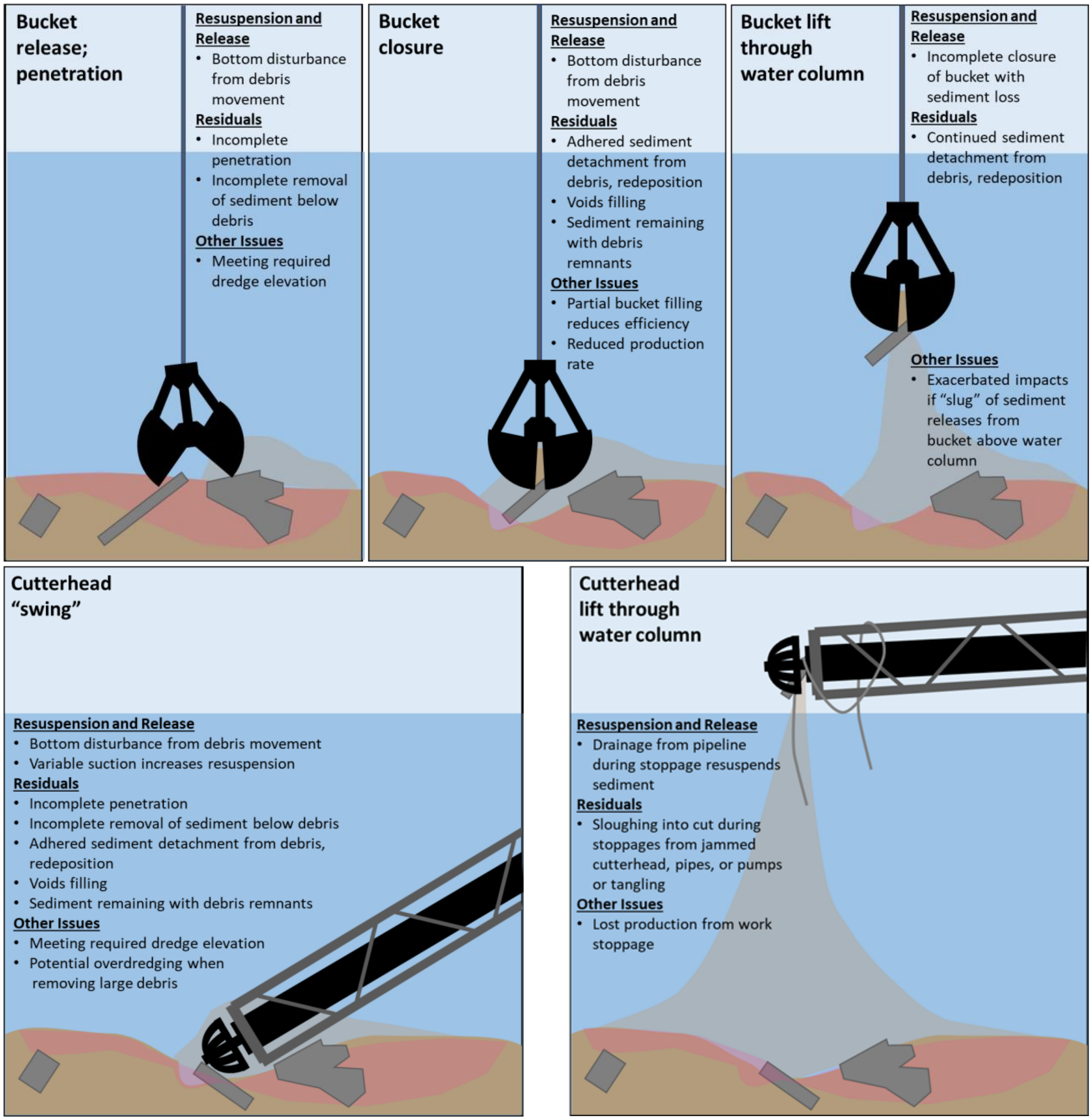

Figure 1. Schematics of debris impacts on environmental dredging operations.

Specific impacts are summarized in Table 1. A section of this paper is devoted to Debris Impacts on the 5Rs of Environmental Dredging.

Project Duration

Debris removal operations and implications on dredging production are discussed separately and are components that impact project duration. Changes to dredging sequencing and redredging are additional impacts to operational efficiency. The amount of redredging required as the result of a single debris item varies. In the best circumstance, the initial dredging attempt moves the debris from the targeted dredging area—either by removing it or pushing it to the side—and the second dredging attempt is fully successful at removing sediment in the area to the required depth. If that were always the case, a relatively straightforward statistical approach could be applied to estimate added construction duration. For example, if debris is expected to be encountered every 100th bucket, then extending the schedule by 1 percent would theoretically cover the additional time required associated with debris.

Table 1. Debris impacts on resuspension, contaminant release, and post-dredging residuals.

Dredge Type	Debris Impact	Sediment Resuspension	Contaminant Release	Post-Dredging Residuals
Mechanical	Incomplete bucket closure	X	X	X
	Incomplete bucket penetration			X
	Unable to remove debris in same pass as dredging		X	
	Disturbance of surrounding sediment when debris is removed	X	X	X
	Disrupts clean cut between target and underlying sediments (loosens/softens for reduced sediment density)	X		X
Hydraulic	Failure to intake sediments			X
	Incomplete penetration			X
	Unable to remove debris in same pass as dredging		X	
	Disturbance of surrounding sediment when debris is removed	X	X	X
	Disrupts clean cut between target and underlying sediments (loosens/softens for reduced sediment density)	X		X

Dredging equipment is typically not designed for debris removal. Therefore, removing or moving the debris out of the dredge area does not routinely occur during the first contact. It may take several attempts for a clamshell bucket to “grab” one debris item sufficiently to raise it to the surface. An environmental bucket designed to provide complete closure to limit loss of sediment and often to provide level cuts for precision removal is relatively lightweight compared to a conventional clamshell bucket and may have difficulty grabbing and moving large or heavy debris. Large, heavy debris may even damage some buckets. Most buckets also have a closure pattern designed to contain soft sediment, which will be ineffective for any debris that is not fully contained within the closing bucket. It has become increasingly common for a separate conventional clamshell bucket or other attachments to be readily available (mobilized and on-hand at the project site) to deploy in the event the environmental bucket cannot effectively remove contaminated sediment with debris; even this approach has limitations when debris is not easily captured and held by the weight of the partially closed bucket. A cutterhead dredge may push debris out of the dredge path; however, the delay can be extensive if it gets caught in the cutter. If that happens, the dredge must shut down, the ladder must be raised, and a contractor must remove the debris from the cutter by hand. Debris may also become lodged in intake screens and dredge pump, pipeline, or sediment processing equipment. Such an operation could easily involve delays that range from a single starting and stopping cycle that slows production rate to a multiple hour event (or events). Such labor-intensive operations can also present significant safety concerns.

Failed dredging attempts can also destroy the sediment structure making it more difficult to remove due to lower density/higher mobility, possibly leading to sediment mobility caused by the dredge equipment disturbances, which may transport these materials from the dredging area. Consider, for example, a clamshell bucket that successfully snags a debris item in the process of capturing a full bucket of sediment that prevents complete bucket closure. It would be typical for most of the captured sediment to remain in the bucket while it is below the water surface. However, as soon as the bucket breaks the water surface, captured sediment will likely flow from the bucket with the water. While most of the sediment mass will likely resettle quickly to the bottom, some sediment liberated (i.e., resuspended) throughout the water column may be transported away from the dredging area by currents. Even if the bucket retains its grip on the debris and successfully removes it from the dredging area, the previously captured sediment now exists in a much lower density. Removing it again may require multiple additional dredging attempts, likely recovering only a percentage of the volume, thus contributing to the need for residual covers or sediment capping to achieve remediation goals.

Schedule delays and project cost increases resulting from debris impacts should be included in the project planning phase[7], or identified to owners as part of risk registers or contingency planning. The effect of multiple removal attempts resulting from the presence of debris on dredging efficiency is obvious; each additional attempt takes time and increases the project duration and cost. Even single digit percentages of increase can represent significant cost. In addition to cost implications, each attempt for debris removal may further impact the accumulating residuals and add resuspension events, which may reduce environmental protectiveness. Unfortunately, a proven method to reliably estimate schedule delays resulting from debris removal and management does not currently exist.

Debris Questionnaire Survey and Results

The authors believe experience-based feedback from practitioners engaged in environmental dredging for contaminated sediment remediation projects is important to fully understand the debris issues and some of its potential solutions. Thus, a survey was prepared to obtain both qualitative descriptions and site-specific details (and data if available) for projects that have included debris as a key factor during project planning or construction. Surveys were distributed to 10 experienced professionals, primarily environmental dredging contractors.

The survey consisted of two parts: four general questions and a project-based questionnaire. The four general questions are included as the numbered questions below along with a summary of the responses. The remainder of the questionnaire that examined additional details specific to individual projects is not provided in the conference paper due to page number requirements; however, this summary provides the primary feedback.

Six survey responses were received. Feedback from the general questions is summarized as follows:

1. In your experience, when projects involve debris as a significant technical and/or constructability consideration, what additional technical guidance and/or procedures are needed to address debris-related issues?

   Responses Summary: Additional technical guidance and/or resources are needed.
   - Technical guidance that provides a common framework for approved approaches to address environmental concerns for debris removal operations is needed. Currently, this can vary significantly among projects in differing regulatory settings. Are turbidity curtains required for pre-dredging debris removal operations? Can debris be placed on barges that allow the water to decant, or will all water in contact with debris require containment in barges and treatment? What means and methods can be identified as acceptable practice irrespective of location?
   - Detailed computations of debris quantity based on site-specific data, considering debris types and sizes, rather than generalized estimates developed during design should be made available to the dredging contractor. This includes characterization and quantification of surface versus buried debris.

[7] The use of the phrase “project planning phase” in this paper generally refers to the stages of the project following the investigation phase (e.g., feasibility study, design, and pre-construction bid support).

- Recognition in the design process that variable characteristics of debris materials should be considered when developing specific requirements and estimating costs, such as these examples:
  - Under the category of debris types, wood versus concrete considerations (removal and management of a disposal unit of wood are significantly different than a disposal unit of concrete).
  - Under the category of debris types, metal cable has special considerations, UXO has safety and handling considerations, historically significant artifacts have federal/state/local agency notification and requirements, and removal and management considerations
- Consistent application of considerations regarding impacts of debris on dredging operations, such as these examples:
  - Acknowledging needs for changes in operations in contract documents, such as provisions that allow alternative buckets to environmental buckets for large debris removal and/or when in areas of dense debris.
  - Additional overdredging allowance when buried debris occurs, especially large debris or concentrated debris pockets or zones.
  - Identification of special removal (pre-removal) and debris handling requirements (grapple) in contract documents.
  - Many others may apply.

2. What are some of the more significant issues you have encountered with debris that could be better mitigated during the investigation and planning phases prior to construction?

   Responses Summary: Significant debris issues that have been encountered on projects may be partially or fully mitigated with debris investigations prior to construction. Examples of significant debris issues or implications were provided.
   - Avoid requirements for contractors to investigate debris during bid period or during construction—insufficient time is available during the bid period and, although during-construction methods such as test pits and diving may be useful, the timing of these approaches is problematic for planning appropriate logistics and, as a result, project costs and schedule may be impacted.
   - Larger-sized debris may necessitate separate removal equipment and crews.
   - Additional BMPs such as bubble curtains and/or supplementary turbidity barriers, increased maintenance and repair activity for BMPs, and additional water quality monitoring may result.

3. With projects involving debris, have you found the challenges are more commonly related to contractual issues (quantity of debris and cost implications, lost production, cost of additional logistics) or the impact debris can have during dredging operations such as water quality impacts, dredge residuals generation? Or is it both? The remainder of the questionnaire can be used to elaborate with examples.

   Responses Summary: Both contractual issues and operations impacts are common when difficult debris conditions are encountered.
   - Projects often transfer risk to the contractor in technical requirements for operations and/or payment structure as lump sum for debris.
   - Achievable production rate and logistics for management and disposal operations may be impacted by debris, which directly involves bid price assumptions that would justify change orders.

4. Have dredging projects you are experienced with required special handling and disposal operations for certain debris(?); if yes, please explain. Additionally, what is the most common handling and disposal processes for dredged debris for your projects?

   Responses Summary: Yes, special handling and disposal requirements are common.
   - Landfills may require special sizing or separation.
   - Special transportation requirements may apply.
   - Archaeological items and UXO require special removal, handling, and final disposition. Significant impacts to project schedule and cost may occur if encountering these items unexpectedly.
   - Metal recycling may be applicable.
   - Local authorities may become involved under certain circumstances (e.g., if recovering automobiles or if debris includes weapons or other materials, additional time for police investigation or inspection may be necessary).

The overall summary of the remaining project-specific viewpoints is as follows:

- Construction project requirements should balance risk between the owner and contractor (e.g., with approach to payment: reduction in added cost for contingency for debris operations may occur by using fixed unit price per ton payment approach, using time and materials, or using a daily rate when significant debris is encountered).
- Investigations for surface and buried debris during design phase are important, using a range of technologies; investigations prior to construction may aid in understanding debris impacts and increasing efficiency and cost-effectiveness of operations.
- Debris impacts production for both mechanical and hydraulic operations, binding cutterheads or clogging dredge pumps/manifolds, sediment losses from buckets requiring additional cycles, etc.
- Debris impacts material handling by posing several challenges (e.g., is there special handling and disposal requiring segregation of certain fraction of debris [metal, artifacts, munitions])?; does debris management require processing such as chipping wood or cutting down large pieces?
- Water quality impacts and increased dredge residuals may occur due to debris; if separate debris removal operations are required, BMPs may be necessary to manage turbidity, etc.

DEBRIS IDENTIFICATION METHODS

Developing a comprehensive understanding of debris quantity, types, and sizes for both surface and buried debris is an important goal during the investigation phase. While debris investigations benefit most projects, they are particularly valuable for projects with known or suspected debris issues or when historical site uses imply a high probability of significant debris item quantities and/or concentrated debris pockets or zones. The appropriate range of equipment types and expected operations for managing both expected and unexpected debris should be considered during the feasibility study to provide a more complete remedial alternative; therefore, the remedial alternative's dredging, material management, and disposal process is more accurately predicted, and a more representative cost estimate may be prepared for comparisons. A more complete understanding of debris from the investigation phase may also influence the selected remedial alternative. The project's selected remedial alternative may then include an additional debris investigation in support of the design, facilitating greater confidence in the estimation of debris removal and management activities that will be required during construction.

Investigation technologies that may provide data to support identification and characterization of debris are listed below. Table 2 provides a summary of debris investigation technologies, the limitations associated with each technology, and the applicability/relevance to specific types of debris or project conditions. Although not included in Table 2, initial research of the site's history can provide considerable insight into potential debris and aid in developing the scope of debris investigations.

Debris investigations are primarily field methods that are commonly phased so the cost of obtaining additional detail can be weighed against the cost of potential debris-related impacts to project costs. Hydrographic surveys provide bathymetric information essential for almost every project. They also provide data that may help identify surface debris. The size and frequency of potential debris identified by hydrographic surveys can be combined with site location and site history information to map suspected debris locations and provide generalized estimates of debris characteristics for further investigation. Project planners can weigh the value of higher resolution surveys to further refine debris characteristics at each specific project phase.

Table 2. Summary of Debris Investigation Technologies

Investigation Method	Description	Interferences or Limitations	Applicability for Debris Identification and/or Characterization
Multibeam Bathymetry (Hydrographic Survey)	Acoustical energy method typical for project investigation phase, which can also be used to identify debris or features suspected as debris. Sonar reflections on the bed of the water body are digitally processed to map the surface.	Shallow water depths may reduce effectiveness. For remediation projects, both single beam and multibeam configurations are suitable for providing bathymetric mapping; however, for debris investigation, the multibeam configuration is necessary for debris identification.	Applicable for surface debris, not buried debris. Debris must be above sediment surface and large enough and/or distinctly shaped to be interpreted from the surrounding sediment surface. Most useful for large and some medium debris sizes. An advantage of using bathymetry for initial debris screening is that given most all projects include this data collection in the early stages of investigations, it provides an opportunity for early identification of large surface debris and may identify debris-like features that warrant further investigation.
Side-Scan Sonar	Acoustical energy method, using active sonar to scan and map bed surface features. Technology can produce a high-resolution image of the bed surface and debris.	Shallow water depths may reduce effectiveness. For some systems, deep water conditions may present challenges with resolution.	Similar to bathymetric survey; however, data density provides a higher resolution of bed features. Large and some medium-sized debris is identifiable if there is a sharp contrast with surrounding sediment. Very precise mapping of surface texture allows for improved identification of debris type and size.
Magnetometer	Local changes in the magnetic field are measured for changes in field strength given presence of ferrous metals.	Significant interferences from sheet pile bulkheads, steel piles, and metal structures may occur if surveying for metal debris in sediment.	May identify anomalies, but likely requires further investigation to confirm and characterize debris. Anomalies without further investigation may be used in the project planning phase, but this may result in unexpected debris conditions during construction.
Electromagnetic Induction	Electrical current transmission to a pipe or wire occurs without direct contact, and a receiver analyzes the signal to determine metal position and depth.	Interferences from metal objects may occur. Pipes without good metal-to-metal connection, broken wires, or breaks in the utility will limit effectiveness. In the coil configuration, can be used to locate ferrous and non-ferrous objects in subsurface (e.g., UXO survey, metal debris, etc.).	May effectively identify utility crossings and allow some estimation of cover depth. Results typically have a range of confidence with data interpretation. Higher confidence interpretations may allow establishment of offsets for dredging. Similar to magnetometer regarding results in terms of anomalies or detections that require further investigation and/or verification.
Sub-bottom Profiling	Acoustical energy reflections from differing sediment (and subsurface geology) densities produce sonar reflections with differing return times to the instrument. High frequency energy may penetrate further than low frequency energy.	Attenuation of energy by sediment may lessen penetration. Gas may leave voids in data. Reefs, rock, or very dense materials may produce a strong return preventing further penetration.	Limited applicability for debris survey. Strong contrasts in density and composition may result in changes in the magnitude of energy reflection occurring in the subsurface. Most often this technology is used to determine distinct geologic layers below soft sediment deposits but may also identify "anomalies" that may signify debris. Further investigation is required to identify and characterize the anomalies. May have limited effectiveness with large-sized buried debris.
Remotely Operated Vehicle Videography and Photography	Controlled vehicle positioned at specific locations or surveyed along transects to record videos or photographs of objects. Light source is provided.	Turbidity in water will impact visibility.	Applicable for surface debris, not buried debris. Ideal as a secondary exploration technology to refine understanding of debris identified using other technologies. Effective for localized investigation, but not practical for use over large areas. If surface debris is encountered and sufficient proportion of the debris is exposed and observable given the orientation of the remotely operated vehicle, the video may provide a relatively high degree of confidence for identification and characterization of the debris. A remotely operated vehicle can combine other remote sensing with videography, etc.

Diver	Certified and experienced dive team may investigate specific features such as near waterfront structures, or further investigate anomalies identified by other technologies to identify and characterize the debris.	Turbidity in water will impact visibility. There are numerous safety considerations for methodology; additionally, environmental suit and specific equipment types are required to isolate diver from sediment and water column for environmental remediation projects.	Applicable for surface debris, not buried debris. Due to potential hazards, only visual inspection may be appropriate, rather than disturbing sediment to attempt a better view of the debris. Effective for localized investigation, but not practical for use over large areas. A clear water box can be used in turbid water to improve visibility of the features. A diver can become the "survey vessel" for high frequency sonar to image structures or debris.
Test Pits	Test pits during in-water work may be accomplished by barge-based excavator or by dredging equipment before production dredging begins; therefore, equipment mobilized by the contractor is used for the investigation.	This method should be employed after other debris investigations have occurred during the project planning phase, at the start of the construction phase if cost-effective. Resulting data provides distribution of debris in sediment; also, allows direct observation of debris types and sizes.	Effective investigation method for refining contractor means and methods; however, the focus of the investigation at the construction stage of the project would be for improving efficiencies or, for example, verifying anomalies from other investigations (to confirm or adjust debris removal and material management activities). This should not be the primary method for debris investigation.

Figure 2 is an example of large debris identifiable by multibeam bathymetry. The automobiles are evident given both the debris size and the technology's ability to scan the entire surface of the sediment bed at high resolution. An additional technology that can be coupled with hydrographic surveys is side scan sonar, which provides even more of a three-dimensional perspective of the sediment bed surface, contributing to identification of debris and some characterization of type, size, and quantity of the debris. A more complete understanding of surface debris conditions may improve predictions of buried debris conditions, but this should not be expected to provide accurate quantity estimates. Methods such as side scan sonar and sub-bottom profiling may identify some fraction of the buried debris, leaving the potential for significant unexpected debris to be discovered during construction.

Quantifying approximate locations, sizes, and characteristics (e.g., density) of debris leads to cost-savings for many projects by leading to the development of the efficient logistics for debris removal, management, and disposal. In addition to facilitating contractor selection of the appropriate equipment, etc., more significant changes to typical dredging operations such as adding pre-dredging debris removal of large debris items or concentrated debris pockets or zones can be included among expected project costs. Despite adding to project costs, this separate operation may provide overall cost-efficiencies for dredging. Even if pre-dredging debris removal does not occur, plans can be developed in advance for removal and management of known debris during the dredging operation.

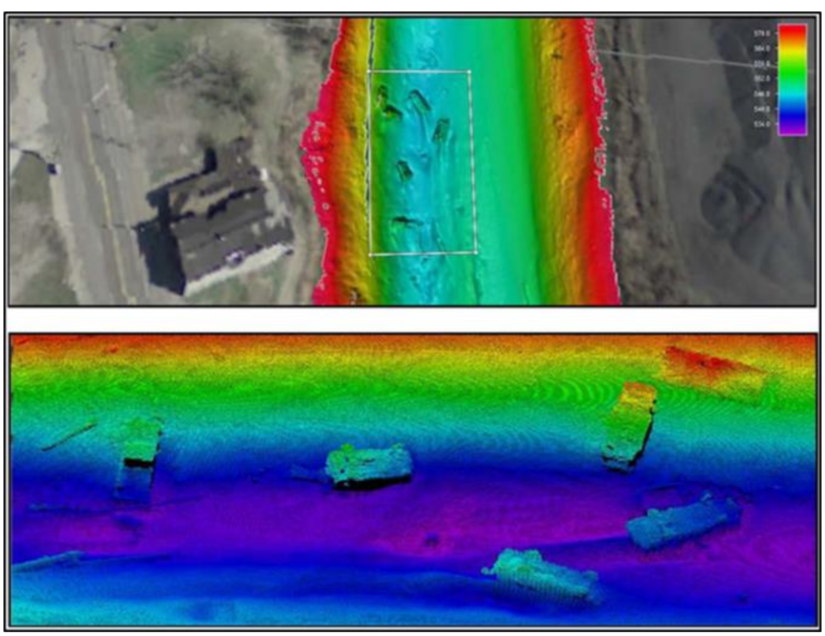

Figure 2. Images from high-resolution multi-beam sonar showing debris.

However, it is unrealistic to expect technologies to precisely locate, identify, and characterize all debris using current methods. Buried debris is particularly challenging. Thus, most environmental dredging operations will encounter some amount of "unexpected debris" that must also be managed, and this debris quantity is unlikely to be addressed during pre-dredging debris removal operations.

PRE-DREDGING DEBRIS REMOVAL AND MANAGING DEBRIS DURING DREDGING

Removal Equipment and Strategy

The primary considerations for the approach and timing of debris removal are the physical characteristics of the debris and its final disposition. Requirements for debris separation from sediment and processing for disposal/recycling/reuse are significant drivers for determining the most appropriate means and methods employed for debris removal. While a detailed discussion of sediment processing approaches is beyond the scope of this paper, it is important to note that a thorough understanding of the extent and type of debris management operations that are necessary, such as debris washing, screening, shredding, crushing, and grinding, is paramount for determining effective means and methods for debris removal.

Equipment and Methods for Removal

Common equipment attachments used for debris removal on dredging projects include excavator buckets, thumb attachments, fork/tine grapples, orange-peel grapples, and clam shell buckets on excavators or cranes deployed on platform barges. Examples of debris removal equipment are provided in Figures 3 through 5. This equipment is readily available to the contractor and effective for the removal of a variety of small to medium-sized debris types. Environmental buckets (excavator bucket with an actuating lid) frequently used for mechanical environmental dredging are capable of picking and removing some light debris materials; if this is successful, it may reduce the need for separate debris removal equipment, thereby avoiding the loss in efficiency associated with changing attachments on the dredge equipment. It should be noted, though, the efficiency of using an environmental bucket for debris removal diminishes quickly with increasing debris weight, size, quantity, occurrence of concentrated debris pockets or zones, as well as shapes of debris incompatible with typical removal equipment.

Less common attachments for debris removal include weed rakes or skeleton baskets that are sometimes used for cobbles, rocks, and vegetation. Hydraulic shear attachments may be used to cut root mass, stumps, and trunks of trees embedded in the banks (or submerged in the dredge area) to minimize waste generation, maintain bank integrity, and size debris. Vibratory pile pullers are employed for removing wooden and steel structures and piles. Contractor have been innovative developing site-specific debris removal approaches. For example, Sevenson Environmental Services, Inc. (Sevenson) designed and developed a rotating screen bucket (pictured, Figure 3) to separate cobbles from sediment during dredging. Ultimately, the equipment and attachments used will depend on the range of debris characteristics, sizes, burial depths, and distribution expected to be encountered at the project site. Specific to hydraulic dredging equipment, cutterhead baskets and chain ladders cutterheads have been used to reject and move large debris away from the pumping zone (USACE 2001). In some instances, debris removal operations can occur from the bank of the water body (particularly along rivers where debris naturally accumulates at the water's edge) using conventional heavy equipment (e.g., excavators). This approach can be advantageous in shallow areas where access may be limited to barges until dredging has commenced. Divers may also be used to facilitate debris removal by cutting embedded debris or rigging large debris such as cars and boats that are sometimes found in the bottom of urban waterways. Although this approach is costly, resource-intensive, and has significant health and safety considerations, in certain conditions it may be necessary.

Debris removal does pose risks for the generation of resuspended sediment materials in the water column. While this risk depends significantly on the debris type, physical characteristics of the sediment, and the hydraulics of the water body, the debris removal equipment used and the approach taken may significantly influence the level of resuspension that occurs. The dredge team should carefully consider the equipment and approach anticipated to be used for debris removal to minimize resuspended materials.

Figures 3. Rotating screen for cobble materials (courtesy of Sevenson); debris scow mechanical offloading operation (courtesy of Sevenson); grapple for debris removal operation (courtesy of Mack Manufacturing).

Effective Sequencing of Debris Removal Operations

Pre-dredge debris removal operations, or sometimes known as debris sweeps, are conducted to remove known debris within the dredge area to facilitate effective and efficient dredging. Whether debris removal is conducted as an operation before dredging or is conducted as concurrent operation will be primarily a function of the type of dredging (hydraulic versus mechanical) as well as the quantity, density, size, and distribution of debris. While hydraulic dredging equipment has some limited capacity to manage rock and wood debris by passing or casting this material from the intake, this operation is at greater risk of potential downtime and maintenance challenges due to debris. Cable and wire debris can be particularly troublesome for hydraulic dredging equipment. Normally, hydraulic dredging requires separate equipment to address medium and large debris (materials size or type too large or potentially damaging to the intake of the dredge) if expected in the dredge area. Gatlin plates, hardened steel plates welded at the intake of the dredge, are used to limit the potential of drawing in debris that could clog or damage the dredge impeller or subsequent processing equipment and piping. Gatlin plates vary in size and are intended to be large enough to exclude the expected debris at the site but minimize the impact to production rate from the reduced cross section of the intake from the steel plate. For dredging efforts that rely on hydraulic dredging or sites that have significant quantities of buried debris that cannot be removed as a part of a pre-dredge debris removal event, debris removal equipment may be mobilized and maintained at the dredging site to conduct debris removal as the items are located. Some contractors find improved efficiency by assigning debris removal crews (which are not typically needed full-time) other work responsibilities such as maintaining turbidity controls.

Alternatively, mechanical dredging equipment is generally capable of removing and managing small and medium-sized debris during dredging operations reducing the need for pre-dredge removal operations or the need for debris sweeps during dredging. Grapples, buckets, and other attachments can be changed during operations to allow debris removal periodically throughout the dredging sequence. As mentioned earlier, depending on the size and character of the debris, environmental dredging buckets can be used to remove some debris eliminating the necessity of switching attachments during dredging.

DEBRIS REMOVAL IMPACTS ON 5RS

Environmental dredging guidelines place emphasis on the primary factors that influence the effectiveness of dredging for environmental protectiveness of the sediment remediation project. These factors are known as the 5Rs of environmental dredging and are increasingly incorporated into evaluations during the planning phase of projects (Palermo et al. 2008; Bridges et al. 2010). Following investigations to provide physical properties of sediment and chemical concentrations for extent of contamination, insights will be available to better understand the relative importance of these factors during dredging operations. Figure 4 shows the 5Rs as a widely referenced schematic of how these factors interact during a mechanical bucket cycle; similar effects are applicable to the swing of a hydraulic dredge ladder.

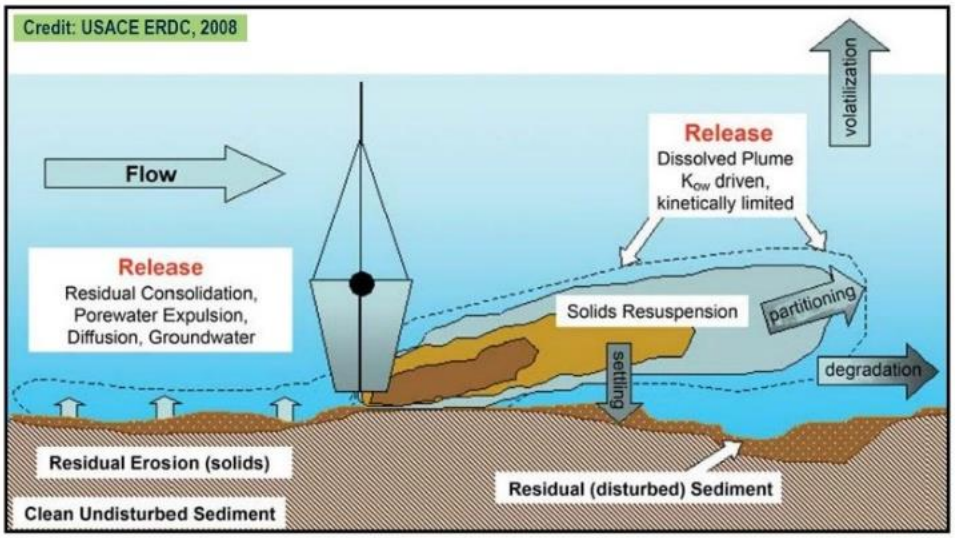

Figure 4. Schematic of contaminant release sources and mechanisms associated with contaminated sediment removal or disturbance (USACE 2008).

The challenges these factors present for projects can be difficult to overcome even when debris is not present in significant quantities at a project site. When debris is present at sufficient percentage of the removal volume, it makes goals to control resuspension, limit dredge residuals generation and mobility, and maintain cost-effective dredging production rates even more difficult.

The impact of debris on the 5Rs is related to how debris limits the ability of the dredge to remove sediment to the desired cut elevation without causing high levels of sediment resuspension. The mechanics of both mechanical dredges and hydraulic pipeline dredges are impacted by debris somewhat differently. The mechanics of each type of dredge are discussed in more detail.

Mechanical Operations

- Debris that is dislodged is loosening and dislodging sediment surrounding the debris items. Disturbances are occurring as the shifting debris is extracted from the sediment. As debris items are lifted, disturbances continue; and, if this debris is partially dislodged (and not fully grabbed by the bucket), it may be dropped and disturb the sediment surface due to the momentum.
- Dislodged debris may create irregular voids that cause sloughing of adjacent sidewalls of the cut, loosening and creating resuspension and residuals in the process.
- Voids from debris removal may remain when in proximity to the dredge prism removal limits, which may collect other resuspended sediment as a sedimentation feature.
- Sediment falling through the water column from partially closed buckets may encounter the sediment bed and alter the density of the sediment locally increasing the mobility of the sediment and/or the erodibility.

Hydraulic Operations

- Debris accumulating in cutters may add to disturbances of the sediment bed, increasing resuspension and residuals.
- Large and medium debris, and some small debris, cannot enter the intake of the dredge pipe; therefore, the dredge may strike the debris items while dredging near it, and increasing the sediment disturbances would be expected to increase resuspension and residuals.
- Large debris items may be dredged around (avoided by the dredge) to allow extraction by a grapple or separate debris removal operation. Voids may be created below the debris, causing surrounding sediment to slough into the voids, likely contributing to residuals.

The potential impacts of debris on each of the 5Rs can be summarized as follows, referencing Figure 4 for the respective illustrations:

- ***Removal***—The process by which sediments are dislodged from the sediment bed and lifted or transported out of the dredge cut. Removal is also related to the ability of the dredge to remove targeted sediment to a defined elevation, or Depth of Contamination (DOC), and the ability to accomplish sediment removal at an acceptable rate such that production targets and timelines for project completion can be met. Depending on the nature and extent of debris, a dedicated debris-removal operation may be required. Such an operation directly increases the timeline for project completion. If a debris removal operation is not required, debris may have potential impacts on the ability to reach the desired DOC, slowing the operation or potentially requiring changes in buckets, or other measures to mitigate the problem. With incomplete bucket closure, repeat attempts may be required for sediment removal and would reduce overall production rates. In addition, increased levels of resuspension and residuals may require increased monitoring and the possibility of requirements to slow or modify operations, or introduce engineered control measures for turbidity (e.g., silt curtains) to reduce water quality impacts.
- ***Resuspension***—The process whereby bedded sediments are dislodged and dispersed in the water column by the dredging operation. Most practitioners have seen the classic example of debris lodged in a mechanical bucket that has prevented it from closing. As the bucket is lifted above the water surface, the sediment fraction leaks from the bucket as it moved to the scow barge, leaving a visible turbidity plume when done. If sediment is cohesive enough to persist as a semi-coherent mass falling through the water column, resuspension would be expected when the rapidly sinking material encounters the sediment bed. As mentioned earlier, debris can affect bucket closure, resulting in increased losses of sediment during operations. Dedicated debris-removal operations call for the use of grapple, conventional dredging bucket, or other technologies to remove debris before production dredging. This equipment is not designed to minimize resuspension, and holds the potential for higher rates of resuspension, release, and residuals. Any debris-removal operation potentially creates turbidity conditions that must be managed by engineered control measures or other BMPs.
- ***Release***—The process by which the dredging operation results in the loss of contaminants from the pore water of the sediment bed or from contaminants adsorbed to resuspended sediment into the water column or air. With increased sediment resuspension, the potential for release of contaminants to the dissolved phase also increases, potentially impacting the ability to meet water quality standards.
- ***Residuals***—Contaminated sediments remaining in or adjacent to the dredging footprint after completion of the removal/dredging operation. The same issues related to resuspension also apply to residuals. Incomplete bucket closure due to debris results in increased "fallback" from bucket leakage as the bucket is raised, contributing to increased residuals. Similarly, the resuspended sediment that redeposits as generated residuals does so with a reduced sediment density from mixing and water entrainment. These materials are potentially fluidized (behaving

more like a fluid than a loosely deposited sediment until sufficient self-weight consolidation occurs). The resulting generated residuals are therefore less efficient to remove with subsequent dredge passes. Higher residuals may trigger the need for additional dredging passes at reduced efficiency or imposition of increased controls such as post-dredging residuals covers or caps. Higher residuals also would potentially impact the ability to meet water quality standards due to additional releases to the dissolved phase as the residual layers self-consolidate.

- ***Risk***—Refers to the likelihood for an adverse environmental consequence or outcome. Each of the potential impacts related to resuspension, release, and residuals translates to a potential increase in the risk associated with the presence of debris. Any impacts to the production rate for the operation increase the duration of potential impacts due to exposure times for resuspension, release, and residuals, leading to the possibility that the post-dredging ecological/human health risk conditions may be affected, or debris may create unanticipated costs to achieve the goals (i.e., increased use of dredge residuals covers).

The descriptions above apply to the effects of sediment released from a single bucket with debris preventing complete bucket closure. If the incomplete bucket closure were occurring every other bucket, or every fifth bucket, the cumulative effects for the project may be significant. As explained, other impacts may occur due to the debris directly interacting with sediment during removal. The net result may be increased resuspension and residuals during construction, exceeding what has been anticipated in design and, therefore, expected by regulatory agencies and permitting authorities; further, the added complication of changes to the dredging operations and/or increases in engineered control measures and other BMPs (i.e., turbidity barriers of different types or multiple barriers) may become relevant.

Recent studies have shown that sediment characteristics such as in situ dry density can be used to estimate the post-dredging residuals conditions following environmental dredging (Patmont et al. 2018). Sediment density changes would also be expected in the process of removing individual debris items. Consequently, this would be expected to directly impact the tendency for residuals generation in the sediment associated with medium- and large-sized debris for significant debris quantities. For example, sediment with physical properties lending to relatively lower dry density conditions will be disturbed to a greater degree during debris removal than sediment with relatively higher dry density conditions. Based on discussions with Mr. Patmont (Patmont 2021), a challenge for understanding these issues specific to debris contributions is the limited available peer-reviewed data sets for environmental dredging projects in general and, therefore, most certainly, limited available data for the subset of these projects that involve significant debris quantities. In addition to debris quantities and the range of types and sizes of debris removed for the project by area, the data sets would ideally include measurements of residual thickness, post-dredging physical and chemical properties of sediment compared to in situ conditions for these same measurement locations, and any sampling and analyses of water quality performed in the vicinity of the dredging operations (the latter of which would not be typically measured and in general is of less urgency as post-dredging debris-related residuals data).

This paper is a call to practitioners to collect additional data to better understand the impacts of debris. With additional data, predictions can be improved. Sediment resuspension is often not measured directly at the removal location where the impact of debris would be more evident; therefore, this paper places the emphasis on post-dredge residuals data collection. Consider the measurement of residuals thickness using sediment profile imaging and from post-dredging cores, as well as sampling and testing of physical and chemical properties of the residuals following dredging for representative dredging units. Applying the sampling and analysis activity to areas directly affected by debris removal as compared to other locations in the same dredging unit may allow prediction of a percentage increase in expected residuals that may correlate to the quantity of debris for that dredging unit, representing the sediment substrate's physical properties for that project. The goal of this expanded data collection and analysis from the construction phase would be to establish a sufficient database over time that can be used in the project planning phase.

This, combined with improved debris quantities from the project planning phases, occurring because of more complete characterization of the types and sizes of debris that are developed from the investigation phase, may lend to greater cost efficiency in dredging operations and improved environmental protectiveness of environmental dredging as a remedial technology for projects that involve significant quantities of debris.

SUMMARY AND CONCLUSIONS

The following summary and conclusions apply regarding managing debris for environmental dredging projects:

- Debris impacts to dredging operations are an aspect of the practice that has not received sufficient attention to establish guidance for investigations and planning. As a result, a wide range of construction contracting approaches are used that may not properly balance the debris-related risks between owner and contractor during construction.
- A debris definition is offered in the paper, along with debris classification, as well as relationships for the ranges of types and sizes of debris with dredging operations and debris removal technologies in the form of a debris matrix included as a link. The debris matrix is intended as tool to support project planning phases but requires site-specific surface and buried debris investigations to be effective. In fact, the authors emphasize the importance of applying an appropriate array of technologies specific to site conditions during investigations to provide usable debris characterization.
- Further research is needed to better understand the direct impacts of debris removal for each major category of dredging operations (pre-dredging debris removal, mechanical dredging operations, and hydraulic dredging operations). Additional data collection for post-dredging residuals during construction may lead to improved project estimates of debris impacts for these issues. Based on operations, post-dredging residuals thickness and comparative physical and chemical properties of the sediment are more likely candidates for consistency in procedures for a given project than resuspension.
- A vast array of equipment has been developed for providing debris removal and management. Preparation of a remedial design that allows the contractor to have the appropriate equipment available for efficient operations is a challenge, especially due to the common problem of "unexpected debris."

The authors hope this paper encourages further study of debris and development of more detailed technical guidelines that can be applied consistently from project to project, leading to greater efficiencies when debris is an important factor for environmental dredging projects.

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