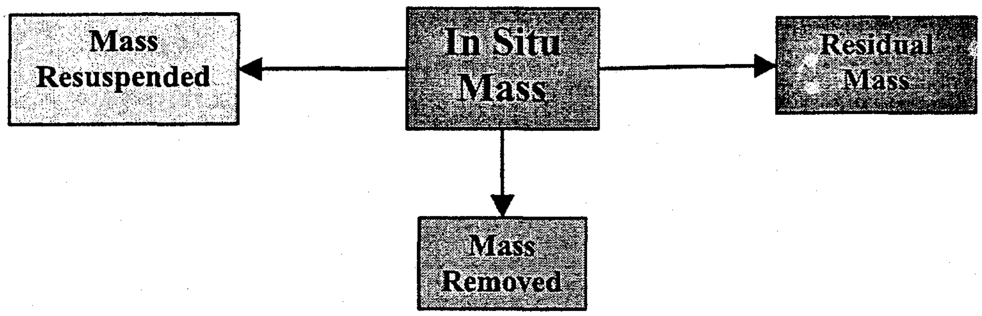
70618

Toxic Constituent Losses During Dredging of Contaminated Sediments[1]

Donald F. Hayes, Ph.D., P.E.
Civil & Environmental Engineering, University of Utah

INTRODUCTION

Even though dredges are effective sediment movers, some sediment escapes into the water column. Elevated suspended sediment concentrations in the water column impair water quality and the potential for redeposition raises additional concerns. Many of these concerns are addressed for navigational dredging projects by imposing dredging windows. Environmental dredging of contaminated sediments, however, raises additional concerns including the potential release of toxic constituents into the water column.



Basics

A mass balance analysis of the in situ sediment volume illustrates potential contaminant release pathways. The figure above and equation below show the pathways of potential sediment and contaminant loss (note that volatilization is included implicitly in dissolved contaminant mass released into the water column):

In Situ Mass = Mass Removed + Mass Resuspended + Residual Mass

Mass balances can be written specifically for sediment and toxic constituents:

Sediment: $\phi\rho_{sed}V_{sed} = P_{dredge}\phi\rho_{sed}\Delta t + f_{res}(P_{dredge}\phi\rho_{sed}\Delta t) + V_{remain}\phi\rho_{sed}$

Toxics: $c_{sed}(\phi\rho_{sed}V_{sed}) + c_{pw}V_{sed}(1-\phi) = c_{sed}(P_{dredge}\phi\rho_{sed}\Delta t) + c_{sed}(f_{res}P_{dredge}\phi\rho_{sed}\Delta t) + c_{sed}(V_{remain}\phi\rho_{sed})$

[1] Paper summary of poster presented at the EPA Superfund Workshop on Contaminated Sediments, Alexandria, VA, May 30-June 1, 2001. Author contact info: Hayes, D.F., Associate Professor, Civil & Environmental Engineering, University of Utah, 122 S. Central Campus Dr., Suite 104, Salt Lake City, UT 84112, USA, (801) 581-7110, (801) 585-5477 (fax), hayes@civil.utah.edu.

11.2726

where f = porosity of in situ sediment (unitless), ρ_{sed} = in situ sediment bulk density (kg/m3), V_{sed} = in situ volume of sediment to be dredged (m3), P_{dredge} = dredge production rate in term of in situ sediment volume per time (m3/hr), Δt = dredging duration (hr), f_{res} = fraction of sediment mass resuspended by dredging operations (unitless), V_{remain} = volume of residual sediment; i.e. sediment included in initial volume, but not removed by the dredging operation or suspended into the water column (m3), c_{sed} = contaminant concentration on sediment (mg/kg), and c_{pw} = concentration in the pore water of in situ sediments (g/m3).

These mass balances demonstrate the close connection between bottom sediment mass and contaminant mass, regardless of its environmental location. In fact, algebraic manipulation shows that the contaminant loss rate and sediment loss rate are equivalent, unless the dissolved contaminant mass in the pore water is significant compared to the contaminant mass associated with the sediment mass. Thus, estimating suspended sediment losses to the water column also gives an estimate of potential total contaminant loss.

RESUSPENSION LOSSES[2]

A variety of mechanical and mixing actions occur in the immediate vicinity of dredging operations. These actions do not discriminate against particles sizes; all sediment size fractions are initially suspended into the water column. The actions result in mechanically induced mixing that dominates transport in this "near-field" area. The physical dimensions of this mixing area vary with dredge type, operation, and local environmental conditions, but are unlikely extend more than a few meters in any direction. Sand (and larger) particles that are suspended by the dredging operation resettle quickly, probably within this zone except under extreme flow conditions. Only silt and clay particles (i.e. particles smaller than 74 mm) in the water column are subject to transport away from the immediate vicinity of dredging. Hayes and Wu (2001) define the Resuspension Factor, R, as the rate of sediment mass flux leaving this near-field area.

$$R = \frac{360g}{f_{74} V_S C_S}$$

where g = mass rate of sediment resuspension (g/sec), R = resuspension factor or sediment mass loss rate (%), f_{74} = fraction of particles with a diameter smaller than 74 µm, V_S = volumetric rate of in-situ sediment removal (m3/hr), and C_S = in situ sediment concentration (g/m^3).

Available Field Data

Given the simplicity of the mass balance approach, it may initially seem logical to to determine resuspension losses by carefully measuring the dredge production rate and residual mass. Closer inspection shows that errors associated with these measurements would likely be larger than the

[2] This section summarizes information presented in Hayes, Donald and Wu, Pei-Yao (2001). "Simple Approach to TSS Source Strength Estimates," *Proceedings of the WEDA XXI Conference*, Houston, TX, June 25-27, 2001.

losses themselves. Correctly considering these errors in a mass balance method results only provide an upper bound with an unacceptably large margin of error.

A number of projects have collected water column observations of suspended sediment, turbidity, and toxic constituents upstream and downstream of dredging operations. This approach provides useful data to evaluate water quality impacts associated with dredging operations. It can not, however, provide a reliable estimate of loss rate unless a very dense spatial sampling pattern is sampled frequently during the operation. Most monitoring programs incorporate substantial compromise in both sampling density and frequency to keep monitoring costs manageable. Sample compositing is also often used to reduce costs, especially for toxic constituent analyses. However, accurate compositing requires flow-weighted sample volumes which are difficult to determine correctly in the field.

Theoretically, transport modeling could be used to estimate the source generation rate; realistically, uncertainty about dispersion and settling rates precludes this approach. It is also unusual for sufficiently detailed information on the dredge operation to be collected. These data are essential to accurately evaluate water quality data.

Loss rates are best estimated by intense sampling in the immediate vicinity of the dredging operation itself (see Figure 1). While this has been accomplished around several dredging operations, the available database is limited. It is also not easy to accomplish and is particularly difficult for mechanical dredging operations. The available data and resulting loss rates are summarized below by dredge type.

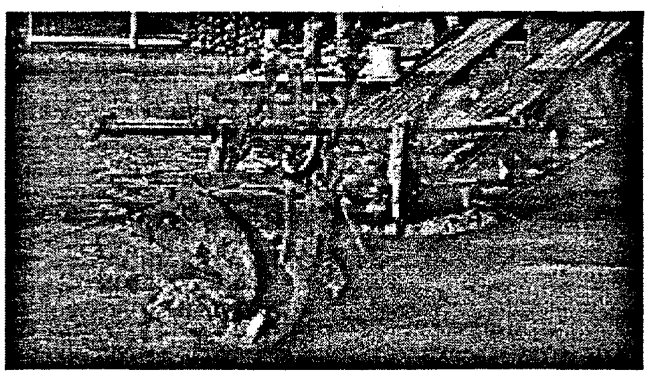


Figure 1. Near-field sampling device for hydraulic cutterhead dredge.

Hydraulic – Conventional Cutterhead Dredge Studies

Hayes, et al. (2000) and Wu and Hayes (2000) present almost 400 observations of resuspension rate from five field studies. The characteristics of these studies are summarized in Table 1. Resuspension factor, R, was calculated for near-field resuspension data from these dredging operations. The results are shown in Figure 2. Table 1 also summarizes resuspension factor values and their statistical characteristics for each field study.

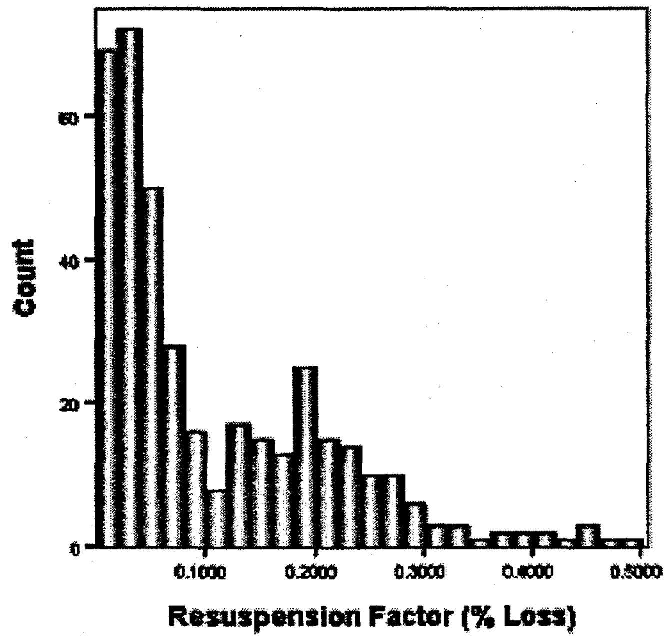


Figure 2. Histogram of observed resuspension factors for hydraulic cutterhead dredges.
The hydraulic cutterhead dredge results are consistent with expectations. The highest resuspension factor is from Lavaca Bay - Phase II. The combination of a small dredge with relatively low horsepower removing highly consolidated, sticky clay in a dynamic environment would be expected to be a poor combination. Small particle sizes and a relatively low production rate exacerbate the problem. New Bedford Pilot Study (Acushnet River) observations were also elevated because of low dredge production, soft sediment (in situ moisture content > LL), and extensive debris. The DUBUQUE operated under almost ideal conditions in Calumet Harbor and the resuspension factor reflects that the operation was quite effective.**Mechanical – Clamshell Bucket Dredge Studies**

Resuspension data are available from several bucket dredging studies. The proximity of the data to the source is less convenient than for the cutterhead dredging operations; the operation of bucket dredges makes it difficult to get data in the immediate vicinity of the source. There are, however, sufficient data to develop representative resuspension factor values for bucket dredging operations. Since all observations are away from the immediate vicinity of the dredging operation, it is assumed that all particles larger than 74 mm have already settled and the resuspension factor was not adjusted for this fraction.

Table 1. Characteristics of cutterhead field studies used to develop resuspension factors.

		James River	Back River	Calumet Harbor	Acushnet River	Lavaca Bay – Phase II
Dredge		*ESSEX*	*CLINTON*	*DUBUQUE*	*Ellicott 370*	*Tyro, Jr.*
Size		18" diam.	18" diam.	12" diam.	10" diam.	12"
Water Depth (m)		10	6.1, 11.6	8.2	0.6 - 1.5	1.1 – 2.5
Swing Width (m)		58	46, 61, 92	30	18	18
Cutter Tip Speed (m/s)		0.2 - 0.4	0.2 - 0.4	0.2 - 0.4	0.15	0.03 – 0.64
Cutter Diameter (m)		1.5	1.8	0.9	0.8	0.8
Sediment Removal (m)		1.5	~ 0.9, 6.1	0.9	0.6	0.8
Cutter Rotation Speed (rpm)		20, 28, 32, 35, 37, 40	6.6, 12, 16	15, 20, 27	20	8.5, 19
Production (m^3/hr)		504 - 2252	161 - 7379	33 - 56	28	28
f_{74}		0.98	0.99	0.83	0.74	0.75
Environment		Estuary (< 1 ppt)	Estuary	Freshwater Lake	Estuary	Estuary
In Situ Sediment	**Type**	Very soft silty clay (CH)	Soft, organic clay/silt mixture	Silty loam	Soft organic clay/silt mixture	Fat Clay
	Moisture Content (%)	186	*	71.1	117-159	43
	Atterberg Limits	LL > 120% PL ≅ 40%	*	LL = 25.4% PL = 25%	LL = 107-123% PL = 55-77%	LL = 58.5% PL = 26%
	Debris Present?	No	No	No	Yes	No
	Specific Gravity	2.73		2.71	2.46-2.55	
	Organic Content	*	*	*	*	*
Ambient Currents (m/s)		0.1 – 0.8	0.03 – 0.8	0.0 - 0.07	< 0.07	0.0 – 0.07
Observations		15	28	12	51	282
Characteristics of Calculated Resuspension Factors, R (%)						
Average		0.023	0.041	0.003	0.082	0.13
Standard Deviation		0.017	0.052	0.002	0.087	0.11
Minimum		0.004	0.003	0.0005	0.01	0.001
Maximum		0.054	0.21	0.006	0.33	0.51

*missing data

11.2730

Standard (Open) Clamshell Buckets

A number of field studies have used standard clamshell buckets, often referred to as "open" buckets to distinguish them from enclosed buckets in an attempt to reduce turbidity. These data have been reported and analyzed by a number of authors. Hayes and Wu (2001) summarize the studies and estimate resuspension factor values.

Kuo and Hayes (1991) used average sediment loss rates from the Thames River, St. Johns River, and Black Rock Harbor to calibrate their transport model for bucket dredging operations. Sediment loss rates for the Thames River and Black Rock Harbor are the same as those presented by Kuo and Hayes (1991), 0.88 and 0.28% respectively. Sediment loss rates for the St. Johns River, however, were adjusted for what appears to be an error in the initial concentration used by Kuo and Hayes. Collins (1995) estimates the source strength to be 0.45 kg/sec rather than the 0.31 kg/sec published by Kuo and Hayes. Since an earlier version of Collins' report was the source of this value, it is assumed to be in error. This increases the sediment loss rate to 0.16%, more in line with the other studies.

A study of open clamshell dredging in the Calumet River (Hayes et al. 1988) also included scow overflow. Collins (1995) calculated a sediment loss rate of 243 g/sec for the Calumet River field study. Although a production rate is not provided, assuming a full bucket and 50 cycles per hour, the production rate would be 380 m^3/hr. Assuming that the sediment characteristics are the same as those found in the Calumet Harbor field study (in situ concentration of 920 kg/m^3), the resulting loss is 0.25%.

All of these dredging operations included scow overflow; that is the sediment scow was filled beyond the initial filling to displace supernatant liquid with sediment and increase the economic load. The supernatant overflows the barge and discharges solids into the water column. These solids increase TSS concentrations in the water column and become mixed with solids resuspended by mechanical actions of the dredge. Hayes and Welp (2000) present results from a 1999 dredging study in Boston Harbor. Scow overflow was not allowed during these dredging operations; thus, measured sediment resuspension values result from dredging actions only. The conventional 26-cy bucket removed about 2 feet of silt plus a foot or so of virgin clay from the 38-ft bottom. The production rate is assumed to be about 1,530 m^3/hr based upon the dredge operation and bucket capacity. TSS observations during dredging yield a depth-averaged TSS concentration above background of 201 mg/L. The width of the plume was not measured. Considering the short distance between the bucket and sampling location, it is unlikely to be more than twice the bucket width of about 3 m. Assuming that concentration occurs across a 6-m width in a current velocity of 0.17 m/sec the source strength is about 2.4 kg/sec. Assuming an in situ sediment concentration of 844 kg/m^3, the sediment lost to resuspension was 0.66 percent.

All of these studies show higher resuspension factors than the cutterhead dredge studies described previously. Resuspension factors range from 0.16 to 0.66. The results for the Boston Harbor field study are surprising in that they are among the highest value even though barge overflow was not allowed. The other values seem to be in a reasonable range, particularly considering that barge overflow was included. If overflow accounts for 50% of the suspended sediments, the remaining resuspension factors are not substantially different from those for the cutterhead dredges.

The apparent increase in resuspension factor for Boston Harbor may result from the samples being collected much closer to the actual dredging location (within 2 to 7 m) than in the other studies. TSS concentrations at the source for the other studies were extrapolated from samples collected farther downstream. A substantial amount of the TSS in the Boston Harbor study was near the bottom; without that value, the average TSS concentration and source strength would have been reduced by 30% yielding a resuspension factor of about 0.47. This is much more in line with the other studies. It is likely that these additional solids would have settled in the near vicinity of the dredging operation and not been measured in downstream samples as taken in the other studies.

Enclosed Clamshell Bucket Dredge Studies

Data are available for two bucket dredging studies that used enclosed clamshell buckets. The first study was conducted in the St. Johns River at the same location and under the same conditions as the open bucket dredging study described above. Collins (1995) did not estimate source strength for the enclosed bucket operation in the St. Johns River, but did report an estimated TSS concentration at the bucket location of 150 mg/L. The estimated TSS concentration at the open bucket was 285 mg/L; since the conditions are the same, the resuspension rate is proportional. Thus, the representative resuspension rate for the enclosed bucket during the St. Johns River study was 0.27 kg/sec and a sediment loss rate of 0.10 %. The resulting resuspension factor is 1,000 and includes bucket overflow.

The most recent data were collected in Boston Harbor in August 1999 (Hayes and Welp 2000) during the operation of a 39-cy enclosed bucket. The enclosed bucket was a conventional 26-cy bucket converted to an enclosed bucket with a 39-cy capacity. The bucket removed about 2 feet of sediment from the 38-ft bottom with an observed depth-averaged TSS concentration of 50 mg/L. Assuming that concentration occurs across a 6-m width in a current velocity of 0.17 m/sec the source strength is about 0.66 kg/sec. The dredge production was about 2,000 cy/hr. Assuming an in situ sediment concentration of 844 kg/m^3, the sediment lost to resuspension is 0.22 percent. The associated resuspension factor is 0.22.

Matchbox Dredgehead

Hydraulic dredges outfitted with matchbox dredgeheads were tested in both Calumet Harbor and New Bedford. The Calumet Harbor operation showed even lower resuspension rates than the cutterhead dredge operating in the same location, although both were so low it is difficult to distinguish significant differences. At New Bedford, the dredge operated under similar conditions to both the cutterhead and horizontal auger dredges. Data collected in the near vicinity of the dredgehead and the resulting TSS resuspension rates were reported by the Corps of Engineers (1990). Fifty-seven (57) observations are reported along with average production rates for each dredging area. The resulting resuspension factors range from 0.1 to 10 with an average of 2.3 and standard deviation of 2.0. These values are considerably higher than those for the cutterhead dredge at New Bedford, which were all less than 0.33. This substantiates the data presented in the original report (USACE 1990), which show that the matchbox had resuspension rates about five times higher than the cutterhead dredge and a much lower production rate. The production rate was depressed because of the thin lifts removed to avoid difficulty with debris.

Horizontal Auger Dredges

The portability and control of horizontal auger dredges have made them a popular choice for many Environmental Dredging projects. An Ellicott SP-915 Mudcat Dredge with 175 HP and an 8-inch suction intake was used for 8 days during the New Bedford pilot study. The dredge removed 6-inches of sediment in each pass moving ahead at 6 to 20 ft/minute. The US Army Corps of Engineers (1990) present 42 observations of resuspension rate for the horizontal auger dredge and average production rates for each period. The resulting Resuspension Factors range from 0.6 to 56 with an average of 12.6 and standard deviation of 11.8. These values are markedly higher than any other dredge type at other locations or at New Bedford. Some of this increase is due to the difficulty the dredge had with debris and the nature of the soft sediments that make them subject to higher resuspension rates. The cutterhead and matchbox encountered similar debris, but were more successful in dealing with it. Lower production rates and suction intake velocities across the 8-ft wide head are also expected to be contributing factors.

Horizontal auger dredges were also used in the Grasse River and Fox River projects. Analysis of these data is not complete, but both projects seem to show substantial sediment resuspension likely occurred. Steuer (2000) estimated the dissolved PCB loss from the Fox River SMU 56/57 project to be 2.2%. This is generally consistent with observations from New Bedford Harbor reported by DiGiano, et al (1993) which showed about one order of magnitude more dissolved PCB release for the horizontal auger dredge than the conventional cutterhead.

In general, studies that have used horizontal auger dredges seem to have shown substantially higher water quality impacts than those using more conventional dredges. This is probably due to increased agitation associated with the auger rotation, smaller suction intakes, and lower horsepower pumps generating less suction pressure.

Table 2. Summary of Resuspension Factors

Dredge Type	Range	Average
Hydraulic Dredges		
Conventional Cutterhead	0.01 – 0.51	0.11
Matchbox	0.1 - 10	2.3
Horizontal Auger	0.6 - 56	12.6
Mechanical Dredges		
Open Clamshell Bucket	0.16 - 0.66*	*Insufficient data*
Enclosed Clamshell Bucket	0.10 – 0.22	*Insufficient data*

*Some of these data include scow overflow that is indistinguishable from resuspension due to dredging.

TOXIC CONSTITUENT LOSSES AND TRANSPORT

Although the complexities of contaminant interactions and transformation of specific constituents are not completely understood, the basic theories associated with toxic constituent transport in surface waters are relatively well developed. The near-field area can likely be approximated as a well-mixed tank, i.e. CFSTR. Suspended sediment and toxic constituent concentrations in the immediate vicinity of dredging can be approximated by:

Solids: $V_{nf}\frac{dm}{dt} = qm_{in} - qm - v_s A_h m + \dot{M}_R$

Toxics: $V_{nf}\frac{dc}{dt} = qc_{in} - qc - kV_{NF}c - v_v A_{ws} F_d c - v_s A_h (1 - F_d)c + 10^{-6}\dot{M}_R c_{sed}$

where V_{nf} = volume of the near-field area (m^3), t = elapsed time (sec), m_{in} = TSS concentration of flow entering the near-field volume (g/m^3), m = TSS concentration in the near-field volume (g/m^3), q = flow through the near-field volume (m^3/sec), v_s = settling velocity of suspended particles in near-field volume (m/sec), $\dot{M}_R$ = rate of mass resuspension into the near-field area due to dredging (g/sec), c = toxic constituent concentration within the near-field volume (g/m^3), c_{in} = toxic constituent concentration flowing into the near-field volume (g/m^3), k = contaminant transformation rate (1/sec), v_v = volatilization mass-transfer coefficient (m/sec), A_{ws} = horizontal area of the near field exposed to the water surface ($m2$), A_h = horizontal area of the near field of the near-field volume ($m2$), F_d = fraction of contaminant mass in dissolved form (unitless), and c_{sed} = contaminant concentration on bottom sediments (mg/kg). In most cases, some of these parameters can be neglected. For example, volatilization need be considered only when the near-field area extends to the water surface. Note that the term *qm* in the solids transport equation equates to the resuspension loss rate as defined by Hayes et al (2000) as m_R. Assuming steady-state conditions, minimal background concentrations, and short retention times in the near-field zone allows the equations to be simplified to:

$\dot{m}_R = \dot{M}_R - v_s A_h m$ and $\dot{c}_R = 10^{-6}\dot{M}_R c_{sed} - v_s A_h F_p c_{sed}$

Given a short retention time and the preferential association of toxic constituents with fine particles, it is reasonable to further assume that settling in this zone is not a major influence on contaminant water column concentrations. If so, these can be further simplified to:

$\dot{m}_R \cong \dot{M}_R$ and $\dot{c}_R = 10^{-6}\dot{m}_R c_{sed}$

where $\dot{c}_R$ = mass flux of toxic constituent out of the near-field volume (g/sec).

Downstream transport is more complex, because of spatial and temporal variability in current velocity and direction result in incompletely mixed transport. The general transport equations are:

11.2734

Solids: $\frac{\partial m}{\partial t} = -\nabla(um) + \nabla^2(Em) - \frac{mv_s}{h} + \dot{m}_R$

Toxics: $\frac{\partial c}{\partial t} = -\nabla(uc) + \nabla^2(Ec) - kc - \frac{v_v F_d c}{h} - \frac{v_s F_p c}{h} + \dot{c}_R$

where u = current velocity (m/sec), E = rate of diffusive transport (m^2/sec), and $\dot{m}_R$ = mass flux of toxic constituent into the water column. Common simplifications to this equation include steady-state conditions and neglecting either diffusive or advective transport depending upon the value of the estuary number. Suspended solids transport models have been applied to dredging operations by several authors; Cundy and Bohlen (1980) is a classic example. More general solutions have also been developed for specific dredge types by Kuo et al (1985) and Kuo and Hayes (1991).

If concerns related to toxic transport are primarily associated with particulate concentrations, water column contaminant can be estimated from suspended solids concentrations by applying equilibrium partition. Given a water column TSS concentration of m, the contaminant concentration associated with the sediment mass, c_{sed}, and an associated partitioning coefficient, K_d (m^3/g), the dissolved and particulate fractions can be estimated as:

$F_d = \frac{1}{1+K_d m}$ and $F_P = \frac{K_d m}{1+K_d m}$

or $c_d = F_d c_{sed}$ and $c_p = F_p c_{sed}$. Although this approach involves a number of simplifying assumptions, the particulate-associated concentrations should be reasonably accurate, albeit conservative. Recent observations of elevated dissolved constituent concentrations, however, suggest that a more rigorous analysis of contaminant transport, especially the dissolved component, may be needed. Dissolved constituents are of greater concern because silt curtains do not impede their transport and they are generally more bioavailable to fish and other aquatic organisms.

It has already been shown that the rate of toxic constituent loss and sediment loss must be essentially the same. The question of how much of the constituent mass is in the dissolved form. It has been implied (NRC 2001) that the high rate of dissolved release results from low level TSS concentrations in the water column downstream of the dredging operation since the fraction of constituent in the dissolved phase at low TSS concentrations can be quite high (> 50%). However, a fairly simple analysis shows this is unlikely. Even if the entire contaminant mass were completely dissolved, the loss rates would still not be less than suggested in some studies; e.g. Fox River SMU 56/57. Higher dissolved constituent releases may result from higher initial resuspension loads in the immediate vicinity of the dredgehead that resettle so close to the dredgehead that they have not been accurately measured. This may explain the excessively high losses for horizontal auger dredges.

Figure 3 shows the conditions required to obtain a dissolved constituent loss in the range of several percent of the total constituent mass. The basic loss equation is:

$$R_{dissolved} = \frac{100R}{1 + K_d R \eta}$$

where

$$\eta = \frac{Q_d C_d}{q}$$

where $R_{dissolved}$ = fraction of in situ toxic constituent mass loss to the water column in a dissolved form, Q_d = dredge flowrate (m^3/sec), and C_d = solids concentration of sediment during dredging (g/m^3). It should be pointed out that this approach assumes the mass rate of sediment removal during dredging and the mass flow through the dredging operation are essentially equivalent. Since residuals certainly exist, the result is slightly conservative. Figure 3 shows that the highest dissolved releases occur when a combination of low production rates (resulting from low solids concentrations in the slurry and low flow rates), significant flow through the area, and high resuspension rates. This probably explains, at least partially, the higher dissolved constituent observations during horizontal auger dredging operations. It also points to the need for caution in applying operational controls that substantially reduce dredge production rates.

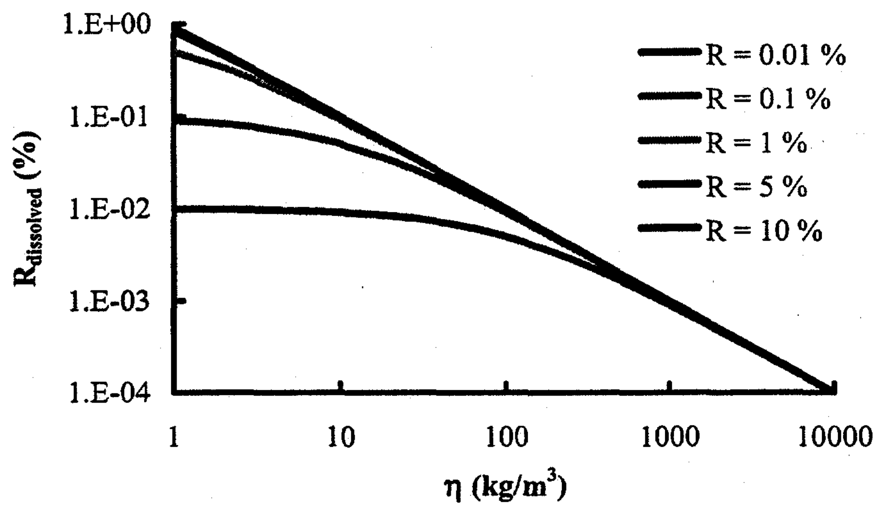


Figure 3. Fraction of total constituent loss in dissolved form ($K_d = 10^5$ L/kg).

ARE SILT CURTAINS EFFECTIVE AT REDUCING DOWNSTREAM TRANSPORT?

Silt curtains and silt screens are common appurtenances in environmental dredging operations. These consist of sections of either permeable or impermeable fabric hanging down into the water column from a floating boom. The fabric may extend into the water column as little as a meter or for the entire water depth. Sections can be connected together to form long, mostly continuous barriers. Under ideal conditions, silt curtains can contain much of the sediment resuspended by the dredging operation. It would seem that dissolved contaminants would flow directly through the curtain; however, headloss associated with flow through small mesh usually results in redirection of most flow, rather than flow through the curtain itself. Typical silt curtain installation involves several problems. It is very difficult to maintain silt curtains in strong currents, windy conditions, or even heavy waves. Even relatively light surface winds, waves, and ambient currents can exert strong forces on the curtain. Anchoring the curtain to a fixed object such as a dock or pier increases its stability. However, securing the curtain to the bottom is more challenging. As illustrated in Figure 4, even a slight current can generate enough force to lift the curtain above the bottom and allow the turbidity plume to escape. Headloss associated with flow through the curtain usually exceeds the maximum anchoring weights that can be dealt with in open water environments; as a result, the curtain lifts redirecting much of the flow between the lifted curtain and bottom sediment. Such discharges do not entirely negate the effectiveness of the silt curtain. Forcing the suspended sediment closer to the bottom probably increases sediment removal due to settling even if it does not reduce contaminant flux beyond the curtain.

NRC (2001) implies that when properly deployed under proper conditions, suspended sediments within the silt curtain can be considered to be at a uniform concentration and at the toxic constituents at equilibrium much like a CFSTR. These conditions are mostly likely to exist when the volume within the silt curtain is small and the curtain is securely attached to the bottom sediments and completely encircles the dredging operation. However, such small enclosures require more intensive management and frequent repositioning. Thus, silt curtains are more frequently deployed in larger circles. Incomplete mixing and significant variations in suspended sediment concentrations within the curtain itself usually characterize these larger volumes.

While silt curtains are simple devices and used frequently, additional research is needed to evaluate the manners in which they can be best deployed to reduce downstream contaminant transport. There seems to be room for design advances that may increase their effectiveness for a wider range of applications.

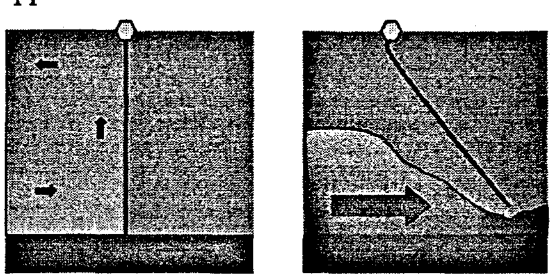


Figure 4. Typical silt curtain response to current.

OPERATIONAL CONTROLS

Operational controls are popular for environmental dredging projects. Hydraulic dredges, in particular, often have limits on swing speed, cutter rotation speed, and cutting depth imposed. Controls on mechanical dredges are often in the form of limits on bucket fall and raise velocities and total cycle speeds. Both types of restrictions result in lower production rates as a tradeoff for reduced water quality impacts. And, both are based upon research showing that these operational factors influence sediment resuspension and, probably, toxic constituent releases. A closer look at the research shows that the concerns arise from extreme operating parameters and that normal operational ranges do not normally result in disproportionate increases in sediment resuspension. It is also not clear that such controls result in an overall decrease in toxic constituent release. For example, increasing the raising speed of a dredge bucket increases the acceleration force applied to sediments in the bucket. This acceleration likely results in an increased leakage rate of sediment laden water from the bucket. However, the leakage occurs for a shorter period and it is possible that a longer raising time could result in more mass release into the water column. In essence, an inappropriate operational control for bucket dredges could increase the total mass released during a removal operation. Operational controls for hydraulic dredges tend to reduce the concentration of sediment being pumped from the site. Reduced production rates decrease the productivity of the dredging operation, increase the water that must be treated, and according to Figure 3 may increase the dissolved contaminant release.

Operational controls are an effective means to ensure that careless dredge operation does not lead excessive losses. However, additional research is needed to determine the best application of operational controls for environmental dredging operations. Until then, operational controls should focus on avoiding extreme conditions and encouraging "typical" operations that are more efficient.

REFERENCES

Bohlen, W.F., Cundy, D.F., and Tramonano, J.M. (1979). "Suspended material distributions in the wake of estuarine channel dredging operations," *Estuarine and Coastal Marine Sci.*, 9, pp. 699-711.

Collins, M.A. (1995). "Dredging-Induced Near-Field Resuspended Sediment Concentrations and Source Strengths," *Miscellaneous Paper D-95-2*, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Crockett, T.R. (1993). "Modeling Near Field Sediment Resuspension in Cutterhead Suction Dredging Operations," M.S. Thesis, University of Nebraska-Lincoln, Lincoln, NE.

Cundy, D.F. and Bohlen, W.F. (1980). "A Numerical Simulation of the Dispersion of Sediments Suspended by Estuarine Dredging Operations," *Estuarine and Wetland Processes*, Hamilton and McDonald, eds., Marine Science 11, Plenum Press, New York, pp 339-352.

DiGiano, F.A., Miller, C.T., and Yoon, J. (1993). "Predicting the Release of PCBs at Point of Dreding," *Journal of Environmental Engineering*, 119(1), January/February 1993, ASCE.

Hayes, D.F. (1986). "Development of a Near Field Source Strength Model to Predict Sediment Resuspension from Cutter Suction Dredges," M.S. Thesis, Mississippi State University, Starkville, MS.

Hayes, D.F., Borrowman, T., and Welp, T. (2000). "Near-Field Turbidity Observations During Boston Harbor Bucket Comparison Study," *Proceedings of WEDA XX*, Providence, RI, June 2000.

Hayes, D.F., Crockett, T.R., Ward, T.J., and Averett, D. (2000). "Sediment Resuspension During Cutterhead Dredging Operations." *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 126(3), May/June 2000, ASCE.

Hayes, D., McLellan, T., and Truitt, C. (1988). "Demonstrations of Innovative and Conventional Dredging Equipment at Calumet Harbor, Illinois", *Miscellaneous Paper EL-88-1*, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hayes, D.F. and Wu, P.Y., "Simple Approach to TSS Source Strength Estimates," *Proceedings of WEDA XXI*, Houston, TX, June 2001.

Kuo, A.Y. and Hayes, D.F. (1991). "A Model for Turbidity Plume Induced by Bucket Dredge," *ASCE Journal of Waterways, Port, Coastal, and Ocean Engineering*, November 1991.

Kuo, A., Welch, C., and Lukens R. (1985). "Dredge Induced Turbidity Plume Model," *ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering*, Vol. 111, No. 3.

McLellan, T., Havis, R., Hayes, D., and Raymond, G. (1989). "Field Studies of Sediment Resuspension Characteristics of Selected Dredges," *Technical Report HL-89-9*, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nakai, O. (1978). "Turbidity Generated by Dredging Projects," *Proceedings of the 3rd U.S./Japan Experts Meeting*, US Army Engineer Water Resources Support Center, Ft. Belvoir, VA.

National Research Council (2001), *A Risk-Management Strategy for PCB-Contaminated Sediments*, National Academy Press, Washington, DC.

Steuer, J.J. (2000), "A Mass-Balance Approach to Assessing PCB Movement During Remediation of a PCB-Contaminated Deposit on the Fox River, Wisconsin," USGS Water Resources Investigations Report 00-4245, December 2000.

USACE (1990), "New Bedford Harbor Superfund Pilot Study: Evaluation of Dredging and Dredged Material Disposal," US Army Corps of Engineers, New England Division, May 1990.

Wu, P.Y. and Hayes, D.F., "Verification and Enhancement of TSS Source Strength Models for Cutter Dredges," *World Dredging, Mining, and Construction*, August 2000.