URBAN RIVER REMEDIATION DREDGING METHODS THAT REDUCE RESUSPENSION, RELEASE, RESIDUALS, AND RISK

Paul F. Fuglevand¹ and Robert S. Webb²

ABSTRACT

The process of dredging can increase sediment resuspension, contaminant release, residual contamination, and environmental risk (the “4Rs”) in a variety of ways. Methods to reduce the 4Rs during dredging in urban rivers are the subject of this paper.

Dredging has been shown to produce a layer of remolded sediment (generated residuals) on the bed of the dredged area. The remolded sediment typically will have considerably lower shear strength and will be far more erodible than the undisturbed sediment. Prolonged river flows across the generated residuals result in increased scour and downstream transport of the chemical compounds associated with the residual sediment.

This paper presents an evaluation of dredging methods from the perspective of managing residuals and water quality while maintaining effective dredge production rates. The intent is to identify dredging methods that reduce the release, resuspension, residuals, and risk associated with dredging of contaminated sediment from urban rivers for medium sized projects (40,000 M³ to 225,000M³ [~50,000 CY to ~300,000 CY]).

This paper also presents specific remediation dredging methods (RDMs) for mechanical dredging in urban rivers targeted toward practical, implementable activities that can effectively reduce the 4R’s. The remediation dredging methods focus on reducing the formation of generated residuals during dredging and on providing timely cover of the generated residuals. Topics discussed include sediment characterization, dredge cut design to account for dredge tolerance and site conditions such as high-bank cuts, selection of dredging equipment (derrick vs. fixed arm), selection of dredging buckets (level-cut vs. double-arc closing buckets), and dredging of sloping ground including that often found outside of navigation channels.

Keywords: Sediment characterization, dredge equipment selection, dredging BMPs, sand cover, river remediation.

INTRODUCTION

This paper describes dredging equipment and methods intended to reduce the sediment resuspension, contaminant release, residual contamination, and environmental risk (the “4Rs”) that can occur during remediation dredging in urban rivers. These dredging methods and equipment are reviewed with regard to the following performance criteria for medium sized (40,000 M³ to 225,000M³ [~50,000 CY to ~300,000 CY]) remediation dredging projects:

- **Residuals** – Remove the targeted sediment using dredging methods that are specifically designed to limit the formation of dredging-generated residuals on the bed of the waterway, and thereby limit sediment resuspension and release to the water column.

- **Water Quality** – Remove the targeted sediment using dredging methods that are specifically designed to limit suspension of sediments into the water column and thereby limit impacts to water quality during the dredging project.

- **Productivity** – Remove the targeted sediment in an efficient manner that is compatible with the site constraints, limiting excess removal of non-targeted sediment.

¹ Senior Consulting Engineer, Dalton, Olmsted & Fuglevand, Inc., 10827 NE 68th Street, Kirkland, WA 98033 USA, T: 425-827-4588, Fax: 866 370-9466, Email: pfuglevand@dofnw.com.
² Senior Consulting Engineer, Dalton, Olmsted & Fuglevand, Inc., 1236 NW Finn Hill Road, Poulsbo, WA 98370 USA T: 360-394-7917, Fax: 866 370-9466, Email: rwebb@dofnw.com.
DREDGING TECHNOLOGIES

A screening of readily available dredging methods is used to identify technologies applicable for medium sized dredging projects in urban rivers. Technologies are assessed based on their effectiveness relative to the stated performance criteria.

Identification of Dredging Technologies

Dredging is the removal of sediment from a water body using either mechanical or hydraulic dredging equipment working through the water column. Dredges are typically deployed on floating barges or pontoons. Each of the major types of dredging equipment is described briefly below.

Mechanical Dredges

Mechanical dredges employ a bucket to remove sediment from the bed of the waterway, move the sediment up through the water column, and place it into a haul vessel (such as a barge) for transport and disposal. There are two major classes of mechanical dredges, based on how a bucket is deployed. The first class uses a wire rope attached to a crane or derrick to lower the bucket to the bed and retrieve sediment. A classic clamshell dredge consists of a bucket deployed on a wire rope. The second class deploys a bucket at the end of the arm of an excavator or backhoe, and is referred to as an articulated fixed-arm dredge. Mechanical dredges can be further classified by the type of bucket, such as conventional clamshell bucket, enclosed bucket, or level-cut bucket. Palermo et al. (2008) described the following types of mechanical dredges:

- **Conventional Clamshell** – This conventional dredge consists of a wire-supported, open clamshell bucket deployed from a crane or derrick barge (Figure 1).
- **Enclosed Bucket** – The enclosed bucket is a wire-supported, near watertight or sealed bucket as compared to the conventional open bucket, also deployed from a crane or derrick barge. Most designs incorporate a level-cut capability as compared to a circular-shaped cut for conventional buckets.
- **Articulated Bucket** – The articulated bucket (hydraulic-closing bucket) is deployed on an articulated fixed arm dredge (Figure 2). Articulated buckets come in several configurations, including conventional open clam shell, enclosed level-cut closing mechanism, and enclosed double-arc closing mechanism.

Figure 1. Conventional clamshell dredge, Puget Sound Washington
Mechanical dredges are normally defined by the capacity of the bucket. The capacity of wire-supported buckets can range from less than 1 M\(^3\) (1.3 CY) to over 40 M\(^3\) (~50 CY), depending on the size and capability of the crane used for the dredge and the nature of the project. Buckets deployed from articulated fixed-arm dredges can range from less than 1 M\(^3\) (1.3 CY) to over 20 M\(^3\) (~25 CY) but tend to be on the order of 1 to 8 M\(^3\) (~1-10 CY), depending on the size of the articulated fixed-arm dredge and the nature of the project.

**Hydraulic Dredges**

Hydraulic dredges add water to the sediment and transport it as slurry through a pipeline to a placement site. Hydraulic dredging normally involves the use of a dredgehead to dislodge the sediment from the bed where it mixes with water for transport through the pipeline. Cutterheads, the most common equipment used to dislodge the sediment, employ a rotating head or basket to dig into the sediment face and release the material for capture by the dredge. Another hydraulic dredging method uses a horizontal auger to plow sediment to a suction pipe. Palermo et al. (2008) described the following types of hydraulic dredges:

- **Conventional Cutterhead** – This is a conventional hydraulic pipeline dredge with a rotating cutterhead at the end of a ladder that moves up and down (Figure 3). The ladder is lowered to the dredging depth and then the dredge including the ladder, cutterhead and intake pipe are all swung back and forth in an arc pattern thru the dredge area. The ladder swing is controlled using cable and anchors; the ladder may be articulated. The dredge is advanced by pivoting on spuds using cable and anchors.

- **Swinging-Ladder Cutterhead** – This hydraulic pipeline dredge employs a rotating cutterhead and ladder that moves both vertically and horizontally, swinging on a pivot (Figure 4). The ladders may be articulated. The dredge advances by kicker spud or traveling spud carriage.

- **Horizontal Auger** – This hydraulic pipeline dredge employs a rotating horizontal auger dredge head, and its advance is controlled by cable and anchors (Figure 5).
Figure 3. Conventional cutterhead dredge, USACE Dredge William L. Goetz

Figure 4. Swinging ladder cutterhead dredge, Lower Fox River, WI
Plain suction dredges operate without the assistance of a dredge head to dislodge the sediment. These dredges are generally of limited effectiveness at removing in-place sediment because of the absence of an effective means to dislodge the sediment from the bed.

Hydraulic dredges are normally defined by the inside diameter of the discharge pipe of the dredge pump. Small to medium-sized dredges used for sediment remediation have discharge pipes ranging in diameter from 15 to 40 cm (6-16 inches).

**Effectiveness of Removal Technologies**

Mechanical and hydraulic dredging technologies are screened against the performance criteria relating to residuals, water quality, and productivity.

**Residuals**

Residuals refer to the layer of impacted surface sediment remaining after a removal program. A 2008 report (Bridges et al. 2008) by the U.S. Army Corps of Engineers presented the findings of a national expert’s workshop on the subject of the post-dredging residual layer. The report identified the following findings regarding residuals:

- Dredging residuals refers to sediment found at the post-dredging surface of the sediment profile. These residuals are grouped into two categories:
  - Undisturbed Residuals are sediments that have been uncovered by dredging but not fully removed.
  - Generated Residuals are post-dredging surface sediments that are dislodged or suspended by the dredging operation and are subsequently redeposited on the bottom of the water body.
- Management options for post-dredging residuals are evaluated on a site-specific basis. Possible management options include monitored natural recovery (MNR), residual covers (e.g., 15 cm (6 inches) of sand or topsoil cover), engineered caps, and redredging (if practicable; redredging will likely be less effective for generated residuals).

A 2007 report by the National Research Council (NRC 2007) reported that resuspension, release, and residuals will occur if dredging is performed. Dredging approaches may present specific limitations, such as residuals and
resuspension, and the project design and selection of remedies should take these limitations into account (Francingues et al. 2009).

A 2010 report of the findings of a peer review of the Phase 1 remediation dredging on the Hudson River in New York (SRA 2010) found that generated residuals were a major contribution to resuspension and release of compounds of concern into the water column.

Controlling the formation of generated residuals contributes not only to improved quality of the post-dredging sediment surface, but also improves water quality during the dredging project. The U.S. Army Corps of Engineers published a guidance document for remediation dredging (Palermo et al. 2008) that compares the ability of various dredging methods to control the generation of residuals, as summarized in Table 1 and described below.

Table 1. Equipment factors and ability to control dredging generated residuals (Palermo et al. 2008)

<table>
<thead>
<tr>
<th>Equipment Method and Removal</th>
<th>Effectiveness in Controlling Residual Generation</th>
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<tbody>
<tr>
<td>Mechanical Dredge</td>
<td></td>
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<tr>
<td>Conventional clamshell – wire rope</td>
<td>Low</td>
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<tr>
<td>Enclosed level-cut bucket – wire rope</td>
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<tr>
<td>Articulated bucket – articulated fixed arm</td>
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<tr>
<td>Horizontal auger</td>
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</table>

**Mechanical Dredging – Residuals**

Mechanical dredging with an articulated, fixed-arm dredge (excavator) deploying an articulated bucket (hydraulic closing enclosed clamshell bucket) is more effective in controlling the generation of residuals than dredging with wire-supported buckets (from a crane or derrick). The improved performance of a properly operated and instrumented articulated fixed-arm dredge derives from the improved accuracy in placing and closing the bucket underwater (where it can’t be seen but can be tracked with electronic instrumentation) at a desired location. This improved accuracy offers several advantages:

- Avoiding over-penetration of the bucket,
- Improved ability to control closing of the bucket and to monitor the closing of bucket, and
- Ability to precisely control the bucket when removing material from a sloping bottom.

Wire supported buckets are essentially a pendulum and are consequently more difficult to accurately place on the bed. This is especially true in areas where there is a river current that can push and spin the bucket. Wire-supported buckets also tend to tip and slide when placed on a sloping bed, making accurate removal less likely.

**Hydraulic Dredging – Residuals**

The cutterhead or auger used for hydraulic dredging disturbs and mixes sediment to a depth greater than is normally recovered by the dredge suction pipe, leaving behind a “spillage” layer of mixed sediment (Fuglevand et al. 2009a, 2009b) (Figure 6). As a rule of thumb, the thickness of the spillage layer for a conventional cutterhead dredge can be about 0.2 times the diameter of the cutterhead or about 0.5 times the diameter of the discharge pipe (Palermo et al. 2008). A dredge with a 30 cm (12-inch) diameter discharge pipe and a 75 cm (30 inch) diameter cutterhead could leave a spillage layer of generated residuals on the order of 15 cm (6 inches) thick. In some cases a secondary dredging pass with a suction dredge has been used with some success to remove the disturbed and loose spillage layer.
Water Quality

Impacts to water quality during dredging can occur due to resuspension of sediment particles into the water column (EPA 2005) as well as release of compounds from sediment pore water and sediment particles into the water column (Bridges et al. 2008). The authors’ estimate of the effectiveness of different dredging methods to limit resuspension and release into the water column are summarized in the Table 2 and described below.

**Table 2. Equipment factors and effectiveness at limiting water quality impacts**

<table>
<thead>
<tr>
<th>Equipment Method</th>
<th>Removal</th>
<th>Effectiveness in Limiting Water Quality Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Dredge</td>
<td>Conventional clamshell – wire rope</td>
<td>Low</td>
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<tr>
<td></td>
<td>Enclosed level-cut bucket – wire rope</td>
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<td>Low</td>
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</table>

Dredging methods that limit the disturbance and remodeling of the sediment will in turn limit sediment resuspension and release. Equipment that shields the sediment from the water column during removal also helps to reduce sediment release and resuspension.

**Mechanical Dredges – Water Quality**

**Conventional Clamshell.** This is a typical dredge bucket that has historically been used for navigational dredging projects. It has two halves, is open on the top and is supported by wire ropes (Figure 7). A series of pulleys cause the bucket to close as the closing wire rope is retrieved. The wire-supported bucket closes on a semi-circular arc around the sediment, limiting sediment disturbance during capture. When raised through the water column, however, the open bucket allows sediment to erode and become resuspended into the water column. (Low effectiveness)
Enclosed Level-Cut Bucket. A level-cut bucket, deployed on a wire rope, is the most commonly used enclosed bucket for remediation dredging (Figure 8). The enclosed bucket shields the sediment from the water column while the bucket is being raised, reducing the potential for sediment erosion from the bucket. The level-cut bucket is designed to remove a fairly large but thin footprint of material from the bed by plowing the sediment within the bucket footprint toward the center of the bucket as it closes. The plowing of sediment associated with a level-cut bucket remolds the sediment with water which can generate low-strength residuals and associated releases. (Low to medium effectiveness)

Articulated Fixed Arm Dredge Bucket. Several styles of buckets are available for use on articulated, fixed-arm dredges. These include standard excavator-style digging buckets that can be used to dredge hard materials as well as enclosed environmental buckets. The clamshell style bucket on an articulated fixed arm dredge can be more accurately positioned and held in position as it closes as compared to a wire-rope supported bucket. The level-cut buckets for articulated fixed arm dredges plow and remold the sediment as the bucket closes, same as the wire-rope
supported level-cut bucket, which can generate low-strength residuals and associated releases. There are some buckets that approximate a level cut and appear to do less remolding of the sediment. The Young rehandling bucket is an enclosed bucket that closes on a double arc rather than level-cut, while digging under and around the material (Figure 9). This closing mechanism reduces remolding of sediment and thereby reduces the potential for release. The double-arc closing mechanism also results in a fairly level cut in the center two-thirds of the bucket footprint, avoiding excess removal of underlying material (Figure 10). The enclosed Young rehandling bucket is expected to be more effective at controlling releases than either the conventional clamshell bucket or the enclosed level-cut bucket. (Medium effectiveness)

![Figure 9. Young Manufacturing rehandling bucket (vents added)](image)

![Figure 10. Closing profile of Young Manufacturing rehandling bucket](image)

**Hydraulic Dredges – Water Quality**

Conventional cutterhead, swinging-ladder cutterhead, and auger hydraulic dredges all mechanically shear the sediment from the bed and mix it with water to create slurry. While the dredge can capture a good portion of the turbid water and slurry generated by the dredgehead, a portion is released to the surrounding water column and these dredges leave a spillage layer which can they be moved by currents, impacting water quality. (Low to medium effectiveness)
Productivity

This section evaluates the effectiveness of various dredging techniques relative to productivity. Urban rivers present a number of primary constraints to dredging productivity including:

- **Water Depth.** A wide range of water depths are found within urban rivers, from zero at the shoreline to water depths ranging from 5 to 15 M (~15 to 50 feet) in the navigation channel.
- **Cut Thickness.** Sediment cut depths below the mudline can range from 30 cm (1 foot) to greater than 3 M (10 feet) within a single project area depending on site conditions.
- **Soft to Hard Sediment.** The primary material to be removed by remediation dredging is often soft, relatively recently deposited, fine-grained sediment. Areas of harder material can also be encountered, for example dredge cuts that are advanced into the older native deposits to assure removal of the recent sediment.
- **Debris.** Large debris (such as trees, riprap, concrete rubble, timber piling, buried timber walls, chains, cables, and variable urban/industrial debris) is often present in sediment found in urban waterways.
- **Slope Cuts.** Remediation dredging often includes areas located outside of the navigation channel where the bed of the waterway slopes up in transition from the navigation channel towards the shoreline.

The authors’ estimates of the relative productivity of alternative dredging techniques for moderate sized projects located in urban rivers are summarized in the Table 3 and described below.

<table>
<thead>
<tr>
<th>Equipment Method</th>
<th>Removal Method</th>
<th>Productivity</th>
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<tbody>
<tr>
<td>Mechanical Dredge</td>
<td>Conventional clamshell – wire rope</td>
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<td></td>
<td>Horizontal auger</td>
<td>Very low</td>
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</table>

**Mechanical Dredges – Productivity**

**Conventional Clamshell.** This bucket is compatible with four of the site constraints (water depth, cut thickness, soft to hard sediment, and debris) but is not efficient at performing remediation dredging on sloping ground. Some heavy-wall clamshell buckets are particularly effective at capturing widely varying debris as well as digging harder material. On the down side, the bucket closes on a circular arc that tends to pull the bucket deeper as it closes, resulting in cuts below the required dredge elevation, which results in excess dredging to capture the targeted material. Over-penetration of a couple of feet below the target layer is possible depending on the size of the bucket. (Low to medium effectiveness)

**Enclosed Level-Cut Bucket.** The bucket is compatible with two of the site constraints (water depth and cut thickness). Many of the enclosed level-cut buckets deployed on a wire rope are relatively light weight and not effective with large debris or cutting into hard sediment, and can be damaged by debris. Buckets deployed from a cable are not efficient at digging sloped dredge cuts. On the plus side, the level-cut bucket can be effective at limiting excess removal of sediment due to its tendency to not cut into harder, native sediments. (Low to medium effectiveness)

**Articulated Bucket** (for articulated fixed-arm dredge). The articulated bucket (hydraulic closing enclosed bucket) is deployed on an articulated fixed arm dredge. While the dredging depth is limited by the length of the articulated
fixed arm, the dredges have been effective dredging in 12 M (~40 feet) of water (DOF 2011) and to greater depths at other sites. The equipment is compatible with four of the site constraints (water depth, cut thickness, soft to hard sediment, and slope cuts) and can handle moderately sized debris. Large debris such as trees and large concrete blocks can be beyond the lifting capacity of some articulated fixed arm dredges and the dredge buckets. Because the bucket is attached to the rigid arm of the dredge, and closed with hydraulic rams, it is capable of accurately removing material from sloping dredge cuts in a controlled fashion. Both level-cut and double-arc cutting buckets can be deployed from an articulated fixed arm dredge and operated to limit the penetration of the bucket below a required depth of removal. A bucket deployed from an articulated fixed-arm dredge can be much more accurately controlled than a bucket deployed on a wire rope, so dredging with an articulated fixed-arm machine will have greater effectiveness at limiting excess sediment removal as well as limiting the formation of residuals. (Medium effectiveness)

**Hydraulic Dredges – Productivity**

Conventional cutterhead dredges and large swinging-ladder cutterhead dredges are compatible with two of the site constraints (water depth, cut thickness) and can be configured to accommodate sloped dredge cuts. However the effectiveness and efficiency of these hydraulic dredges are impaired by the potential presence of considerable debris in urban waterways. Hydraulic dredges are not capable of removing debris of any significant size or in place piling; and small debris can obstruct the dredge pipeline causing shutdowns of the dredge while the debris is removed (Palermo et al. 2008). Hydraulic dredges used for remediation dredging are typically smaller than those used for navigational dredging, and are also less effective at removing hard material. Auger dredges can accommodate fine-grained sediment but are not compatible with the deeper water depths, inclined dredge cuts, or debris at the site. While the digging depth of some hydraulic dredges can be controlled effectively, the cutterhead must penetrate deeper than the required depth of dredging, leaving behind a disturbed layer of material (spillage discussed above). Prior to hydraulic dredging (and during dredging as additional debris is encountered), the debris would likely have to be removed by mechanical dredging equipment.

Hydraulic dredges produce a slurry that needs to be consolidated prior to as part of disposal. In addition to consolidating the slurry, water treatment is often required to remove contaminants of concern from the dredge water prior to discharge back to a receiving water body. The design, construction, and operation costs of water treatment systems capable of effectively supporting a hydraulic dredging project are significant, and may not be cost effective for small to medium sized urban river dredging projects. The dewatering and water treatment systems have been shown to be cost effective for some large dredging projects (750,000 M^3 [~1 million CY]) plus.

The incorporation of a large dewatering and water treatment plant can adversely impact the productivity of hydraulic dredging, particularly on shorter duration projects. A recent hydraulic remediation dredging project completed with a swinging-ladder dredge documented 50 percent downtime over the course of the first dredging season due to issues at the water treatment plant and dewatering operations and another 10 percent downtime to remove debris from the dredge and booster pumps (Rule and Cieniawski 2008). (Low to very low effectiveness depending on dredge type)

**Screening of Removal Technologies**

The authors’ findings regarding the overall effectiveness of various dredging technologies for moderate sized projects (40,000 M^3 to 225,000M^3 [~50,000 CY to ~300,000 CY]) in urban rivers are summarized in Table 4 and described below.

**Mechanical Dredge Effectiveness.** The overall effectiveness of wire-supported mechanical dredges is low to low-medium because of residuals control limitations, water quality impacts, and productivity issues. The overall effectiveness of mechanical dredging with an articulated fixed-arm dredge-deployed bucket (enclosed double-arc closing bucket) is medium because of improved residuals and water quality control.

**Hydraulic Dredge Effectiveness.** The overall effectiveness of any of the hydraulic dredges under consideration for medium sized projects on urban rivers is low to low-medium because of residuals control limitations, water quality and productivity.
Table 4. Comparison of effectiveness of dredging technologies for urban rivers

<table>
<thead>
<tr>
<th>Equipment Removal Method</th>
<th>Effectiveness</th>
<th>Residuals Control</th>
<th>Water Quality</th>
<th>Productivity</th>
<th>Overall Effectiveness</th>
</tr>
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<tbody>
<tr>
<td><strong>Mechanical Dredge</strong></td>
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<tr>
<td>Conventional clamshell – wire rope</td>
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<td>Low</td>
<td>Very low</td>
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<td>Low</td>
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</table>

Based on the evaluation, mechanical dredging using an articulated fixed-arm dredge with an enclosed bucket is a preferred method of remediation dredging for medium sized projects on urban rivers. The applicability of this equipment and method should be verified at each site depending on site-specific conditions.

MECHANICAL REMEDIATION DREDGING METHODS (RDMs)

This section describes mechanical remediation dredging methods (RDMs) that are intended to reduce the 4Rs during dredging.

Dredging RDMs – Recent Developments

SRA (2010) presented comprehensive and recent evaluation of resuspension, release, and productivity of remediation dredging with articulated fixed-arm dredge equipment. The report documents the independent peer review of the first year (Phase 1) of remediation dredging on the Hudson River in upstate New York. The purpose of the peer review was to consider the implications for engineering performance standards for resuspension, residuals, and productivity based on the experience gained during the Phase 1 dredging of 215,000 M$^3$ (280,000 cy) of sediment impacted by polychlorinated biphenyls (PCBs).

Phase 1 of the Hudson River project demonstrated that the generation and management of residuals had a substantial direct impact on resuspension and release:

“Dredging generates a layer of residual sediment with a higher water content and lower shear strength than the native deposit, commonly referred to as dredge-generated residuals. This residual layer is more easily eroded than the native, undisturbed sediment bed, and consequently results in more erosion and resuspension of PCBs than the pre-dredge condition. Leaving the disturbed residual sediment exposed in the river for long periods increases resuspension to the water column.”  

SRA, 2010

The Hudson River peer review panel found that the prolonged exposure of generated residuals on the river bed resulted in increased PCB resuspension and release. The panel recommended several revisions to the dredge plan and incorporation of RDMs to reduce resuspension and release while maintaining productivity. A number of these RDMs are also considered applicable to dredging in urban rivers.
**Urban River Mechanical Remediation Dredging Methods (RDMs)**

The following mechanical RDMs are intended to reduce suspension of sediment into the water column while maintaining productivity for urban river dredging projects.

**DoC Elevation**

**RDM-1.** Pre-define the elevation of the depth of contamination (DoC) using high-quality sediment core data integrated into a digital terrain model (DTM) of the site.

The purpose of this RDM is to accurately characterize the extent of the target material with a high degree of confidence prior to dredging. Achieving the required level of accuracy may require multiple sediment coring events in order to fill data gaps and improve the certainty of DoC DTM. Failure to accurately map the DoC results in incomplete removal of impacted material and can increase residuals if multiple dredge and sampling steps are then necessary.

**Design Dredge Elevation and Dredge Prism**

**RDM-2.** Set the design dredge elevation (DDE) below the DoC DTM to account for the vertical accuracy and precision of the selected dredge equipment.

The purpose of this RDM is to establish a target elevation for dredging that takes into account the expected vertical accuracy and precision of the dredge. Currently the most accurate positioning of the dredge bucket (within +/- 10-15 cm [4-6 inches]) is achievable only if: RTK-GPS based dredge positioning systems are employed; dredging is completed with a fixed arm dredge; dredging is completed by experienced and skilled operators; there is limited debris and obstructions to dredging; a proper quality control system is employed to verify the positioning systems at least once per day throughout the full range of dredge motion. Without these factors in place the overall accuracy of dredges can be reduced to +/- several feet (Palermo et. al. 2008). When using an appropriately instrumented articulated fixed-arm dredge (accuracy of +/- 10-15 cm [4-6 inches]) the DDE DTM can be set 10-15 cm (4-6 inches) below the DoC DTM to assure that even when the dredge positioning is off by its stated tolerance, it will have achieved the DoC DTM.

The DDE DTM is then used as the basis to develop the dredge prism, which accounts for the operational characteristics of the selected dredge. While the DDE DTM will typically be a computer-generated curved and warped surface that follows the lay of the target material on the river bed, this must be converted to a dredge prism, typically a grid of cells, each with an individual constant elevation. At its smallest scale, each cell of the grid will represent the footprint of a single dredge bucket placement. The constant cut elevation for the dredge prism cell is set at the lowest elevation of the DDE DTM within the cell to assure that the cut of the bucket achieves the DDE throughout its footprint (Figure 11).

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**Figure 11. Design dredge elevation and dredge prism**
Once and Done

RDM-3. Perform planned dredging in a controlled and organized manner according to the dredge prism without post-dredging chemical monitoring and associated re-dredging.

This RDM is built upon the development of a reliable DoC DTM coupled with accurate dredging by the contractor. When both are achieved the remediation dredging program is effective at removing the target material.

Dredging is confirmed complete based on post-dredging bathymetric surveys, requiring at least 95 percent of the dredge area to be at or below the DoC elevation (not the DDE), and no area more than six inches above the DoC. The DDE is used to guide the dredging and position the bucket such that removal of material to the DoC is achieved. The 95 percent standard allows for there to be some objects to be protruding above the DoC elevation after dredging, such as sticks and rocks, that would be detected by a multibeam survey. Based on contractor performance, the offset between the DoC and the DDE (and dredge prism) is adjusted to assure that dredging is consistently achieving the DoC without excess over dredging.

Sand Cover

RDM-4. Place a sand cover (nominal 15 cm [6 inches]) over dredge cuts in each subunit of the site in a timely manner, as soon as practical, after dredging of the subunit is complete.

The purpose of the Sand Cover RDM is to promptly cover the dredged area and thereby limit the potential for resuspension and release of sediment from the loosened post-dredging residual material. Since residuals are a normal outcome of remediation dredging, placement of a sand cover as each dredging sub-area is completed is a standard method to limit the potential impacts of the residual layer. Final backfill or capping, as required by the project can be placed at a later point in the project without interfering with the dredging program. Normally the final backfilling would occur after all upstream and adjacent dredging is complete.

Dredging Equipment

RDM-5. Select the appropriate dredging equipment based on the site conditions and accuracy requirements.

The above screening of technologies resulted in the selection of an articulated fixed-arm dredge as the primary dredging equipment for medium sized urban river dredging projects. A conventional derrick with clamshell, grapple, or vibratory hammer may be used for removal of large debris and piling.

Dredging Bucket

RDM-6. Use an enclosed double-arc cutting bucket to limit loss of sediment to the water column by reducing the plowing/remolding of the sediment during capture. A standard clamshell bucket on a derrick may be required for denser sediments and debris removal. A level-cut bucket may be considered for the final cleanup pass after the bulk of sediment has been removed.

The purpose of this RDM is to limit the loss of sediment to the water column due to dredging, both from erosion from the bucket as it is moved through the water column and due to erosion of loosened residual sediment by the flow of the river. Other heavy-duty equipment, such as a standard clamshell bucket or grapple, will be used only as needed to remove large debris or dense sediment, when encountered.

Dredge Bucket Positioning

RDM-7. Use sub-foot accuracy global positioning system (RTK-GPS) for accurate bucket positioning. The purpose of this RDM is to provide on-board digital equipment capable of displaying the location of the dredge bucket within 10-15 cm (4-6 inches) horizontally and vertically as a means of assuring that the target material is captured by the dredge. Recent studies have shown that conventional DGPS (differential global positioning system) equipment can generate positioning data that vary widely (up to 2 M [~6 feet]) over a period of minutes, which means that the location where the bucket is placed can be off by the same amount and miss some of the targeted material. All positioning equipment must be maintained and verified throughout the project.
Stair-Step Dredge Cuts on Slopes

RDM-8. Implement stair-step dredge cuts for steeper slopes to reduce sloughing of sediment.

The purpose of this RDM is to limit the bank sloughing that can occur with deep vertical cuts into the sediment (referred to as “box cuts”). Dredge cuts that extend several feet vertically into the sediment bed will eventually slough to a flatter and more stable slope. The sloughed sediment will be remolded with water, and come to rest on the bed as a lower density, higher water content, and lower strength generated residual that is more easily eroded and suspended than native intact sediment. Stair stepping the dredge cuts helps to reduce the formation of generated residuals and reduces the potential for resuspension and release.

Dredge Slopes with Articulated Fixed-Arm Dredge

RDM-9. Use an articulated fixed-arm dredge for improved bucket control and reduced sediment disturbance on steeper slopes.

The purpose of dredging slopes using an articulated fixed-arm dredge, as opposed to a wire-supported bucket, is to limit the disturbance of impacted sediment on the slope during dredging, and in turn limit resuspension and release. A wire-supported bucket from a conventional derrick or crane barge can tip and slide downslope as the bucket engages the inclined face of submerged slope. Also, a wire-supported bucket is like a pendulum and the positioning of a swinging bucket can be difficult to accurately track. On the other hand, a bucket deployed on an articulated fixed-arm dredge can be held in place at a known location and elevation on the slope while the bucket is closed, reducing the disturbance of the sediment on the slope.

Water Management

RDM-10. Remove water from sediment barges actively during dredging (no direct overflow) for processing and management as dredging return water.

The purpose of this RDM is to limit the release of sediment and potentially dissolved contaminants back into the waterway from the sediment barge. The findings from a case study of mechanical dredging document that barge overflow can represent a significant contribution to the formation of a residual layer of sediment (Fuglevand and Webb 2006) and can directly impact water quality and create a risk for offsite contamination.

When dredging with an environmental mechanical dredge using an enclosed bucket, each bucket of material placed in the barge contains a portion of sediment and a portion of water because water is not allowed to drain from the bucket. During precision remediation dredging projects, a fill factor of 50%, meaning the dredging bucket is only half full of sediment on average over the course of the project should be targeted due to relatively thin cuts intended to avoid removal of non-impacted sediment and to avoid over-penetration of the bucket. The volume of water placed in the barges for a remediation dredging project can therefore equal the volume of sediment dredged from the waterway. Thus, a 100,000 M$^3$ dredging project can result in that volume of sediment placed into barges plus another 100,000 M$^3$ of water. Failure to manage the water in the barge during dredging can result in the release of turbid water back into the dredged area with the potential for increased sediment resuspension and release and additional generated residuals.

Implementation of this RDM can include activities such as pumping of the excess water from the sediment barges during dredging, thereby limiting the amount of ponded water within the barge and preventing direct overflow from the barge back to the waterway. Removed water is pumped to a water management system designed to remove excess sediment and chemicals of concern prior to discharge of the water back to the waterway as dredging return water. With proper capture and management, the turbid water placed in a barge by the enclosed dredging bucket can be processed to remove suspended sediment and chemicals of concern that would otherwise be released back into the waterway causing releases.
Active Oversight and Monitoring

RDM-11. Perform continuous competent, technical monitoring of the dredging process; qualitatively and quantitatively evaluate dredge process and results.

Recently there has been considerable national attention paid to the potential adverse impacts of remediation dredging. A national workshop sponsored by headquarters of EPA and USACE focused on the 4Rs – Release, Resuspension, Residuals, and Risk (Bridges et. al. 2008) and a National Research Council report (NRC 2007) focused on the effectiveness of dredging. The studies demonstrated that there are contaminant releases during remediation dredging, and that the mechanisms are not yet fully understood. The current approach to remediation dredging projects incorporates adaptive management to allow for ongoing monitoring of the effectiveness of the dredging program, and modifications to improve environmental outcomes. Accordingly the effectiveness of RDMs should be monitored during dredging and modified as appropriate to achieve the desired objectives.

Without continuous, competent monitoring by skilled personnel that understand dredging and its nuances, the process of implementing the above RDM’s is compromised and cannot be verified. Without the feedback loop of intended process to observed outcome, true results of any program or modification cannot be known.

CONCLUSIONS

An evaluation of dredging methods concluded that mechanical dredging using an articulated fixed-arm dredge with an enclosed bucket is a preferred method of remediation dredging for medium sized projects on urban rivers, from the perspective of managing residuals and water quality while maintaining effective dredge production rates.

Eleven specific remediation dredging methods for mechanical dredging in urban rivers are presented, as summarized in Table 5. The RDMs are targeted toward practical, implementable activities that can effectively reduce the 4R’s. The remediation dredging methods focus on reducing the formation of generated residuals during dredging and on providing timely cover of the generated residuals.

Table 5. Mechanical remediation dredging methods (RDMs)

<table>
<thead>
<tr>
<th>RDM-1 DoC Elevation.</th>
<th>Pre-define the elevation of the depth of contamination (DoC) using high-quality sediment core data integrated into a digital terrain model (DTM) of the site.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDM-2 Design Dredge Elevation (DDE) and Dredge Prism.</td>
<td>Set the design dredge elevation (DDE) below the DoC DTM to account for the vertical accuracy of the selected dredge equipment.</td>
</tr>
<tr>
<td>RDM-3 Once and Done.</td>
<td>Perform planned dredging according to the dredge prism without post-dredging chemical monitoring and associated re-dredging.</td>
</tr>
<tr>
<td>RDM-4 Sand Cover.</td>
<td>Place a sand cover over dredge cuts in each subunit of the site in a timely manner, as soon as practical, after dredging of the subunit is complete.</td>
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<tr>
<td>RDM-5 Dredging Equipment.</td>
<td>Select the appropriate dredging equipment based on the site conditions and accuracy requirements, with an articulated fixed-arm dredge identified for small to medium sized urban river projects.</td>
</tr>
<tr>
<td>RDM-6 Dredging Bucket.</td>
<td>Use an enclosed double-arc cutting bucket to limit loss of sediment to the water column to limit the plowing/remolding of the sediment during capture.</td>
</tr>
<tr>
<td>RDM-7 Dredge Bucket Positioning.</td>
<td>Use sub-foot accuracy global positioning system (RTK-GPS) for accurate bucket positioning.</td>
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<tr>
<td>RDM-8 Stair-Step Dredge Cuts on Slopes.</td>
<td>Implement stair-step dredge cuts for steeper slopes to reduce sloughing of sediment.</td>
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<td>RDM-10 Water Management.</td>
<td>Remove water from sediment barges actively during dredging (no direct overflow) for processing and management as dredging return water.</td>
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<tr>
<td>RDM-11 Active Oversight and Monitoring.</td>
<td>Perform continuous competent technical monitoring of the dredging process with an integrated adaptive management program to adjust and modify the RDMs as needed to</td>
</tr>
</tbody>
</table>
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