PROCESS-BASED ESTIMATION OF SEDIMENT RESUSPENSION LOSSES DURING BUCKET DREDGING

ABSTRACT

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Water quality impacts resulting from dredging operations are of particular current interest. Resulting suspended sediment plumes potentially impact the local aquatic environment in a variety of ways, including the burial of benthic organisms, contaminant transport, negatively affecting recreational uses, and modifying fish behavior. These potential impacts have often been cited in requests for restrictions on dredging operations in the form of environmental windows in many areas of the country and the focus of concern for many remedial dredging operations. While some resuspension data are available and a few empirical tools have been developed to make *a priori* estimates of sediment resuspension associated with dredging operations, the limited database hampers the applicability of these approaches. Hayes and Wu (2001) proposed the Resuspension Factor approach as a simplified approach to estimating sediment resuspension losses during dredging. Recent research has refined that approach by evaluating specific loss mechanisms and developing a generic framework for all types of bucket dredges. While the existing database does not allow sediment resuspension loss models to be developed and calibrated for each loss mechanism, the fundamental approaches presented provide a basis on which to focus future research efforts. Focusing research efforts on specific loss mechanisms holds significantly more promise for eventually developing reliable predictive methods for a wide-array of equipment working under a variety of conditions.

Keywords: Sediment resuspension; environmental dredging; water quality impacts

INTRODUCTION

Reliable tools are required to make accurate *a priori* estimates of water quality resulting from a specific dredging operation. Computational tools such as DREDGE and SSFATE (Johnson, *et al* 2000) allow estimates of temporal and spatial dynamics of suspended sediment transport resulting from dredging operations. However, suspended sediment transport models require the rate and, possibly, the geometry of suspended sediment release during dredging to compute the fate and transport of the suspended sediment particles. This paper presents a simple, straight-forward approach for estimating the rate of sediment release during mechanical bucket dredging operations.

BACKGROUND

Dredging operations suspend bottom sediments into the water column through a variety of physical processes. Potential impacts resulting from those sediments and associated constituents are of substantial concern. Whether that potential impact is to environmental resources due to deposition of resuspended sediments, to fish behavior because of increased turbidity, or increased water column concentrations of toxic constituents, any evaluation first requires an estimate of sediment release into the water column at the dredge. Suspended sediment transport models require the mass rate of sediment resuspension at the dredge (i.e. the source term) as the basis for computing suspended sediment transport into other areas of the water body (the model domain).

Suspended sediment data for specific dredging operations have been published by several authors and a few rudimentary methods for estimating release have been developed. However, the available data do not cover a sufficient range of sediment, environmental, and operational conditions to serve as a predictive base for distinctly different dredging operations. Predictive techniques developed by Nakai (1978), Collins (1995), and Hayes *et al*. (2000b) either suffer from limited empirical data sets, apply to only a relatively narrow set of conditions, or require information seldom known early in the project when these estimates are needed most. This paper builds on available

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data and these existing predictive techniques by considering fundamental physical mechanisms associated with sediment release. The results are presented in an easy-to-apply Resuspension Factor formulation. The impact of specific sediment loss mechanisms on a base resuspension factor is considered independently to formulate a matrix-based approach for estimating sediment resuspension from dredging operations.

APPROACH

A variety of mechanical and hydraulic mixing actions occur in the immediate vicinity of dredging operations that result in the suspension of bottom sediments into the water column. These actions vary temporally and spatially as well as by dredge type and operation. Accurately modeling these processes in detail is beyond current capabilities. Fortunately, average rates of suspended sediment mass flux to the water column in the immediate vicinity of the dredging operation, referred to hereafter as the "near-field," are adequate for suspended sediment transport models that have significant temporal time steps (e.g., hours or days) or assume steady-state conditions. Additionally, even though all sediment size fractions in the bottom sediments will likely be suspended into the water column, only those subject to transport away from the dredging location are of concern.

Hayes and Wu (2001) presented the Resuspension Factor concept to estimate the average rate of sediment resuspension leaving the immediate vicinity of dredging operations. They proposed the following equation for the mass rate of resuspension[3]:

$$g = R\left(\frac{f_{74}}{100}\right)\left(\frac{\dot{V}_S C_s}{360}\right) \tag{1}$$

where g = mass rate of sediment release (g/sec), R = resuspension factor or sediment mass loss rate (%), f_{74} = fraction of particles with a diameter smaller than 74 µm, $\dot{V}_S$ = volumetric rate of *in situ* sediment removal (m^3/hr), and C_s = *in situ* solids concentration (kg/m^3). The resuspension factor, R, represents the mass of sediment suspended into the water column relative to the mass of sediment removed via dredging in units of percent; e.g., R = 1.0 represents a mass loss rate of 1%.

Except under extreme conditions, sand and larger particles resettle within a few meters of the dredging operation, leaving only fine particles in suspension to be transported downstream. Equation 1 implicitly assumes that all sediment particles smaller than 74 µm are subject to transport downstream while larger particles immediately resettle. While this division is reasonable for most conditions, very small changes in ambient currents can increase or decrease the largest particle size that stays in suspension. Thus, a more general form is used here:

$$g = R\left(\frac{f_T}{100}\right)\left(\frac{\dot{V}_S C_s}{360}\right) \tag{2}$$

where f_T = fraction of particles smaller than the largest size subject to transport. In the absence of better information, assuming that $f_T = f_{74}$ is typically acceptable for first order estimates.

Equation 2 represents the mass rate of release resulting from a specified value of the Resuspension Factor, R; note that R is the sediment loss rate in percent. Thus, Equation 2 applies to any dredging operation for which a correct value of release rate is available for use as R. Hayes and Wu (2001) presented some site-specific R values and others could be developed from available project data. However, the available data is very limited and those site-specific R values only apply to other projects with identical conditions.

This paper defines a set of "standard" conditions and proposes *characteristic resuspension values, R_c*, for specific dredge types operating in those conditions. The characteristic resuspension factor may either be a single value or the sum of individual values representing different dredge operations or processes, i.e.

[3] All mass values reported as dry mass.

$$R_c = \sum_{i=1}^{n} r_i \quad (3)$$

where r_i = characteristic resuspension value for one of n different dredge operations or processes. Each characteristic resuspension factor can be adjusted to account for site-specific conditions that are different from the "standard" conditions. That is, the Resuspension Factor for a set of site-specific conditions is computed as:

$$R = \sum_{i=1}^{n} F_i r_i \quad (4)$$

where r_i = characteristic resuspension value for each process or dredging component (%) and F_i = combination of dimensionless factors that increase or decrease the characteristic resuspension factor for a specific process or dredging component (i). Depending upon the process or operation and the conditions being adjusted, F_i may be the sum or product of dimensionless adjustment factors, $f_{i,j}$, applicable only to the "j" dredge operation or process.

LIMITATIONS

This paper proposes characteristic resuspension values and adjustment factors for bucket dredges, one of the major types of dredges and commonly used for environmental dredging. Despite being a common dredge, sediment resuspension data is available for only a few types of bucket dredges and those data are limited. Thus, the methods and values presented should be considered preliminary. It is hoped that this approach will encourage additional research to validate the presented values and approaches or propose more accurate and robust values. The approach is flexible and new or modified adjustment factors can be provided as our understanding of site-specific conditions and resuspension processes improves.

ADJUSTING FOR SEDIMENT PROPERTIES

Characteristic Sediment properties used as the basis for the characteristic resuspension values are defined in Table 1. The *Characteristic Sediment* is typical of maintenance dredging operations in a marine environment. Since it is the basis for the characteristic resuspension values presented later, sediments with these properties are assumed to not need adjustment, i.e. $f_{sed} \cong 1.0$.

Table 1. Characteristic sediment properties

General Description	Marine sediment typical of maintenance dredging operations.
Grain size	Primarily a silt with some clay and some sand (15% sand, 50% silt, 35% clay, < 3% organic)
In situ water content	150% of the Liquid Limit
Specific Gravity	2.65
Atterberg Limits	Liquid Limit = 90, Plastic Limit = 35, Plasticity Index = 55, Liquidity Index = 1.82, Activity = 1.57
Depth	Sediment extends beyond the anticipated dredging depth
Salinity	> 10 ppt

Variations in sediment properties and characteristics can significantly influence sediment resuspension during dredging. Very soft, unconsolidated, high organic content sediments require little mechanical effort to dredge, but are much more susceptible to resuspension. They often erode easily with minor disturbances and can be difficult to capture because of their fluid-like nature. In contrast, stiff, purely mineral sediments may require significant mechanical effort to dredge, sometimes even blasting, but often remain as large chunks that behave much more like gravel or rocks than silts and clays. Not surprisingly, small increases in sediment plasticity can significantly increase cohesion and reduce resuspension. Similarly, increased organic content tends to increase the sediment liquidity and increase resuspension.

Although a plethora of sediment properties influence resuspension, experience suggests that average specific gravity of the solids and *in situ* moisture content relative to the Atterberg limits are among the most influential properties. Further, organic content modifies *in situ* moisture content and Atterberg limits just as it influences the average specific gravity. The Liquidity Index integrates the in situ water content and Atterberg Limits into a single sediment property. It is defined as:

$$LI = \frac{\omega_0 - PL}{LL - PL} \tag{5}$$

where LI = Liquidity Index, ω_0 = in situ water content (%), PL = Plastic Limit, and LL = Liquid Limit.

Several authors (Yilmaz 2004 is an example) have correlated the Liquidity Index (LI) with undrained shear strength of soils. LI should be similarly related to the sediment strength and sediment resuspension processes. The following adjustment for sediment properties is proposed:

$$f_{sed} = \left(\frac{LI}{1.82}\right)^4 \tag{6}$$

where f_{sed} = adjustment factor for sediment properties (dimensionless). Table 2 shows specific values of f_{sed} for the characteristic sediment at a few identifiable water contents.

BUCKET DREDGING OPERATIONS

Bucket dredges (sometimes called clamshell or grab dredges) are commonly used in navigation and environmental dredging operations. They are generally readily available and easy to mobilize. Even though most are dedicated dredges with a crane and boom unit permanently mounted on a barge, smaller bucket dredges may be a land-based

Table 2. Example adjustment factors using the characteristic sediment properties.

In Situ Water Content, ω_0	f_{sed}	Rationale
0.8*LL	0.02	Low water content sediments tend to be less susceptible to resuspension and lowest limit of undisturbed sediment
LL	0.1	Lower limit on liquidity
1.2*LL	0.3	Resuspension potential increased rapidly with *in situ* water content and approximately lower limit of undisturbed sediment
1.5*LL	1	Average sediment concentration
1.8*LL	2.6	Lower limit of decant point and infrequently or rarely disturbed sediment
2*LL	4.4	Average decant point, upper limit of undisturbed sediment
2.2*LL	7	Upper limit of decant point and occasionally disturbed sediment
3*LL	30	Disturbed sediment
4*LL	110	Approximately zero effective stress in sediment, very disturbed

crane temporarily attached to a barge. Bucket dredges are able to work in tight spaces, have limited impacts on local traffic, and are able to work effectively at a wide variety of depths. Most bucket dredges use a crane cable system, but clamshell (and other types) buckets can also be attached to a fixed-arm excavator.

Dredge buckets come in a variety of forms. Conventional clamshell buckets usually have open tops and metal-to-metal closures. Buckets for dredging stiff sediments may have teeth along the closing edges to help break the material apart upon impact. Many dredging companies have converted conventional clamshell buckets to enclosed (sometimes called watertight) buckets by welding plates to enclose the upper half of the bucket. These typically require a vent in the upper half of the bucket to facilitate the bucket's descent through the water column and reduce sediment erosion upon impact with the bottom. Some manufacturers have also designed dredge buckets specifically for environmental applications. Typically, these buckets are enclosed, produce level bottom cuts, and have closure mechanisms that reduce leakage. Only standard (open) and enclosed clamshell bucket are considered here because of the limited sediment resuspension data available for other bucket types.

Characteristic Bucket Dredging Operation. The characteristic bucket dredging operation is a typical maintenance dredging operation using a conventional (open) clamshell bucket working in a 30-ft channel. Table 3 presents details of the dredge and its operation.

Based upon available data from bucket dredging operations summarized by Hayes and Wu (2001), a ***characteristic resuspension value* of 0.5%** is selected for the characteristic clamshell dredge operation and site conditions. This characteristic resuspension value includes only the dredge operation itself and can be further broken down into the components of the clamshell dredge cycle as:

$$R_c \text{ (clamshell dredge)} = r_1 + r_2 + r_3 + r_4 \tag{7}$$

Table 3. Characteristic clamshell dredging operation

Bucket Characteristics	10 cubic yard (cy) clamshell bucket on cable hoist dredge Equivalent diameter* = 2.7 m Exposed surface area* = 7.24 m^2 Characteristic sediment removal thickness = 1.2 m
Water Depth	Pre-dredging depth = 8.3 m (27 ft) Post-dredging depth = 9.5 m (31 ft; 30 ft channel + 1 ft overdepth)
Site Characteristics	Ambient current = 0.1 m/sec
Dredge Operation	Average ascending speed = 1.6 m/sec Average descending speed = 1.2 m/sec Reset dredge every 20 bucket cycles at 200 sec/move Cycle time= 50 seconds (8s descending + 10s grabbing + 6s ascending + 10s slew over + 6s discharging + 10s return) Production without downtime: 380 m^3/hr (500 cy/hr) assumes buckets are only 80% full of sediment during production passes (buckets may be only 50% full during cleanup passes

*Computed assuming that the dredge bucket consists of the bottom half of a cylinder with a circular vertical profile and the bucket width equal to the diameter.

where r_1 = 0.01 = loss during bucket descent, r_2 = 0.09 = loss on bucket impact, r_3 = 0.15 = loss during bucket ascent, and r_4 = 0.25 = loss from the bucket during slewing.

ADJUSTMENTS FOR BUCKET DREDGE OPERATIONS

Sediment resuspension processes associated each phase of the clamshell dredge operation influence the total resuspension rate. This section describes those processes for each operational component and, in most cases, recommends specific adjustments to the characteristic resuspension value for deviations from the characteristic clamshell dredge operation.

Empty Bucket Descent through the Water Column

After the bucket returns from discharging its contents, it is lowered through the water column to the bottom. Only residual sediment attached to the inside of the bucket should be available for resuspension. The maximum sediment available for resuspension should be a thin layer over the interior area. The skin area is approximately equal to (assuming the cylindrical shape described in Table 3):

$$A_{skin} = \frac{\pi d_{eq}^2}{2}(bottom) + \frac{\pi d_{eq}^2}{4}(ends) = \frac{3}{4}\pi d_{eq}^2 = 3\left(\pi V_B^2\right)^{1/3} \qquad (8)$$

where A_{skin} = skin area of the bucket (m^2), d_{eq} = equivalent diameter of the dredge bucket (m), and V_B = dredge bucket volume (m^3). For the characteristic clamshell dredge, this would require about 1.6 cm of sediment attached to the entire bucket interior to be entirely eroded during descent to achieve r_1 = 0.01. Although this is plausible, it represents a maximum amount for the relatively non-plastic characteristic sediment.

At least three factors influence sediment resuspension during the bucket descent and should be considered in the adjustment of r_1: the amount of sediment that remains in the bucket, the speed of descent, and the depth of water. The adjustments for these project characteristics should be applied as:

$$r_1' = f_{aa}\, f_{dv}\, f_{dd}\, f_{sed}\, r_1 \qquad (9)$$

where r_1' = adjusted resuspension factor for bucket descent portion of the bucket dredging operation, f_{aa} = adjustment factor for sediment adhering to the interior bucket walls (dimensionless), f_{dv} = adjustment factor for descent velocity (dimensionless), and f_{dd} = adjustment factor for pre-dredging water depth (dimensionless). Adjustments to r_1 for each component are discussion below.

Adjustment for Sediment Stickiness

The total mass of sediment subject to resuspension depends on the sediment's propensity to adhere to the bucket walls. This propensity is both a function of the sediment stickiness and the bucket's roughness. The NRCS (Soil Survey Division Staff 1993*)* refers to this as the "Stickiness" property and provides four qualitative classes for stickiness:

- *Non-sticky* - After release of pressure, practically no soil material adheres to thumb or forefinger.
- *Slightly sticky* - After release of pressure, soil material adheres perceptibly to both digits. As the digits are separated, the material tends to come off one or the other rather cleanly. The material does not stretch appreciably on separation of the digits.
- *Moderately sticky* - After release of pressure, soil material adheres to both digits and tends to stretch slightly rather than pull completely free from either digit.
- *Very sticky* - After release of pressure, soil material adheres so strongly to both digits that it stretches decidedly when the digits are separated. Soil material remains on both digits.

Given the approximate nature of the calculations, these qualitative measures for stickiness are adequate. The characteristic sediment is taken to be moderately sticky and the adjustment factor for sediment stickiness set to 1.0.

Adjustment requires consideration of the total mass of sediment attached to the bucket and the bucket volume, since r_1 represents a fraction of the total sediment in the bucket. The dimensionless adjustment factor, f_{aa}, is:

$$f_{aa} = \frac{r}{r_1} = \frac{\Delta s A_{skin} \gamma_{skin}}{r_1 V_B \gamma_{sed}} = \frac{3\Delta s}{r_1}\left(\frac{\gamma_s}{\gamma_B}\right)\left(\frac{\pi}{V_B}\right)^{1/3} \tag{10}$$

where Δs = sediment thickness remaining on the interior bucket walls (m), γ_s = dry density of sediment attached to the interior bucket walls (kg/m^3), and γ_B = average dry density of sediment in the dredge bucket (kg/m^3). Assuming that $\gamma_s = \gamma_B$ and using $r_1 = 0.01$ for the characteristic clamshell dredge gives:

$$f_{aa} = 300\Delta s\left(\frac{\pi}{V_B}\right)^{1/3} \tag{11}$$

The actual erosion of the material stuck to the bucket is also a function of the sediment erodability. Erodability decreases with stickiness and increases with liquidity. Recommended adjustments for stickiness are based upon average sediment thickness on the interior of the bucket (ΔS_c). Those thickness values, based solely on judgment, are provided in Table 4 along with corresponding values of f_{sed} and f_{aa} for an assumed sediment thickness of sediment remaining o the bucket of 4.5 mm, i.e. ΔS_c = 4.5 mm.

Adjustment for Descent Velocity and Water Depth

The descent velocity influences the shear stress experienced by sediment remaining on the interior bucket walls and, when combined with water depth, determines the duration of that shear stress. The bucket descent velocity beyond the first meter of depth for most conventional dredging operations is thought to be more than sufficient to erode all moderately sticky sediment and less sticky sediment that would associated with the interior walls over the characteristic water depth (predredging depth = 8.3 m). This may not be true for environmental dredging operations where significant operational changes may be warranted and economical. It should be noted that this critical descent velocity will vary with sediment properties. The adjustment for descent velocity is assumed to be:

$$f_{dv} = \left(\frac{u_d}{\hat{u}_d}\right)^2 \tag{12}$$

Table 4. Typical adjustment factors for sediment adhering to the interior bucket walls.

	Non-sticky	Slightly sticky	Moderately sticky	Very sticky
Δs	0.0	$0.5\Delta s_c$	$1.0\Delta s_c$	$2\Delta s_c$
f_{sed}	10	3	1	0.1
f_{aa}	0	$f_{aa} = 0.675\left(\frac{\pi}{V_B}\right)^{1/3}$	$f_{aa} = 1.35\left(\frac{\pi}{V_B}\right)^{1/3}$	$f_{aa} = 2.70\left(\frac{\pi}{V_B}\right)^{1/3}$

Δs_c = average sediment thickness on interior bucket walls associated with the characteristic sediment and clamshell dredging operation; Δs_c = 4.5 mm for the proposed values.

where u_d = average bucket descent velocity (m/s) and $\hat{u}_d$ = characteristic bucket descent velocity (m/s) = 1.2 m/s.

Adjustments for time spent in the water column

Washing the outside of the bucket depends on sufficient water depth for complete removal. It is assumed that the characteristic water depth and velocity completely remove all sediment adhered to the bucket. The adjustment factor below, f_{td}, adjusts linearly for lesser depths or lower velocities.

$$f_{td} = \frac{h\hat{u}_d}{h_c u_d} \leq 1.0 \tag{13}$$

where h = predredging water depth (m) and h_c = characteristic predredging water depth = 8.3 m. If f_{td} is computed to be greater than 1.0, a value of 1.0 should be used.

The final adjustment for r_1 (bucket washing during descent) is

$$r_1' = f_{aa}\ f_{dv}\ f_{td}\ f_{sed}\, r_1 \tag{14}$$

unless the bucket is cleaned between each cycle using a rinse tank; in that case:

$$r_1' = 0 \tag{15}$$

Bucket Impact on Bottom and Closure

Bucket dredging operations often allow the bucket to accelerate through the water column and strike the bottom with maximum impact to achieve maximum penetration. Although environmental concerns have led to some change in this approach to reduce resuspension and control dredge depth in soft sediments, dredge buckets still typically strike the bottom with substantial force. The impact of the bucket into the soft bottom sediments results in some resuspended sediment and will disperse any existing nepheloid layer in the dredging area well into the water column. The nepheloid layer is a transitory suspended layer of material, is not truly part of the sediment layer, contains very little solids mass, and therefore can be neglected. In addition, some portion of fluid mud or disturbed sediment layer will be resuspended into the water column. The amount of sediment resuspended depends upon the descent velocity of the bucket at impact and the characteristics of the bottom sediment. Three adjustment factors are proposed to correct the characteristic resuspension value for this component of the operation, r_2 = 0.10. These adjustments should be applied as:

$$r_2' = f_{bv}\ f_{ec}\ f_{sed}\ r_2 \tag{16}$$

where r_2' = adjusted resuspension factor for bucket impact and closure portion of the bucket dredging operation, f_{bv} = adjustment factor for bucket velocity (dimensionless), and f_{ec} = adjustment for excess bucket capture (dimensionless).

Proposed formulations for each adjustment factor to r_2 are discussed below.

Adjustment for bucket descent velocity

The bucket descent velocity at impact directly influences the amount of sediment resuspended for specific sediment characteristics. Table 5 provides average bucket velocities during descent and rise for three bucket dredging projects. The characteristic vertical bucket velocity during ascent of 1.6 m/sec is based upon these data.

Sediment erosion rates are a linear function of shear stress which is a function of the relative velocity raised to the second power. Thus, the adjustment factor for descent velocity can be estimated as:

Table 5. Example bucket velocities during descent and ascent.

Bucket Velocity (m/s)	Boston Harbor	Bullock Point	Sabine Point	Average
During Descent	1.1	1.2	1.3	1.2
During Rise	1.9	1.6	1.4	1.6

$$f_{bv} = \left(\frac{u_d}{\hat{u}_d}\right)^2 \tag{17}$$

where f_{bv} = adjustment factor for bucket descent velocity (dimensionless).

Adjustments for excess sediment capture

Buckets that penetrate deeply into the soft sediment layer upon impact usually capture excess sediment as the bucket closes, resulting in an overfilled bucket. Sediments piled above the bucket will slough to the angle of repose on closure. Sloughed sediments return to the bottom in a higher water content (lower density) state than when captured. This may make them more difficult to dredge with successive buckets, but it is not thought to contribute significantly to sediment resuspension. The effect of excess sediment capture would be a function of sediment properties and may be adequately captured in the adjustment for sediment properties. Until additional research provides evidence of contributions to resuspension, it is recommended to use:

$$f_{ec} = 1.0 \tag{18}$$

The final adjustment for r_2 is

$$\text{for } (f_{bv}\, f_{ec}\, f_{sed}) \le 1 \qquad r_2' = r_2 \tag{19}$$

$$\text{for } (f_{bv}\, f_{ec}\, f_{sed}) > 1 \qquad r_2' = f_{bv}\, f_{ec}\, f_{sed}\, r_2 \tag{20}$$

Filled Bucket Ascent through the Water Column

After closure and sloughing of sediments above the bucket walls to the angle of repose, the bucket begins its ascent through the water column. Sediment is resuspended during this phase of the operation through erosion of the exposed sediment surface, washing of the bucket exterior, leakage from the bucket seals, and the suction wake of the bucket as it accelerates from its initially closed position. For enclosed buckets, sediment losses occur through the vents at the dredging depth rather than from erosion of surface sediments. The characteristic resuspension value for the filled bucket ascent, r_3, was set at 0.15 based upon the following distribution:

$$r_3 = (w_{la} + w_{bw} + w_{eb} + w_{sw})\, 0.15 = (0.2 + 0.05 + 0.65 + 0.1)\, 0.15 \tag{21}$$

where w_{la} = fraction of characteristic resuspension factor due to leakage from the bucket = 0.2, w_{bw} = fraction of characteristic resuspension factor due to washing sediment adhering to the exterior bucket surface = 0.05, w_{eb} = fraction of characteristic resuspension factor due to erosion from an open bucket surface = 0.65, and w_{sw} = fraction of characteristic resuspension factor due to the suction wake of the bucket = 0.1. Note that

$$w_{la} + w_{bw} + w_{eb} + w_{sw} = 1.0 \tag{22}$$

Adjustment factors are proposed for the processes that affect each component. These adjustments should be applied as:

$r_3' = [(f_{la}w_{la} + f_{bw}w_{bw} + f_{ea}w_{eb})\, f_{td} + f_{sw}w_{sw}]\, f_{sed}\, r_3$ (23)

where r_3' = adjusted resuspension factor for filled bucket ascent portion of the bucket dredging operation, f_{la} = adjustment factor for bucket leakage during ascent (dimensionless) , f_{bw} = adjustment factor for bucket washing during ascent (dimensionless), and f_{sw} = adjustment factor for the resuspension caused by the suction wake of the dredge (dimensionless),

Proposed formulations for adjustment factor to each component of r_3 are discussed below.

Adjustments for bucket leakage

Bucket leakage occurs through the closure joints during the time that the bucket is in the water. Without consistent maintenance of rubber seals, leakage is difficult to control with conventional equipment. The total amount of leakage depends upon the length of the closure joint, depth of sediment in the bucket, and acceleration of the bucket. The closure joint length decreases relative to bucket volume as the clamshell size increases. However, the increase in bucket size increases the pressure on the joints which increases the loss rate. Without definitive research results, these contributions are ignored and the adjustment for leakage is limited to only the relative time that the bucket is in the water, which is incorporated by $f_{av}\, f_{dd}$, and therefore

$$f_{la} = 1 \tag{24}$$

Adjustment for Bucket Washing

The exterior of the bucket gets washed just as the interior does. Similar assumptions apply, but the total mass of sediment that attached to the bucket immediately after being extracted from the sediment should be greater than after discharge. Thus, the formulation in Equation 9 applies here as well, except that we should substitute $w_{bw}r_3$ for r_1. Doing so, assuming that $\gamma_s = \gamma_B$, and using $w_{bw}r_3 = 0.05(0.15) = 0.0075$ for the characteristic clamshell dredge gives:

$$f_{bw} = 400\, \Delta s \left(\frac{\pi}{V_B}\right)^{1/3} \tag{25}$$

Recommended adjustments for stickiness based upon average sediment thickness according to the NRCS descriptive index are provided in Table 6 along with corresponding values of f_{sed} and f_{bw} for an assumed value of ΔS_c = 4.5 mm.

Table 6. Typical adjustment factors for the washing of sediment from the bucket walls.

	Non-sticky	Slightly sticky	Moderately sticky	Very sticky
Δs	0.0	$0.5\Delta s_c$	$1.0\Delta s_c$	$2\Delta s_c$
f_{sed}	10	3	1	0.1
f_{bw}	0	$f_{bw} = 0.90\left(\frac{\pi}{V_B}\right)^{1/3}$	$f_{bw} = 1.80\left(\frac{\pi}{V_B}\right)^{1/3}$	$f_{bw} = 3.60\left(\frac{\pi}{V_B}\right)^{1/3}$

Δs_c = average sediment thickness on interior bucket walls associated with the characteristics sediment and clamshell dredging operation; Δs_c = 4.5 mm for the proposed values.

Adjustments for erosion from the bucket

If the dredge cut is limited to a depth less than the normal cutting depth of the bucket, e.g., there is an underlying stiff clay layer, erosion due to surface impact should not contribute significantly to sediment resuspension. However, significant sediment is released to the water column while the full bucket ascends to the surface because of surface erosion of sediments from the open top of the bucket. Surface erosion rate for an overfilled open bucket is approximately proportional to water velocity across the sediment surface raised to the 2nd power. This surface velocity includes both the rise velocity of the bucket and ambient currents. Surface erosion losses from open buckets also increase with water depth as it increases the time exposed sediments are subject to the erosive forces, and the exposed area of the bucket. Assuming the rate of erosion is constant, sediment loss will increase proportional to the time required to pull the bucket through the water column. These adjustments for time are given later. Combining these effects yields the following adjustment for erosive forces acting on an open bucket:

$$f_{ea} = \frac{A_{ex}V_c}{A_c V_{ex}}\left(\frac{(u_a^2 + u_c^2)}{(\hat{u}_a^2 + \hat{u}_c^2)}\right) \qquad (26)$$

where f_{ea} = resuspension factor adjustment for surface sediment erosion while being raised to the surface, A_{ex} = exposed surface of the dredge bucket (m^2), A_c = characteristic exposed surface of the dredge bucket (m^2), V_{ex} = full volume of the dredge bucket (m^3), V_c = characteristic fill volume of the dredge bucket (m^3), u_a = vertical bucket velocity while being raised to the surface (m/sec), and $\hat{u}_a$ = characteristic vertical bucket velocity (m/sec) = 1.6 m/sec.

Note that for an enclosed bucket, $A_{ex} = 0$ which yields $f_{ea} = 0$, i.e. no erosional losses. However, if the depth of sediment in the bucket, D, exceeds the height of the vents, D_{vent}, excess sediment will be lost through bucket vents and subject to erosion as given in Equation 26 above. The maximum erosion from an enclosed bucket would consist of all material above the vent depth, that is:

$$f_{ea} = \frac{V_{grab} - V_{vent}}{V_{vent}} \qquad \text{for enclosed buckets when } V_{grab} > V_{vent} \qquad (27)$$

$$f_{ea} = 0 \qquad \text{for enclosed buckets when } V_{grab}\ \ V_{vent} \qquad (28)$$

where V_{grab} = sediment volume initially removed by the enclosed bucket and V_{vent} = bucket volume to the bottom of the vents. Additional research is needed to better account for sediment that would remain in an enclosed bucket above the vent level.

Adjustments for suction wake

Soft sediments reform to the bucket shape as it closes. When the bucket begins to accelerate upward, the suction wake causes loosened sediment to redistribute vertically in the water column, contributing to sediment resuspension. The force of the suction wake is relative to the upward velocity of the bucket:

$$f_{sw} = \left(\frac{u_a}{\hat{u}_a}\right)^2 \qquad (29)$$

where f_{sw} = adjustment factor for suction wake (dimensionless).

Adjustment for Ascent Velocity and Water Depth

The ascent velocity and water depth influences the time for the loss mechanisms to occur. The adjustment for ascent velocity and water depth should be

$$f_{ta} = \frac{h\hat{u}_d}{h_c u_d} \tag{30}$$

The final adjustment for r_3 is

for $f_{ta} \leq 1$ $\quad r_3' = [(f_{la}w_{la} + f_{ea}w_{eb} + f_{bw}\, w_{bw})\, f_{ta} + f_{sw}w_{sw}]f_{sed}\, r_3$ (31)

for $(f_{av}\, f_{dd}\, f_{sed}) > 1$ $\quad r_3' = [(f_{la}w_{la} + f_{ea}w_{eb})\, f_{ta} + f_{bw}\, w_{bw} + f_{sw}w_{sw}]\, f_{sed}\, r_3$ (32)

Slewing from the point of dredging to the disposal barge

Once the bucket breaks the water surface during ascent, the differential pressure between the interior and exterior of the bucket increases dramatically which leads to significantly increased leakage. As stated above, leakage increases as the closure joint length and the sediment depth in the bucket increase. The loss of sediment is a function of the sediment properties. However, the rate of increase relative to bucket volume is less clear. Until research can provide clarity on this issue, it is assumed that the there is no proportional increase or decrease. Thus,

$$f_{so} = 1.0 \tag{33}$$

where f = adjustment for leakage during slewing over (dimensionless). The characteristic resuspension due to slewing, r_4, is estimated to be 0.05.

$$r_4' = f_{so} f_{sed} r_4 \tag{34}$$

OTHER RESUSPENDED SEDIMENT CONTRIBUTIONS

Several other actions associated with bucket dredging operations can also lead to resuspended sediment. These include debris, anchoring and resetting the dredge, “sweeping” the bottom sediment, barge overflow, and potentially other actions. The characteristic resuspension value does not include contributions of these actions since they are not necessarily associated with all bucket dredging operations. Further, the sediment resuspension associated with them can vary widely. Unfortunately, very little information is available to quantify their contributions, much less associate them accurately with specific dredging actions or practices. Since one purpose of this paper is to identify contributing factors so that researchers can begin to quantify contributions and develop methods for estimating them a priori, these are presented and discussed. Rudimentary methods are presented where possible to estimate their contributions. These contributions are expressed as additional resuspension factors for the project. Thus, the total resuspension for the project should be estimated as:

$$R = R(\text{clamshell dredging}) + R(\text{bottom sweeping}) + R(\text{debris}) + R(\text{anchoring}) + R(\text{overflow}) \tag{35}$$

Bottom Sweeping

Conventional clamshell buckets produced scalloped bottoms that are a matrix of concave bucket impressions. Swinging an open bucket laterally within a meter of the bottom moves sediment from the higher ridges into the lower concave bucket impressions. Although this may be prohibited for environmental dredging projects, it is a rather common practice for navigation dredging projects. Not surprisingly, this action can generate substantial sediment resuspension. However, no data are known to exist that might provide a basis upon which to estimate the extent of resuspension that might occur as a result of this leveling technique or relate it to operational parameters.

Debris

Debris poses significant problems for clamshell buckets, just as it does for every dredging operation. The impact is stochastic in nature; when debris lies within the bucket footprint, it will likely be captured. If it is larger than the bucket or unfortunately positioned, debris can breach the bucket closure. When that occurs, either part or all of the captured sediment will sluice through the opening either during ascent or when the bucket breaks the water surface.

Although these sediments often resettle to the bottom as a large density current, their impact on the bottom and entrainment during descent can result in a substantial turbidity plume. The lost dredge cycle also reduces dredge production.

When an entire bucket of sediment is lost due to debris (or any other malfunction), most of the sediment falls rapidly to the bottom in a dense flow of sediment. However, experience with STFATE modeling indicates that characteristically about 5% of the fines not in clumps will become suspended in the water column. The actual quantity depends on the sediment properties and can be adjusted using f_{sed}. The resulting resuspension rate is computed as:

$$R_{debris} = \frac{5\ f_{sed}\ N_{debris}}{100} \tag{36}$$

where R_{debris} = resuspension factor for debris losses (%), and N_{debris} = number of cycles per 100 for which debris is encountered.

Anchoring/Resetting

Bucket dredges often use the reach of their boom to make a number of grabs over an area before having to move the entire dredge forward and reset it for another matrix of cycles. These cycles typically comprise a "dredge set" and can range from 10 to 50 bucket cycles depending on the dredge prism and boom dimensions. Once an area is complete, the spuds must be raised and the dredge reset to a new position, either through its own propulsion or using a tug (or other vessel). For short distance resets in the forward direction, dredgers often "cast" their bucket forward as far as possible grabbing a full bucket of sediment in the process, then pull the dredge platform forward using the weight and resistance of the filled bucket. The potential to resuspend sediments obviously exists when the spuds are raised and lowered, by the pulling against the filled bucket, or by a tug or other propulsion to move the platform forward. With no known data on this contribution either, no resuspension factors are proposed.

Barge Overflow

Most bucket dredging operations place the removed sediment in an adjacent hopper barge, although some side-cast sediment and others place it on a deck barge with fencing or short sides around the edges. As the sediments are placed into an unsaturated environment, the soft sediments often compress quickly releasing supernatant waters. Additional water entrained by the dredging process, exacerbates this release of free water. If the sediments are contained in a hopper barge, a layer of supernatant water forms over the surface of the sediment. If dredging is stopped when that layer reaches the top of the barge containment, the loading process will not likely contribute significantly to sediment resuspension; spillage during loading is likely a negligible contribution. However, many dredging operations continue placing sediments into the hopper barge until they achieve an "economic load."

As additional sediments are placed into a filled barge, sediment displaces supernatant liquid causing it to spill over the side of the barge and into the water column. The contribution to sediment resuspension from a hopper barge overflow can be estimated as:

For $V_{ds} \leq V_{hb}$

$$R_{OF} = 0 \tag{37}$$

For $V_{ds} > V_{hb}$

$$R_{OF} = 100\left(\frac{\gamma_{OF}}{\gamma_{sed}}\right)\left[\frac{(bV_{ds} - V_{hb})}{V_{ds}}\right] \tag{38}$$

where R_{OF} = resuspension factor for barge overflow (percent), b = bulking factor due to dredging of the sediments (dimensionless), V_{ds} = in situ volume of dredged sediments placed into a single barge (m^3), V_{hb} = volume of the hopper barge (m^3), and γ_{OF} = dry density of barge overflow (kg/m^3).

The bulking factor, b, adjusts for entrained water during the dredging process; its value ranges from 1.0 to 1.5 depending upon the dredging operation and type of bucket used. In the absence of better data, it is recommended to use b = 1.1 for conventional clamshell buckets, b = 1.3 for enclosed clamshell buckets, and b = 1.4 for other environmental buckets or enclosed clamshell buckets being operated specifically for environmental dredging purposes. These differences account for the additional water typically entrained by the different buckets and resulting from their operation.

The density of the overflow from the barge varies with time, typically very low for the initial volumes displaced and can reach very high densities if the barge is loaded with sediment above the exterior containment. In the absence of better information, an assumption of $\gamma_{OF}/\gamma_{sed} = 0.02$ is recommended.

Tender Vessels and Barge Movement

Like every dredging operation, bucket dredges require a fleet of tender vessels to facilitate various aspects. Their movement, especially in shallow water, can result in significant sediment resuspension. Even more significant impacts may result from tugs moving hopper barges, especially filled barges. These impacts are sporadic and not conducive to estimates relative to the dredging operation. No approaches for estimating these contributions are presented here.

Verification of Results

The procedure for was applied to five clamshell bucket field studies for which significant open bucket resuspension data are available. These projects are summarized in Table 7. Of these five field studies, only the Boston Harbor study included data from the near-field area. Resuspension factors for the other four studies were extrapolated from observations at significant distances from the source rather than direct measurements.

Table 7. Summary of estimated resuspension losses from standard clamshell bucket operations (modified from Hayes and Wu 2001).

		Field Study				
		Thames River	**St. Johns River**	**Black Rock Harbor**	**Calumet River**	**Boston Harbor**
Environment		Estuary	Estuary	Estuary	Freshwater River	Estuary
Bucket Size (yd^3)		13	12	10	10	26
***In Situ* Sediment**	**Type**	Very soft silty clay	Soft, organic clay/silt mixture	Sandy organic clay	Soft organic clay/silt mixture	Stiff clay with silt
	Moisture Content (%)	*	*	300	*	*
	Atterberg Limits (%)	*	*	LL = 170% PL = 65%	*	*
	Debris?	*	*	Yes	*	*
	Specific Gravity		2.40	2.39	*	*
	Organic Content (%)	3-4	*	*	*	*
Cycle Time (sec)		100	43	40	55-65	51
Water Depth (m)		12.8	5.5	6.2	7.5	11.7
Typical Current (m/sec)		0 – 0.2	0 – 0.07	0.07 - 0.25	0 - 0.07	0.17
Scow Overflow		Yes	Yes	Yes	Yes	No
f_{74}		0.90	*	0.90	0.83	0.99
Production (m^3/hr)		600	864	688	380	1530
Data Source		Bohlen *et al.* (1979)	Collins (1995)	Collins (1995)	Hayes, *et al.* (1988)	Hayes, *et al.* (2000a)
Resuspension Factor, R (%)		0.88	0.16	0.28	0.25	0.66

* missing data

The available information for the five projects was used to apply the predictive procedures described above. Unavailable parameters were either estimated or not considered in the analysis. The results are compared with previously reported values in Table 8.

Table 8: Measured and predicted values of R for five clamshell dredging operations assuming r_1 = 0.01.

		Field Study				
		Thames River	**St. Johns River**	**Black Rock Harbor**	**Calumet River**	**Boston Harbor**
f_{sed}		1	1	2.3	1	1
Sediment Description		Very soft silty clay	Soft, organic clay/silt mixture	Sandy organic clay	Soft organic clay/silt mix	Stiff clay with silt
NRCS Stickiness		Moderately Sticky	Slightly Sticky	Moderately Sticky	Slightly Sticky	Very Sticky
Bucket Velocity (m/s)	Down	0.49	1.38	1.36	0.69	1.2
	Up	0.65	1.84	1.81	0.92	1.60
Bucket Descent Adjustments (r_1 = 0.01)						
f_{aa}		0.92	0.47	1.00	0.50	1.46
f_{td}		1.00	0.58	0.66	1.00	1.00
f_{dv}		0.17	1.32	1.28	0.33	1.00
r_1'		0.002	0.004	0.020	0.002	0.015
Bucket Grab Adjustments (r_2 = 0.09)						
f_{bv}		0.17	1.32	1.28	0.33	1.00
f_{ec}		1	1	1	1	1
r_{NL}		0	0	0	0	0
r_2'		0.02	0.12	0.27	0.03	0.09
Bucket Ascent Adjustments (r_3 = 0.15)						
f_{la}		1	1	1	1	1
f_{bw}		1.23	0.63	1.34	0.67	1.95
f_{ea}		0.15	1.23	1.28	0.33	0.73
f_{sw}		0.17	1.32	1.28	0.33	1.00
f_{ta}		3.31	0.50	0.58	1.38	1.23
r_3'		0.16	0.10	0.26	0.10	0.15
Bucket Slew Adjustments (r_4 = 0.25)						
f_{so}		1	1	1	1	1
r_4'		0.25	0.25	0.58	0.25	0.25
Calculated R		0.43	0.47	1.12	0.38	0.51
Measured R		0.88	0.16	0.28	0.25	0.66

SUMMARY AND CONCLUSIONS

The approach described in this paper to estimate sediment resuspension from bucket dredging operations attempts to quantify the specific processes that influence the rate and mass of sediment resuspended during dredging. Since there is limited data available at this level of detail, the approaches were developed from first principles and the authors' general understanding of bucket dredging operation and sediment behavior. Even with the elementary approaches described, however, most of the estimates of R from the approach described are in the general range of observed values.

Although the approaches and equations could be modified to improve the estimates for the comparison studies, it was not attempted as part of this effort. For example, the Black Rock Harbor results – which are the most disparate with a predicted R of 1.12 as compared to a measured value of 0.28 – could be brought significantly closer with just a few minor changes. However, the accuracy of any predictive procedure for estimating sediment resuspension from dredging operations is limited by the paucity of available data. Even for the studies used for comparison, a significant amount of information is missing or uncertain. Further, the "measured" values of R are only approximations based upon limited data and certainly don't represent precise measurements. These estimates also do not include barge overflow which occurred in several of the projects, but were not included in the R estimates because the data to support the calculations were not available.

The computations show that the approach accounts for the many of the most important physical and operational parameters. It is the authors' hope that this general approach will provide the basis for clearly focused research efforts to better quantify the identified processes and develop more accurate predictive measures. Certainly, additional detailed data collection efforts will be essential in this effort. Data sets need to contain sufficient suspended sediment observations in the near vicinity of the dredging operation to prevent individual extreme observations from biasing the data set. The actual number of observations required to accomplish this must be determined on a site-specific basis, but defining the spatial and temporal variations in suspended sediment concentrations accurately typically requires hundreds of observations. Further, detailed data on the dredge operation are essential; extensive water quality data sets without corresponding dredging operation data are of very limited value. Project details such as site characteristics, sediment properties, and dredging equipment specifications are also very important.

As these improved procedures are developed, the approach described in this paper should prove to be a robust and reliable framework for a priori estimates of sediment resuspension rates.

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