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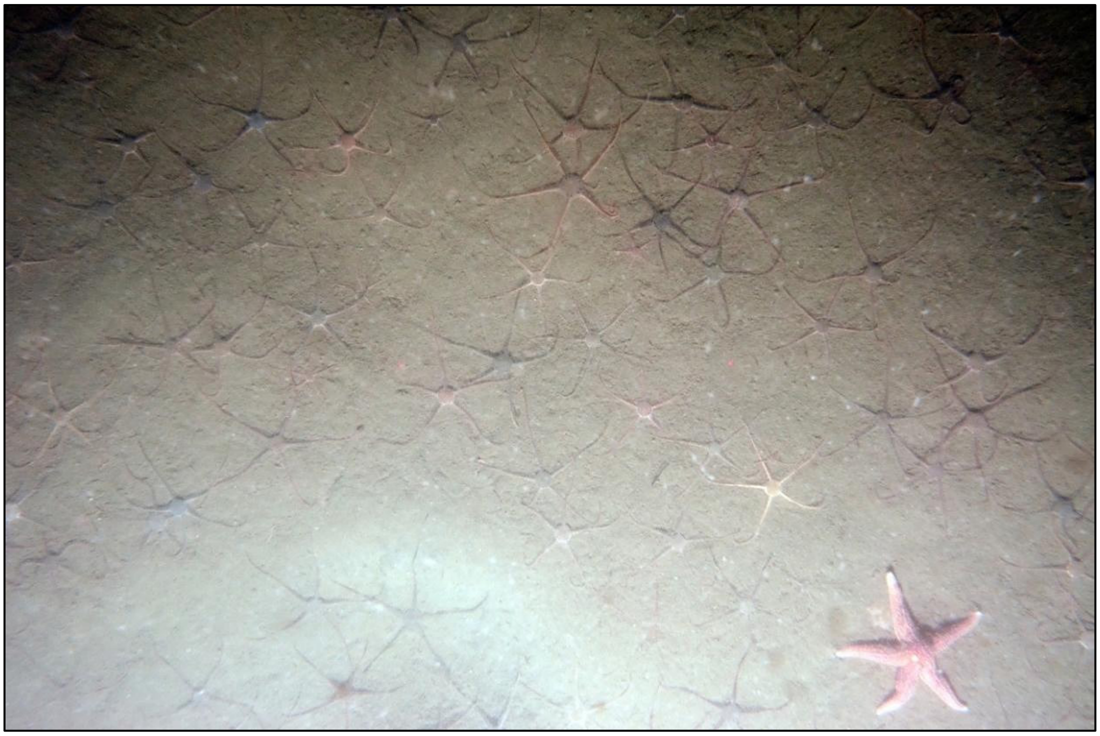

Benthic Conditions at the Cape Cod Bay Disposal Site
(Photo Courtesy of S. Wolf, U.S. Army Corps of Engineers, and Germano and Associates)

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VESSEL-INDUCED SEDIMENT RESUSPENSION

Donald F. Hayes[1], Rohith Chintamaneni[2], Prathyusha Bommareddy[2], and Bhaskar Cherukuri[2]

ABSTRACT

Sediment resuspension has been raised as a water quality concern around dredging and other marine construction activities, but few resuspension sources have been quantified. Some data indicate that the rate of sediment resuspension due to large vessel movement is potentially significant. Smaller vessels also may generate significant sediment resuspension when operating in shallow waters. This paper combines models of bottom shear stress induced by propeller wash with models of erosion rate in order to produce a net sediment resuspension rate for a range of vessels commonly used in dredging and other marine construction activities.

Keywords: dredging, water quality, propeller wash, sediment scour, SEDflume

INTRODUCTION

Propeller-induced and wake-induced shear stresses from waterborne vessels often exceed the critical shear stress of the bottom sediments, resuspending them into the water column. The critical shear stress, in this context, refers to the shear stress required to initiate the motion of sediment grains currently at rest (i.e., erosion) at the sediment-water interface. Figure 1 shows clearly visible turbidity plumes from a tug and cargo ship in a deep-draft channel having an authorized depth of 13.7 m (45 feet). Support vessel operations associated with marine construction, including dredging, represent potentially significant sources of sediment resuspension. Since these support vessels often work in shallow water with soft sediment bottoms, the potential is significant for sediment resuspension resulting from their movement.

A number of studies have evaluated sediment resuspension associated with marine vessel movement (Johnson, 1976; Erdmann et al, 1994; Pettibonea et al, 1996; Ravens and Thomas, 2008). Many of these studies collected site-specific data, and the results can only be extrapolated in the most general sense to other sites. Several researchers, however, have developed bottom velocity and shear stress models that apply to a broad range of vessels (Verhey, 1983; Hamill et al., 1999; and Maynord, 2000). Gailani et al (2001) describes the relationship between bottom shear stress and erosion rate, based upon site-specific laboratory measurements. The combination of these models can provide reproducible estimates of bottom sediment erosion under specific vessel operating conditions. This paper utilizes this approach to compute sediment resuspension rates for vessels representative of those used in dredging and other marine construction operations.

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PROPELLER WASH MODELS

Johnson (1976) published one of the earliest studies on water quality impacts resulting from marine vessel traffic. This study evaluated the effects of tow traffic on sediment resuspension and water quality in the Upper Mississippi and Illinois Rivers. A number of additional studies have been conducted since then, such as those by Erdmann et al (1994), Pettibonea et al (1996), and Ravens and Thomas (2008). All of these studies add credence to the concern over vessel-induced sediment resuspension and provide useful site-specific observations. However, they do not provide sufficient information to generate sediment resuspension flux rates over a range of vessels and conditions. Three models identified in the literature are capable of estimating propeller-induced sediment scour. All three models are based upon work by Albertson et al. (1948) and are described in Verhey (1983), Hamill et al. (1999), and Maynord (2000). Although the models have rather different capabilities, they share the same general purpose: to estimate scour from vessel-induced bottom shear stresses.

Figure 1: Turbidity plumes from a tug with a tow and a cargo vessel in a deep draft navigation channel

Verhey's model was the first attempt to model prop-induced scour found in the literature. It applies only to large stone sizes (approximately 0.1 m to 0.3 m; Verhey 1983). Hamill's model calculates maximum scour and its location relative to the propeller. The model applies only to non-cohesive sediments, and assumes vertical homogeneity in the bottom sediments. It is limited to applications where the depth from the maximum draft (propeller tip) to the sediment is between 50% and 250% of the propeller's diameter. Neither of these models applies to fine sediments, the primary concern with regard to water quality**.**

Maynord (2000) presented a combination of models that provide maximum velocity estimates at locations along the sediment-water interface. This model considers important physical vessel characteristics including length, width, draft, propeller size and depth, and propeller spacing for dual engines. Vessel movement is an important variable; so, the model takes into consideration both forward speed and applied horsepower. The primary environmental characteristic of importance is water depth.

Maynord (2000) presented two models to compute maximum bottom velocities at specific locations relative to the propeller position, resulting from boat movement and propeller action. The models consider physical site conditions and vessel characteristics and operation. The model for Zone 1 predicts velocities within a distance of 10 propeller diameters. The Zone 2 model predicts velocities beyond that distance. Water velocity at the sediment surface, V_Z, is computed for any position (X_P, Y_P) relative to the propeller. Velocity values are zero for all negative values of X_p.

Zone 1 Model: Applies to distances less than 10 propeller diameters behind the propeller ($X_p < 10\ D_p$)

$$V_{Z1}(X_p, Y_{cl}) = AX_P^{-0.524}\left(e^{\frac{-15.4R_1^2}{X_P^2}} + e^{\frac{-15.4R_1^2}{X_P^2}}\right) \tag{1}$$

where:

$$A = 1.45V_2D_p^{0.524} \tag{2}$$

$$R_1^2 = \left(Y_{cl} - 0.5W_p\right)^2 + \left(H_p - C_j\right)^2 \tag{3}$$

$$R_2^2 = \left(Y_{cl} + 0.5W_p\right)^2 + \left(H_p - C_j\right)^2 \tag{4}$$

$$C_j = -\left[0.213 - 1.05\left(\frac{C_p g}{V_2^2}\right)\left(X_p - 0.5L_{set}\right)\right]\left(X_p - 0.5L_{set}\right) \tag{5}$$

$$V_2 = \frac{1.13}{D_0}\sqrt{\frac{T}{\rho_w}} \tag{6}$$

Traditional Propeller	Kort-Nozzle Propeller	
$C_p = 0.12\left(\frac{D_p}{H_p}\right)^{0.67}$	$C_p = 0.04$	(7)
$EP = 23.57P_{hp}^{0.974} - 2.3V_w^2P_{hp}^{0.5}$	$EP = 31.82P_{hp}^{0.974} - 5.4V_w^2P_{hp}^{0.5}$	(8)
$D_0 = 0.71D_p$	$D_0 = D_p$	(9)

The basis and values for C_p, EP, and D_0 depend upon the type of propeller, as shown in Table 1.

Table 1: Description and properties of vessels used in model runs; all have dual engines and propellers

Vessel	Description	Length (m)	Beam (m)	Draft (m)	Depth to Prop Shaft (m)	Width Between Props (m)	Prop to Stern Distance (m)	Total Power All Engines (KW)	Prop Dia. (m)
A	Tug	22.1	7.4	3.2	2.3	3.0	1.5	1342	1.8
B	Pushboat	7.7	4.2	1.5	1.0	1.3	0.7	447	0.9
C	Pushboat	7.7	4.2	1.0	0.6	1.3	0.7	298	0.8
D	Pushboat	7.6	3.1	0.8	0.6	1.0	0.7	134	0.4

Zone 2 Model: Applies to distances greater than 10 propeller diameters behind the propeller ($X_p > 10D_p$)

$$V_{Z2}\left(X_p, Y_{cl}\right) = 0.34 V_2 C_1 \left(\frac{D_p}{H_p}\right)^{0.93} \left(\frac{X_p}{D_p}\right)^{0.24} e^{-\left(\frac{0.0178 X_p}{D_p} + \frac{Y_{cl}^2}{2C_{Z2}^2 X_p^2}\right)} \tag{10}$$

where:

$$C_{Z2} = 0.84\,(X_p/D_p)^{-0.62} \tag{11}$$

$C_1 = 0.66$ for a traditional propeller; $C_1 = 0.85$ for a Kort nozzle propeller (12)

and,

V_{Z1} = Velocity at sediment surface in Zone 1 (m/s)
V_{Z2} = Velocity at sediment surface in Zone 2 (m/s)
X_p= Distance behind the propeller (m)
D_p= Propeller diameter (m)
W_p= Distance between propeller (m)
L_{set}= Distance from ship stern to propeller (m)
H_p = Distance from center of propeller axis to channel bottom (m)
Y_{cl} = Lateral distance from ship centerline (m)
C_j = Vertical distance from propeller shaft to location of maximum velocity within the jet (m)
δ_p = Propeller depth (m)
g = acceleration of gravity (m/s^2)
C_p= Propeller coefficient (dimensionless)
T = Forward Thrust (N)
ρ_w=Density of water (kg/m^3)

The variable X_p represents the distance behind the propeller in the direction of the vessel's path, while Y_{cl} represents the lateral position relative to the boat centerline and normal to the direction of the vessel's path. Many marine vessels have multiple engines and propellers; thus, the model accounts for the interaction and eventual combination of the individual jets. Zone 1 is the region behind the vessel where each propeller jet acts independent and produces a separate velocity field. In areas where the bottom velocity distributions from the two propeller streams overlap, the total bottom velocity is determined by superposition of the velocity distributions. Zone 2 begins after the velocity fields merge into a single velocity distribution, and it is estimated to be about 10 propeller diameters behind the propellers.

Bottom shear stress values induced by these velocities can be compared to the critical shear stress of the sediment to determine the erosion potential. Shear stress experienced by the sediment surface due to this velocity is calculated as the following (Maynord 2000):

$$\tau = 0.5\rho_w C_{fs} V^2_{prop} \tag{13}$$

where,

$$C_{fs} = 0.01\left(\frac{D_p}{H_p}\right) \tag{14}$$

and

C_{fs} = bottom friction factor for propeller wash (dimensionless)
τ = bottom shear stress (N/m^2)
V_{prop} = bottom velocity due to propeller wash (m/s)
ρ_w= water density (kg/m^3)

A sediment-specific relationship between shear stress and erosion rate is used to allow the model to be applied to any sediment, regardless of grain sizes or other sediment characteristics. The impending motion of the sediment grains begins at the point of critical shear stress, and erosion rate increases with increasing shear stress. Typically, the relationship between erosion rate versus shear stress is assumed to be:

$$\varepsilon = 0 \qquad \text{for } \tau < \tau_{cr} \tag{15}$$

$$\varepsilon = a\tau^n \qquad \text{for } \tau \geq \tau_{cr} \tag{16}$$

where,

ε = volumetric sediment erosion rate (m/sec)
τ_{cr} = critical shear stress (Pa)
a = regression coefficient (m/sec/Pa)
n = regression coefficient (dimensionless)

Gailani et al (2001) showed that it is also possible to fit data for moderate shear stresses (< 1.5 Pa) to the equation:

$$\varepsilon = a\left(\frac{\tau - \tau_{cr}}{\tau_{cr}}\right)^{n} \tag{17}$$

The regression parameters *a* and *n* are sediment-specific, and must be developed from laboratory studies. SEDflume testing is one approach to develop the shear stress-sediment scour relationship. The SEDflume allows a sediment core to be subjected to a range of flow-induced shear stress to determine erosion rates. The results can be used to determine the regression coefficients *a* and *n* in Equation 17. Additional information on SEDflume testing can be found in McNeil et al. (1996).

SEDIMENT FLUX MODEL

Linking these models—that is, computing bottom velocities using Maynord's models, then translating these bottom velocities to shear stress using Equation 13, followed by computing erosion rate from Equation 17 with sediment-specific regression coefficients—allows the computation of instantaneous propeller-induced erosion rates. The erosion of bottom sediments changes the bathymetry in the scour area as well as the area where the sediments redeposit if they do not remain suspended. Thus, sediment flux estimates from a moving vessel requires continuous modification of the bathymetry based upon the computed erosion rates. The vessel also is continuously moving, so its position relative to bathymetric changes must be considered. The logistics of applying these linked models to a moving vessel are described below.

The model is applied over a river, channel, or estuarine area with a known bathymetry. While sample computations presented here use a uniform initial bathymetry for the purpose of convenience, any initial bathymetry is possible. The first step is to cover the computational area with a discretized grid in the X-Y (horizontal) plane. The computational area must include any area impacted by the velocity field of the vessel.

Grid cell size is not important to the mathematical formulation, but significantly affects the required computational effort. Cell sizes must be sufficiently small to describe bottom velocity variations produced by the model above. Bathymetry for the computational area is included through a depth for each cell, Z_{ij}, equal to the average bathymetry of that cell. Since velocity and bathymetry changes tend to be gradual, extremely small cells are not necessary. The examples, below, used a cell size of 1 m x 1 m; this is probably adequate for most applications, although smaller cells would provide more accurate results.

Applying Maynord's model to a specific vessel located within the surface grid provides maximum bottom velocities relative to the propeller location. Figure 2 graphically illustrates the overlaying of coordinate systems necessary to facilitate the computations; a vessel moving along a 315° vector is shown to illustrate the necessary mapping between coordinate systems.

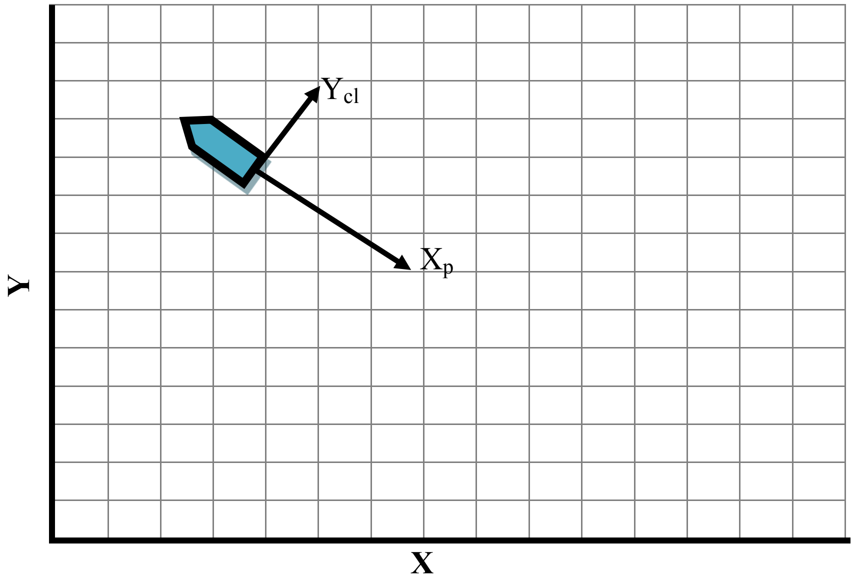

Figure 2: Example grid overlays for flux computations

Bathymetry and propeller positions can be computed with time on a conventional Cartesian coordinate system. However, since Maynord's model provides computations with positions relative to the propeller location, it is easiest to overlay a second coordinate system that moves continuously; the origin remains at the propeller location at all times. It also can be confusing that positive X_p values (relative to the propeller) are in the opposite direction of the vessel's forward movement; for example, if the vessel is moving forward at 1 knot along a 135° vector—notice that these are relative to the X-Y grid, not North—positive X_p values would increase along a 315° vector. Y_{cl} values are normal to the vessel's longitudinal centerline; in the example above, positive values would extend along a 45° vector from the propeller position, while negative values extend along a 225° vector. The relationships between any node in the X–Y grid and the X_p-Y_{cl} grid for a propeller position of X_o,Y_o are:

$$X_p = L\cos(\beta) \tag{18}$$

$$Y_{cl} = L\sin(\beta) \tag{19}$$

where

$$L = \sqrt{(X - X_o)^2 + (Y - Y_o)^2} \tag{20}$$

$$\beta = -\alpha + tan^{-1}\left(\frac{(Y-Y_o)}{(X-X_o)}\right) \tag{21}$$

α = angle from thrust direction to X-axis, degrees

Maynord's models require the depth below the propeller centerline, H_p, to compute the maximum bottom velocity. That depth can be computed for each cell based upon the cell bathymetry as follows:

$$(H_p)_{ij} = Z_{ij} - \delta_p \tag{22}$$

where,

$(H_p)_{ij}$ = depth from propeller centerline to the sediment surface at nodes *i, j, m*
Z_{ij} = total water depth at node *i, j, m*

This discretized application of Maynord's models raises two potential concerns. First, the models were developed for relatively smooth bathymetry and they do not check continuity between locations. The error resulting from this extrapolation should be relatively small, unless abrupt bathymetric variations exist; significant, abrupt bathymetric variations are unusual in most marine environments of concern.

Inconsistent velocity values at the transition between Zone 1 and Zone 2 are also a concern. In some cases, computed velocities at the transition ($X_p = 10D_p$) from the Zone 2 model are higher than Zone 1 velocities preceding the transition. Thus, initial model results indicate abrupt velocity increases at the transition distance. These discontinuities were addressed by substituting the initial Zone 2 velocity (at $X_p = 10D_p$) for lower Zone 1 velocities near the boundary along a constant Y_{cl} line. This forced a smooth transition between the zones. This approach does result in higher velocities within Zone 1 than computed by the Zone 1 models. The discontinuities, however, occurred primarily along the fringes of the propeller-induced velocity field in areas of low velocity and did not significantly increase the computed scour volume.

The highest velocities usually are limited to an oval-shaped area slightly offset from the centerline of each propeller. Figure 3 shows an example of these high-velocity areas behind a twin-propeller tug; bottom shear stress patterns are more exaggerated, given the second-order relationship between bottom velocity and shear stress (Equation 13); that is, areas of high shear stress areas are smaller than the areas of high velocity. Because the scour relationship also is a power function, areas of bottom scour are even smaller. A series of model runs showed that propeller-induced bottom scour typically is limited to a very small area, while most of the grid experienced shear stresses less than the critical shear stress; in other words, no bottom sediment erosion occurred.

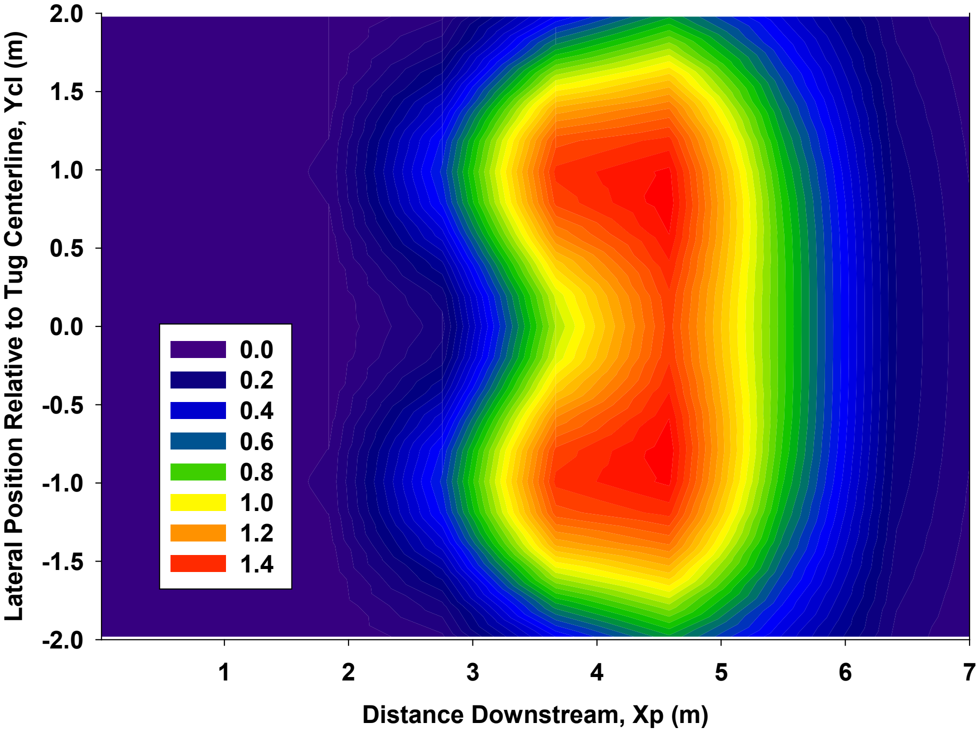

Figure 3: Maximum sediment surface velocities behind a large tug (Applied Power = 671 KW; H_p = 2.7 m)

As bottom sediments are eroded, water depth increases reducing bottom velocities and subsequent scour. Consequently, any erosion rate is accurate only until erosion changes the bathymetry sufficiently to result in a measurable decrease in bottom velocity and erosion rate. An accurate model must be continuously reapplied with updated bathymetry to produce accurate results. As erosion occurs, bathymetric changes can be computed at each node as:

$$Z_{i,j}^{t+1} = Z_{i,j}^{t} - \varepsilon_{i,j}^{t}\Delta t \tag{23}$$

where the superscript t denotes specific time steps and

Δt = time step increment (min).

The suspended sediment flux during the time step can be computed as:

$$g^{t} = \sum_{j=1}^{n}\sum_{i=1}^{m}\varepsilon_{i,j}^{t}\Delta X\Delta Y\gamma_{s} \tag{24}$$

where,

g = suspended sediment flux (kg/sec)
ΔX = x-grid increment (m)
ΔY = y-grid increment (m)
γ_s = dry sediment density (kg/m^3)

Except in unusual cases, the vessel will be moving—or attempting to move—forward. As the vessel moves, the propeller position and X_p-Y_{cl} grid location (which is relative to the propeller position) continuously change, moving along opposite the direction of thrust. Thus, while the locations of the highest bottom velocities remain constant relative to the propeller location, their positions in the X-Y grid continuously change with vessel movement. With sufficiently fine spatial and temporal resolution, continual remapping of bottom shear stress distributions as a vessel moves along a path allows for a relatively accurate estimate of sediment resuspension resulting from propeller-induced scour.

MODEL APPLICATION

Site Characteristics

In this section, the models described above are applied to a simplified, hypothetical site to facilitate the comparison of sediment resuspension flux between vessels. The site was assumed to consist of a perfectly flat initial bathymetry extending infinitely in all directions. Water depths from 2 to 10 m were evaluated to quantify the effect of water depth on scour. The bottom sediment was assumed to consist of infinitely thick, soft, silty clay with an *in situ* water content of 62.5%, a specific gravity of 2.75, and containing 0.53% of organic content. The following relationships between shear stress and erosion rate were developed from SEDflume test results on the sediment:

$$\varepsilon = 0 \qquad \text{for } \tau < 1.21 \text{ Pa} \tag{25}$$

$$\varepsilon = 5.1089\left(\frac{\tau}{1.21} - 1\right)^{0.9182} \qquad \text{for } 1.52 \text{ Pa} \geq \tau \geq 1.21 \text{ Pa} \tag{26}$$

Accurate measurements of erosion rates using the SEDflume were not possible beyond 1.52 Pa. Since the prop-wash models may generate shear stresses in excess of 1.52 Pa, the results were extrapolated beyond the laboratory data, using the following linear relationship:

$$\varepsilon = 1.46 + 24.8(\tau - 1.52) \qquad \text{for } \tau \geq 1.52 \text{ Pa} \tag{27}$$

This relationship was chosen to avoid unrealistic, excessive erosion rates that would overstate sediment resuspension flux; it has not been proven to be accurate, and this work should not be taken as proving its viability. However, the power curve relationship, as expressed above, generates excessively large erosion rates with small increases in shear stress. The resulting extrapolation was thought to likely overestimate resuspension flux.

Vessel Selection and Operation

Dredging and other marine construction operations use a wide range of vessels. A range of representative vessels was selected for comparison. Table 1 provides the physical characteristics of those vessels.

Computational Details

A uniform computational grid with 0.152 m cells in both the X and Y directions was used with 0.1-second time steps for all computations. Each vessel moved forward without turning until a steady-state resuspension flux rate was achieved. The forward speed varied from 1 to 10 knots while applied horsepower was varied as 25%, 50%, 75%, and 100% of the maximum horsepower. Steady-state sediment resuspension flux rates were reached within the first few minutes of movement in most cases.

RESULTS

The purpose of the model development and application was to evaluate the approximate range of sediment resuspension rates that could potentially be associated with vessel movement and also to evaluate the influence of important operational variables—propeller clearance (H_p), forward speed, and applied horsepower—on the resuspension rates and geometry of the scoured bottom area. Model runs for each vessel shown in Table 1 were completed for a matrix of site and operational conditions, with a few exceptions, as follows: water depths of 2, 4, 6, 8, and 10 m; vessel speeds of 1, 2, 3, 5, 7, and 10 knots; and applied horsepower settings of 25%, 50%, 75%, and 100%. A total of 402 model runs were conducted. No runs occurred for Vessel A at speeds greater than 3 knots (5, 7, or 10 knots), and a few combinations at 3 knots were not completed when it became clear that the resuspension fluxes were excessive. Vessel-specific factors, such as increased draft and propeller size, also influenced the results, but were not considered.

Model results show a wide range of scour-induced resuspension rates depending upon vessel characteristics, operation, and site conditions. Table 2 summarizes the statistical characteristics of the modeled flux rates. The results show trends as expected. Vessel A showed the highest average potential flux rate of about 45,000 kg/sec. Average potential flux rates for Vessels B, C, and D were 22,700 kg/sec, 12,300 kg/sec, and 2,300 kg/sec, respectively. These flux rates, while larger than anticipated, follow the expected trend of decreasing with vessel size, even though Vessel A model runs were limited to velocities of 1, 2, and 3 knots; that is, no runs were conducted for velocities of 5, 7, and 10 knots for Vessel A, as was the case for Vessels B, C, and D.

Table 2: Statistical summary of potential resuspension flux rates (1000 kg/sec) from model run

Vessel	Average	Standard Deviation	Maximum	Minimum
A	45.1	28.9	116.4	8.3
B	22.7	26.4	126.6	0.0
C	12.3	18.1	98.4	0.0
D	2.3	6.4	39.6	0.0

The lack of runs at higher velocities did result in a maximum potential flux rate for Vessel A, less than for Vessel B—116,000 kg/sec compared to 127,000 kg/sec. The maximum potential flux rates for Vessels C and D were 98,400 kg/sec and 39,600 kg/sec, following the expected trend of decreasing with vessel size. The minimum resuspension flux rate for Vessel A was 8,300 kg/sec. Vessel B dropped to 10 kg/sec; Vessels C and D had multiple operational scenarios that produced no scour, with a resuspension flux rate of 0.

Because the modeled conditions for Vessels C and D included scenarios that produced no resuspension flux, the results provide some insight into the conditions required to avoid propeller-induced scour. Table 3 summarizes the modeled water depths that bracket incipient scour. This occurred at depths between 10 m and 8 m for Vessel C for 25%, 50%, and 75% power settings; scour occurred at all modeled depths, with a 10 m maximum, for the 100% power setting. Vessel D began to induce scour as the depth reduced from 4 m to 2 m for all power settings. Interestingly, these depths did not vary with vessel speed.

Table 3: Depth ranges at which incipient sediment scour in model results

	Water Depth (m)				**Depth from propeller axis to channel bottom/Propeller diameter (*Hp/Dp*)**			
Vessel	**25**	**50**	**75**	**100**	**25**	**50**	**75**	**100**
A	> 10 m	> 10 m	> 10 m	> 10 m	> 3.7	> 3.7	> 3.7	> 3.7
B	> 10 m	> 10 m	> 10 m	> 10 m	> 9.3	> 9.3	> 9.3	> 9.3
C	8 - 10 m	8 - 10 m	8 - 10 m	> 10 m	8.5 - 11.2	8.5 - 11.2	8.5 - 11.2	> 11.2
D	2 - 4 m	2 - 4 m	2 - 4 m	2 - 4 m	3.9 - 9.4	3.9 - 9.4	9.4 - 15.0	9.4 - 15.0

Table 3 also provides depths in terms of propeller diameters, that is, H_p/D_p. Although the results are not definitive, it is interesting that in order to avoid scour, most of the conditions required water depths close to 10 propeller diameters. The exceptions were Vessel D at 25% and 50% power, for which scour stopped at water depths between 3.9 and 9.4 propeller diameters.

Figure 4 demonstrates the relationship between applied power and resuspension flux for all four vessels operating with a forward speed of 3 knots in a 2-m water depth. It is interesting to note that an incremental increase or decrease in applied power results in an almost linear increase or decrease in potential resuspension flux for all of the vessels modeled. This trend was observed in all cases where scour occurred at all power settings. In addition, almost linear relationships were observed for model scenarios when scour did not occur at one or more of the lower power settings. In those cases, the line seemed to intercept the abscissa at about the power-setting equivalent to incipient scour.

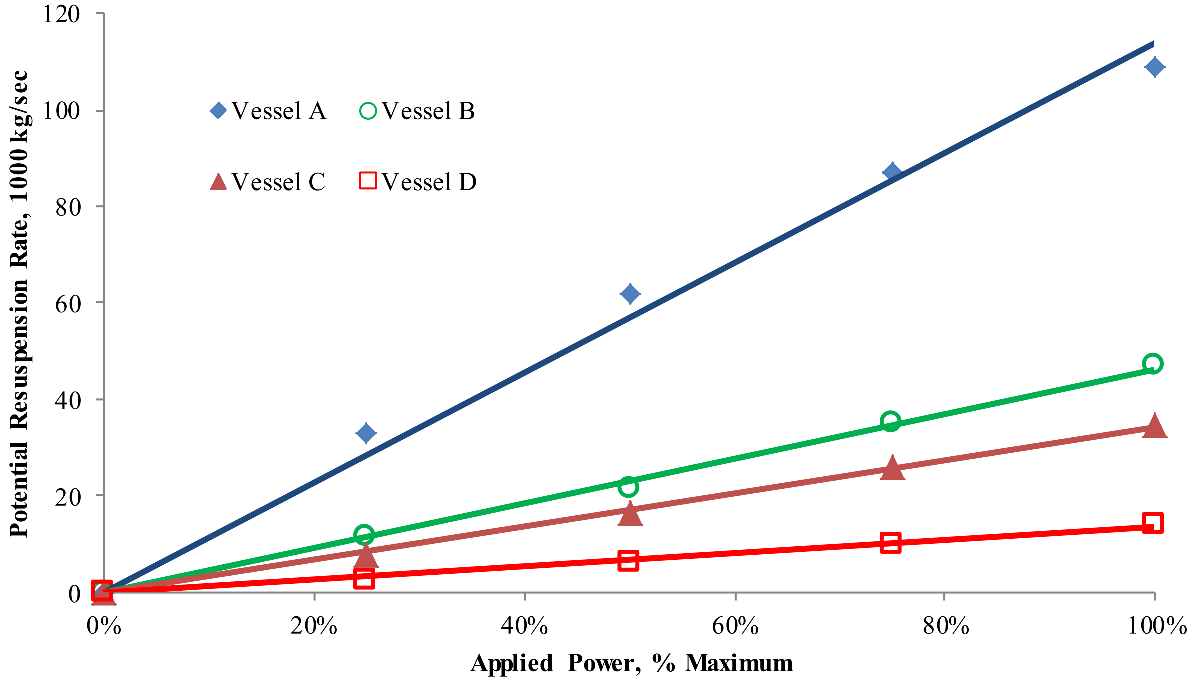

Figure 4: Effect of applied power on potential sediment scour rates for vessels with a forward speed of 3 knots operating in a water depth of 2 m

Resuspension flux is displayed in Figure 5 as the percent of maximum resuspension flux computed for the specific vessel, forward speed, and water depth; thus, by definition, these values are 0% and 100% at 0% and 100% applied power, respectively. The relationship between the three remaining applied power values—25%, 50%, and 75%—and the normalized resuspension flux fit a 45-degree line almost perfectly. The relationship was similar at the other modeled water depths (4, 6, 8, and 10 m) where all power settings resulted in scour.

As expected, model results showed that potential sediment resuspension flux rates decrease as water depth increases, with the others conditions remaining the same. The relationship between potential flux rate and water depth is described in Figure 6 for Vessels B, C, and D, all operating at a forward speed of 3 knots using 75% of available power. Water depth is presented in Figure 6 in terms of propeller diameters. The results show strong decreases in potential sediment resuspension fluxes as water depths increase. All of the model results showed that clearances greater than 10 propeller diameters largely eliminated sediment scour.

The relationship shown in Figure 6 for Vessel B suggests that a threshold depth may exist at which the rate of decrease in potential sediment resuspension flux with increases in H_p/D_p changes significantly; that is, the potential sediment resuspension flux changes at lower H_p/D_p are incrementally much less than changes at H_p/D_p values greater than the threshold value. This phenomenon was observed consistently in other model results for Vessels A and B, especially at shallow depths. It is plausible that a similar characteristic would have been observed for Vessels C and D if model runs had been conducted at sufficiently low values of H_p/D_p. Vessel A was not included in Figure 6 because only two values of H_p/D_p were available for these operating conditions.

Figure 7 illustrates the relationship between propeller clearance, applied power, and potential sediment resuspension flux for Vessel C moving forward at 3 knots. Similar relationships of decreasing sediment scour with increasing water depth and decreasing power were observed for Vessels A, B, and D when moving forward at the same speed.

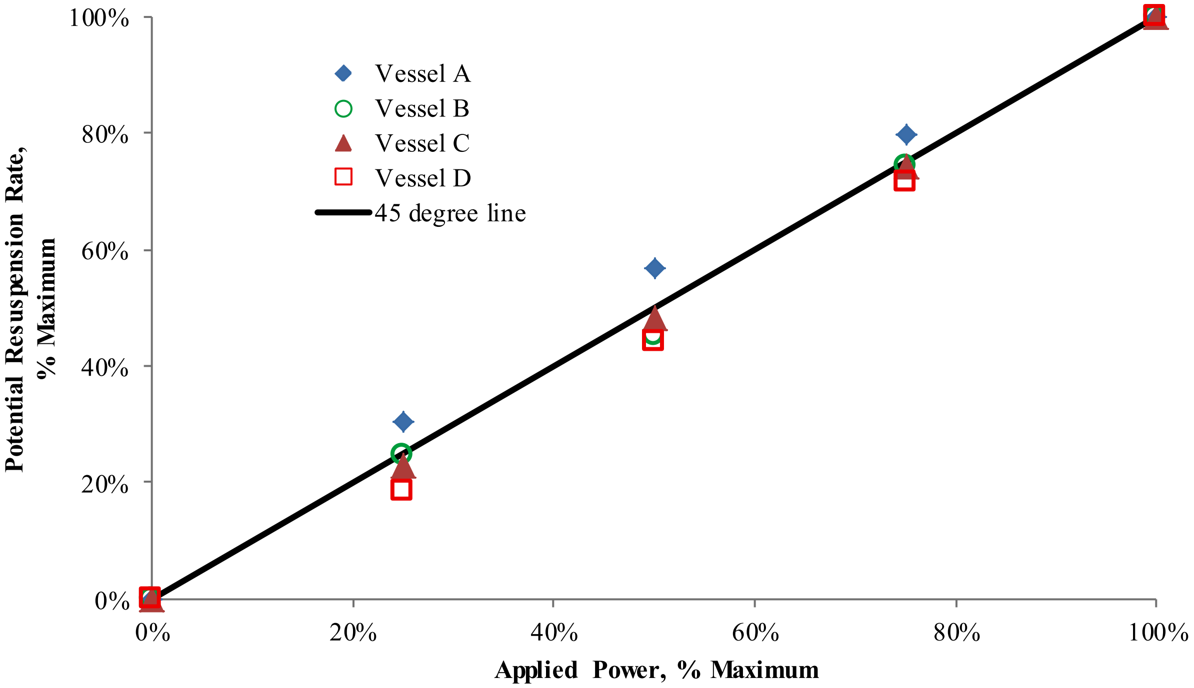

Figure 5: Variation of percent maximum resuspension flux versus applied power for vessels with a forward speed of 3 knots operating in a water depth of 2 m

Vessel speed also can be a significant contributing factor to potential scour. Figure 8 shows the decrease in potential sediment resuspension flux due to propeller scour as vessel speed decreases for Vessel B operating at 75% power. These same trends were seen in all model results that generated scour.

The geometry of the scour area also is an area of concern and was determined for all model runs. Figure 9 shows that the scour width follows a concave pattern with water depth. At shallow depths, the erosion is narrow, but deep. As water depth increases, so does the width until the induced water velocities reach a point at which scour no long occurs. The results also show a clear trend of scour width increasing with applied power.

DISCUSSION

The model runs provided potential resuspension rates that respond to operational and environmental variables as expected. For example, if a tug were pushing an unloaded scow at 3 knots using 25% power, but had to increase to 75% power to push a loaded scow at 3 knots, it is logical that the potential sediment scour would increase for the same water depth. Similarly, faster vessel movement would generate more wake and, thus, potential scour, given the same vessel and power settings. Increased propeller clearance and water depth also decreased the potential sediment scour. Not only did the model results follow expected trends, the magnitude of flux changes induced by modifications to operation or environment or vessel selection were reasonable and consistent. As shown above, the rates of increase or decrease often were consistent or followed consistent trends.

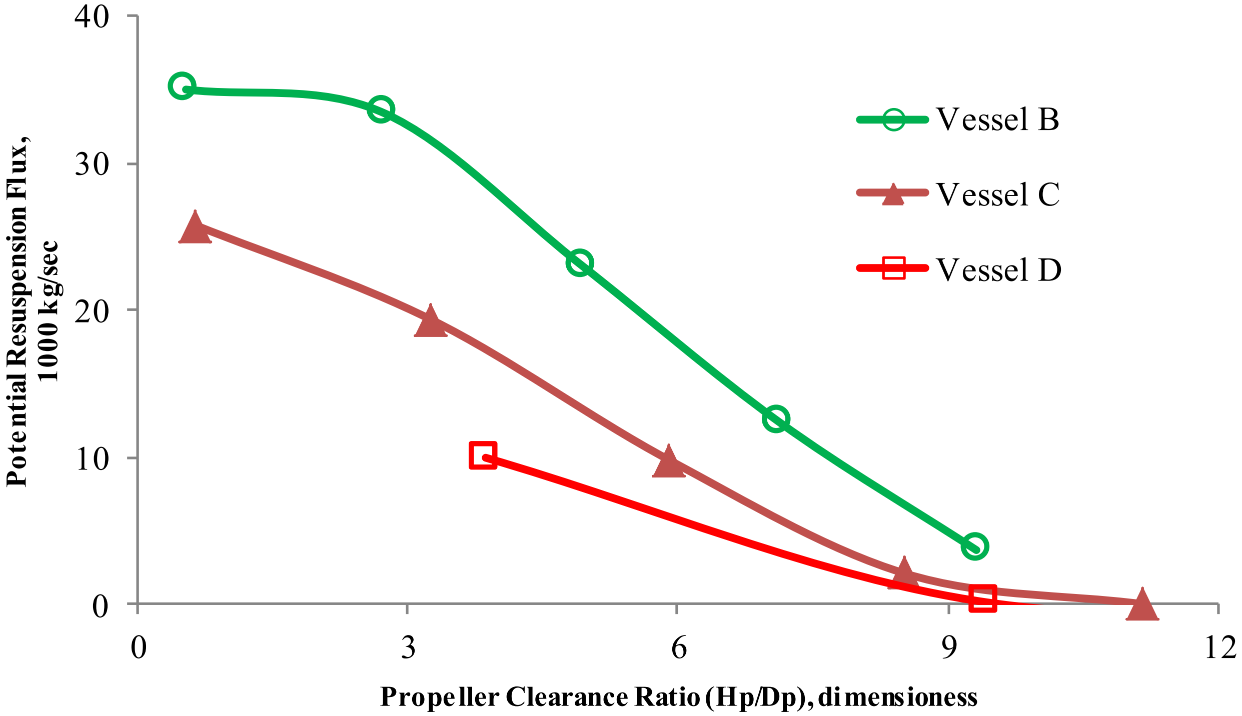

Figure 6: Reduction in potential sediment resuspension rate with increases in propeller clearance; all vessels operating at 75% power and moving forward at 3 knots

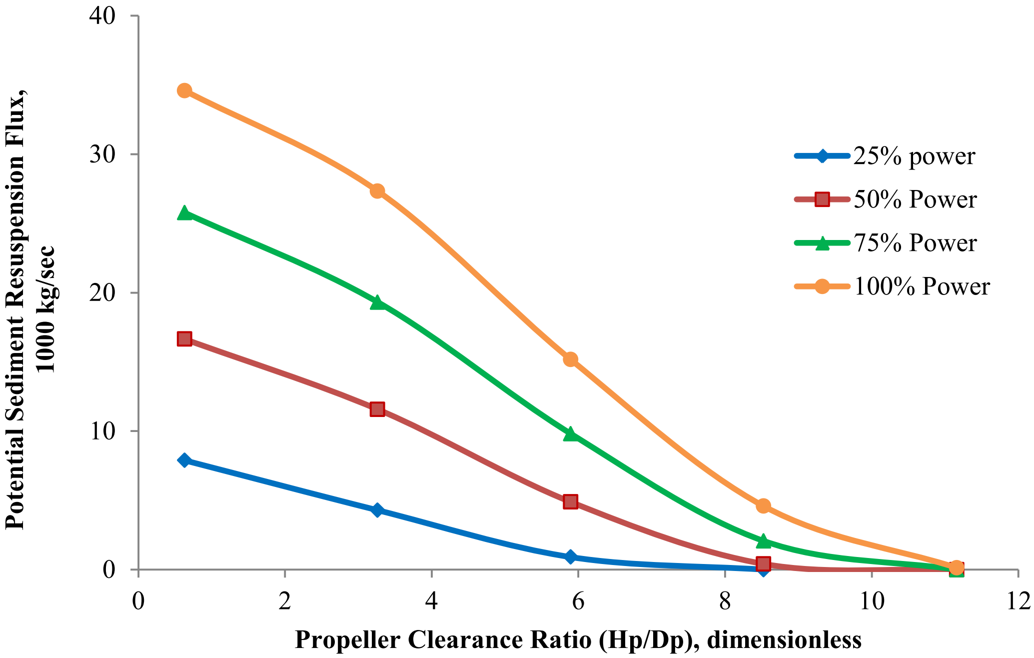

Figure 7: Effects of propeller clearance and applied power on potential sediment resuspension flux for Vessel C moving forward at 3 knots

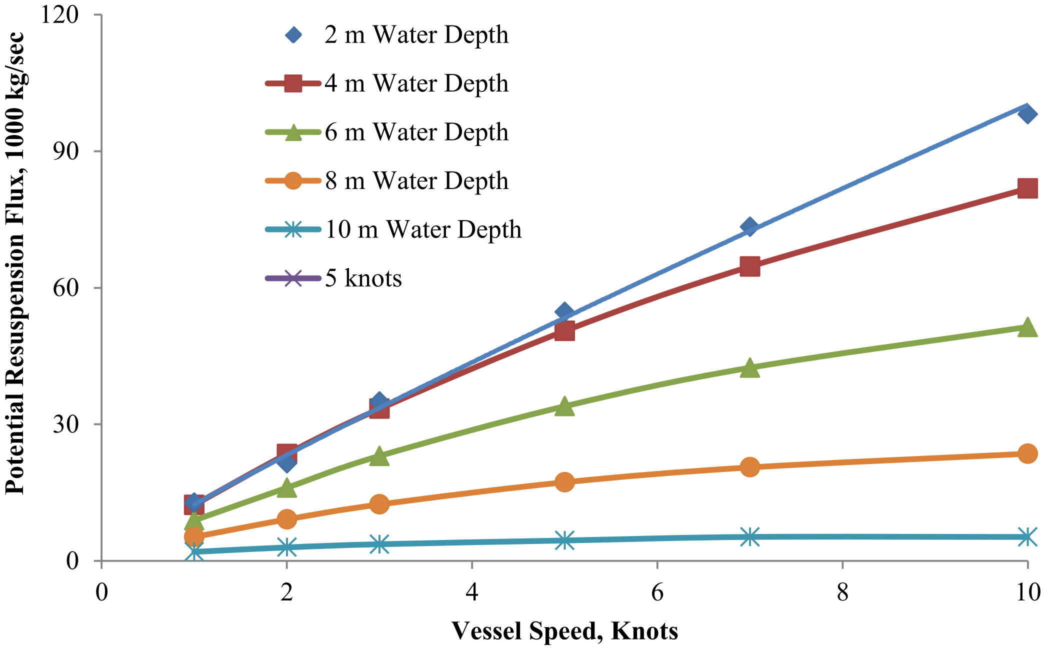

Figure 8: Effects of vessel speed on potential sediment resuspension flux for Vessel B operating at 75% available power

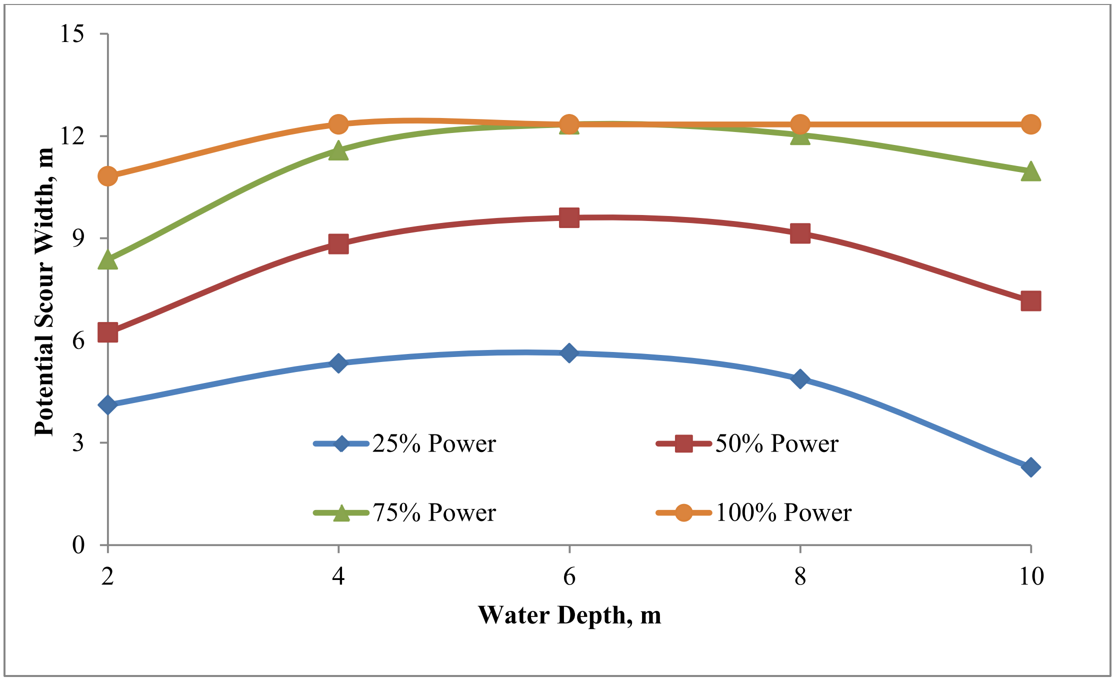

Figure 9: Potential scour width due to Vessel B moving at 3 knots

The consistency of the results suggests that the models responded to input properly despite being applied in an incremental time and spatial framework. While field data are not available to reaffirm the results, there seems to be no clear reason not to accept the results as reasonable estimates of potential resuspension flux resulting from vessel-induced scour. Despite the consistency across the model runs, the magnitude of the potential resuspension flux rates was surprising. The averages for all of the vessels were greater than 1,000 kg/sec. It is important to remember that the models do not consider transport and redeposition of sediment. Much of the eroded sediment may redeposit within a few meters of its point of erosion, particularly for very high erosion rates; this could lead to sediment behavior as a mass rather than a suspension.

For the purpose of comparison, Table 4 shows resuspension rates that might be associated with a bucket dredging operation in the same sediment assuming a perfectly efficient bucket dredging operation with a one-minute cycle time and 1% loss rate. The results show that suspended sediment flux from a 30-m^3 bucket dredge would be many orders of magnitude less than the propeller scour rates, as summarized in Table 2. These large potential resuspension rates result partially from the assumption of an infinitely thick layer of soft, highly erodible sediment. Soft surface sediments are common in estuaries, harbors, and lakes. In most cases, however, firmer, less erodible sediments underlie them. This limits the potential duration of an extremely high erosion rate to the time it takes to completely scour the soft sediment layer away. Since the scour area may be small, the total sediment mass resuspended could be substantially less than the potential scour. Also, vessels seldom operate at high power levels in project areas. As shown above, applied power substantially influences the rate and extent of scour.

Table 4: Sediment resuspension rates for a perfectly efficient bucket dredge with a 1 minute cycle time and 1 percent loss rate

Sediment Volume per Bucket Cycle (m^3)	5	10	15	20	25	30
Resuspended Sediment Flux Rate (kg/sec)	0.8	1.6	2.5	3.3	4.1	4.9

In addition, a careful review of bottom sediment shear stresses, computed as part of the model runs, showed that many of these shear stresses were well outside of the range of the SEDflume laboratory results and the erosion rates; therefore, they are the results of extrapolation. The linear extrapolation method chosen should provide reasonable estimates beyond the laboratory results. However, the results must still be considered estimates and used with caution.

A direct comparison between vessel-induced scour and dredging may not be appropriate for many cases. Dredging typically is a continuous operation, occurring in the same general area for days, weeks, or even months. Vessel use often is more sporadic, especially under higher power conditions, which may exacerbate sediment scour. For example, tugs may operate at higher power settings only when sediment-filled scows are exchanged for empty scows during bucket dredging operations. For safety reasons, larger vessels typically operate at lower speeds in construction areas, where water depths are more likely to be shallow.

The catalyst for this modeling effort was the need to develop best management practices for waterborne activities associated with a large marine construction project in an area where the soft bottom sediments potentially held significant concentrations of toxic constituents. Regardless of specific water quality criteria imposed on the project, there was a strong desire to minimize short-term and long-term impacts. The construction site consisted of a 40-feet deep navigation channel and a large area consisting of undredged depths from 2 to 20 feet in depth. All of the areas were underlain by an almost inexhaustible supply of very soft, highly erodible sediments. Ultimately, a series of navigation channels at various depths were selected to be dredged in order to support the extensive construction vessel traffic anticipated for the project.

The modeling results, however, provide some interesting insights into potential best management practices for vessel traffic in construction areas and their potential effectiveness. Three of the following primary management alternatives exist: 1) restricting vessel access based upon minimum clearance between the propeller and bottom; 2) limiting vessel speeds; and 3) regulating the applied horsepower. It is important to note that these variables are inter-related. For the same vessel and load conditions, increasing the applied horsepower increases vessel speed. An increased load decreases the propeller clearance and increases the applied horsepower required to maintain the same vessel speed.

The model results show that for a given vessel and specific site conditions, potential sediment resuspension rates increase with applied horsepower as expected. Figures 4 and 5 show that the potential sediment resuspension rates decrease almost proportionally with changes in applied horsepower. A more comprehensive view of the relationship from the entire modeling result matrix shows that this proportional relationship actually begins at the conditions representing incipient scour. The conditions represented in Table 3 suggest that this is likely to be at minimum operating conditions for all cases except the smallest vessels. Of the three variables, applied horsepower is the most difficult to control or measure without direct or remote wheelhouse access. Boat captains must retain the ability to adjust throttle settings based upon perceived or real safety threats. For these reasons, applied horsepower may not be a practical choice as a best management practice to control propeller-induced scour.

Figures 6 and 7 show that restricting vessels to water depths with adequate propeller clearance, i.e., the distance between the bottom tip of the propeller and the top of the sediment layer, may be a more practical and effective best management practice. Both graphs show a greater than proportional decrease in potential resuspension rate at shallower water depths; these results are consistent with other model result. Restricting vessel access based upon water depth and draft may be a more practical management practice for many sites. Restrictions may need to include the vessel load as well. It is likely, however, that such restrictions may be impractical at some sites where vessel access in shallow water may be essential to successful completion of a marine construction project and smaller vessels are not able to complete the required tasks safely.

Restrictions on vessel speed are probably the easiest management practice to implement, and Figure 8 shows that it can be an effective management tool. The trends found in Figure 8 are consistent with model results for other vessels and operating conditions. Under conditions where sediment scour is significant, increased vessel speed significantly increases potential propeller-induced sediment scour. Every vessel has a minimum speed necessary for safe maneuvering under a given set of circumstances. However, these speeds usually are very low, and should not be a major issue for most marine construction projects.

SUMMARY AND CONCLUSIONS

Existing near-field and far-field hydraulic models that compute propeller-induced bottom shear stresses associated with moving marine vessels were coupled with an empirical sediment scour model, which computes erosion rate as function of shear stress. Together, the models were used to compute propeller-induced sediment scour rates that might be associated with common vessels used for marine construction projects. SEDflume laboratory studies produced empirical coefficients associated with bottom sediments from a freshwater riverine environment for the erosion model. The computations were based upon a vessel moving across the spatial plane with time; small spatial (0.1 m) and temporal increments (0.1 sec) were used to reduce computation errors.

Model runs were completed for four vessels ranging from 134 to 1342 KW (180 to 1800 HP) over a range of water depths from 2 to 10 m and vessel speeds from 1 to 10 knots. The model results responded appropriately to operational and site variables, suggesting they provide reliable information about the influence of these variables on propeller-induced scour. The magnitude of the flux estimates provided was much higher than expected and the cause is uncertain. They may well be realistic values for the site data provided: an infinite depth of highly erodible sediments. The linear extrapolation of the SEDflume results beyond the available laboratory data may have increased the erosion rates, but any increases should not represent large fractions of the predicted flux values. The comparison of the results to dredging-induced resuspension suggests that vessel traffic could contribute an equal or greater amount of sediment resuspension during marine construction projects, and may deserve more careful assessment for many projects. A more extensive site-specific study would be necessary to fully evaluate potential vessel-induced resuspension for an individual project.

The resuspension flux values produced by the models provide useful insight into how vessel speed, propeller clearance, and applied horsepower influence propeller-induced scour. The results suggest that water depths of about 10 propeller diameters are necessary to eliminate sediment scour. Vessel size—in terms of draft, propeller size, and horsepower—should be carefully considered when selecting marine construction vessels. Once vessels are selected, limitations on vessel speed are the best management tool for minimizing scour associated with most projects.

NOMENCLATURE

Symbol	Description	Unit
a	Regression coefficient	m/sec/Pa
C_{fs}	Bottom friction factor for propeller wash	dimensionless
C_j	Vertical distance from propeller shaft to location of maximum velocity within the jet	m
C_p	Propeller coefficient	dimensionless
D_p	Propeller diameter	m
g	Acceleration of gravity	m/s^2
H_p	Distance from center of propeller axis to channel bottom	m
L_{set}	Distance from ship stern to propeller	m
N	Regression coefficient	dimensionless
T	Forward Thrust	N
V_{prop}	Bottom velocity due to propeller wash	m/s
V_{Z1}	Velocity at sediment surface in Zone 1	m/s
V_{Z2}	Velocity at sediment surface in Zone 2	m/s
W_p	Distance between propeller	m
X_p	Distance behind the propeller	m
Y_{cl}	Lateral distance from ship centerline	m
δ_p	Propeller depth	m
ε	Volumetric sediment erosion rate	m/s
ρ_w	Density of water	kg/m^3
τ	Bottom shear stress	N/m^2
τ_{cr}	Critical shear stress	Pa

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THIRTY-FIVE YEARS OF DREDGED MATERIAL DISPOSAL AREA MONITORING – CURRENT WORK AND PERSPECTIVES OF THE DAMOS PROGRAM

Steven Wolf[1], Thomas J. Fredette[2], Richard B. Loyd[3]

ABSTRACT

Since 1977, the U.S. Army Corps of Engineers Disposal Area Monitoring System (DAMOS) has monitored aquatic dredged material disposal sites along the New England coastline from Downeast Maine to western Long Island Sound. The earliest monitoring focused on understanding the basic behavior of disposed sediment and its near-field, short-term impacts in an aquatic environment. The program developed a consistent and efficient framework under which to design and perform investigations and to interpret and make use of the collected data. As basic questions were answered, program resources were shifted to address longer-term impact questions and evolving dredged material disposal techniques and to provide consistent communication of results through reports, symposia, and related outreach. Over its 35-year history, DAMOS has consistently shown that monitoring information can be used to manage aquatic dredged material disposal sites to minimize environmental impacts.

Current/recent DAMOS investigations include: monitoring the stability and recovery of a disposal mound of contaminated dredged material created 30 years ago in Long Island Sound that was intentionally left uncapped as part of a joint U.S. Environmental Protection Agency/Corps of Engineers program; investigating the long-term stability and self-capping potential of confined aquatic disposal (CAD) cells in Boston Harbor; and evaluating a technique for low impact capping of a historic industrial waste disposal site in deeper waters using standard disposal scows. These investigations, along with standard surveys to confirm the placement of sediment and biological recovery at active disposal sites, will continue to provide the technical information needed by regulators, policy makers, and the public to make critical decisions on dredged sediment management.

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INTRODUCTION

The Disposal Area Monitoring System (DAMOS), operated by the New England District (NAE) U.S. Army Corps of Engineers, has provided 35 years of monitoring aquatic dredged material disposal sites in New England waters extending from Downeast Maine to western Long Island Sound. The program has evolved over this time period in terms of the specific questions being addressed, the types of data gathered and techniques for collection, and the resulting site management decisions. Without exception, 35 years of monitoring supports the conclusion that with well-managed evaluation and placement, aquatic disposal of dredged material has very little adverse impact on the environment. This paper provides a brief history of DAMOS Program development, recent program investigations exemplifying the current range of study, and perspectives on future work.

HISTORY OF DREDGED MATERIAL DISPOSAL MONITORING IN NEW ENGLAND

As part of the overall awakening of environmental awareness that took place in the 1960's and 1970's, there was a growing concern about the disposal of dredged material in the aquatic environment. In response, NAE supported a number of independent investigations during this time period, many of which established the foundations of our knowledge on dredged material disposal impacts in an open-water environment (Gordon *et al.*, 1972; Gordon, 1974; Rhoads, 1973). Evolving from these studies, the DAMOS Program was initiated in 1977 as a joint effort of NAE and the Naval Underwater Systems Center (Newport, RI) evaluating the impacts of dredged material disposal from dredging of the Trident Submarine Base in New London, Connecticut. The earliest DAMOS objectives focused on understanding the basic behavior of disposed sediment and its near-field, short-term impacts. As the program developed, the overall objectives were refined in 1979 (NUSC, 1979) to include the following:

- To monitor dredged material disposal sites in the New England area by empirical methods to ensure that no significant adverse environmental impacts result from disposal operations
- To develop an understanding of the processes and mechanisms affecting dredged material in the marine environment
- To develop an understanding of the interaction between dredged material and the biota of the disposal site
- To utilize this knowledge to develop management techniques that will minimize the adverse effects of disposal
- To distribute the results of the DAMOS Program so as to provide better public understanding of the effects of dredged material disposal

In the years that followed, DAMOS Program investigations contributed key knowledge on disposal impacts and sediment management in the areas of biological recolonization (Rhoads and Germano, 1990; Germano and Rhoads, 1984), the use of capping (Morton, 1980, 1983, 1988; Fredette, 1994; Fredette *et al.*, 1992; SAIC, 1995), and the long-term stability of disposal mounds (Brandes *et al.*, 1991, Fredette *et al.*, 1986; SAIC, 1989). The program also developed a consistent and efficient framework under which to design and perform investigations and to interpret and make use of the collected data. This led to the development and refinement of monitoring tools (Bohlen, 1982; Germano, 1983) as well as a tiered monitoring framework (Germano *et al*., 1994).

As DAMOS reached its twentieth anniversary, an overview of the program from the perspective of a Program Manager (Fredette, 1998), asked two questions: had the program accomplished it objectives, and had it outlived its usefulness? From this perspective, it was concluded that some, but not all of the objectives had been achieved. The program was judged as continuing to be useful, but noted the users of DAMOS information (resource and regulatory agencies, maritime and port interests, environmental groups, and the public as well as internal Corps of Engineers managers and regulators) would provide a more meaningful evaluation.

Fifteen years later, as DAMOS reaches its thirty-fifth anniversary, the program has generated a total of nearly 200 technical reports (DAMOS contribution series) and over 100 journal or conference papers (see http://www.nae.usace.army.mil/damos/index.asp), produced an award-winning informational video, and sponsored periodic symposia dedicated to disposal site monitoring. Through this outreach as well as participation in both Regional and National Dredging Team forums, the program has strived to gain input from stakeholders on refinements and direction to better support the users of monitoring data, and we believe this has allowed the program to remain relevant halfway through its fourth decade of existence.

RECENT/ONGOING WORK UNDER THE DAMOS PROGRAM

Current DAMOS studies fall into two general categories: confirmatory surveys and focused studies. Confirmatory surveys are a component of the original tiered monitoring framework of the program and are designed to test hypotheses related to expected physical and ecological response patterns following placement of dredged material on the seafloor at established, active, or recently active disposal sites. These surveys typically involve collection of both bathymetry and imaging data. Sequential bathymetric measurements are made to characterize the height and spread of discrete dredged material deposits or mounds created at open-water sites as well as the accumulation/consolidation of dredged material into confined aquatic disposal (CAD) cells. Sediment-profile imaging (SPI) surveys are performed to provide additional physical characterization of sediments and to support evaluation of seafloor (benthic) habitat conditions and recovery over time. The data collected during these studies provide confirmation of recovery of the benthic community following cessation of disposal at active sites and provide input for the longer-term management of individual sites.

Focused studies are periodically undertaken within the DAMOS Program to evaluate inactive/historic disposal sites as well as to contribute to development of dredged material placement, capping, and monitoring techniques. Focused studies may consist solely of records and literature review, involve comparison of analytical techniques, or include field surveys using sediment collection and other imaging and geophysical measurements in addition to standard confirmatory tools. A summary of New England dredged material disposal sites that have had significant use and more intensive DAMOS monitoring is provided in Table 1, and examples of ongoing or recent confirmatory surveys and focused studies are provided below.

Table 1: Summary of the more intensively monitored New England disposal sites

Disposal Site	Description	Use	Monitoring Observations [a]
Central Long Island Sound Disposal Site	Centrally located in Long Island Sound just south of New Haven, CT, the current site covers 8.2 km^2 and is in approximately 20 m water depth. The site was most recently designated in 2005.	The general area of this site has received dredged material for over 70 years from multiple harbors. There are numerous distinct disposal features with capped mounds dating back 30+ years.	- Stability and benthic recovery [#135, 139, 142, 159, 163, 192] - Capping process [#165]
New London Disposal Site	Located in eastern Long Island Sound just outside of the mouth of the Thames River, the site covers 3.4 km^2 with water depths ranging from 13 to 24 m. The site is under a temporary designation pending completion of additional site selection studies.	The general area of this site has received dredged material for over 50 years. There are multiple distinct disposal features including capped mounds.	- Stability and benthic recovery [#128, 130, 133, 149, 152, 175, 180] - Capping process [#128, 132, 149, 152, 175, 182, 189]
Rhode Island Sound Disposal Site	Located approximately 21 km south of the entrance to Narragansett Bay, the site covers 3.2 km^2 with water depths ranging from 34 to 39 m. The site was designated in 2004.	This relatively new site received dredged material and CAD cell construction material from recent dredging in Providence River and Harbor.	- Stability and benthic recovery [#155, 156, 176, 178, 183] - Water column [#166, 167, 178] - Fisheries [#174, 178]
Massachusetts Bay Disposal Site	Centrally located in Massachusetts Bay, the site covers 10.8-km^2 site with water depths ranging from 82 to 92 m. The site was most recently designated in 1992.	The general area of this site has received dredged material for over 60 years. There are multiple distinct disposal features including capped mounds.	- Stability and benthic recovery [#134, 162, 181] - Capping process [#147]
Boston Harbor CAD Cells	11 separate CAD cells constructed in the upper reaches of Boston Harbor. The cells were constructed between 1997 and 2008, with one cell currently remaining uncapped.	The 11 CAD cells were constructed to receive material assessed as unsuitable for unconfined open-water placement and was the first large-scale use of cells constructed beneath the navigable channel in the United States.	- Stability and benthic recovery [#148, 168, 185] - Capping process [#124, 148, 150, 185]
Portland Disposal Site	Located off the coast of southern Maine, the 3.4 km^2 site has water depths ranging from 37 to 71 m. The site was designated in 1987.	The general area of this site has received dredged material for over 60 years. Given the varied bathymetry, there are limited distinct disposal features.	- Stability and benthic recovery [#136, 140, 179] - Capping process [#123] - Water column [#153]

[a] [#] refers to recent DAMOS contributions that can be found at http://www.nae.usace.army.mil/damos/index.asp

Confirmatory Survey at the Cape Cod Bay Disposal Site

A 2010 survey performed at the Cape Cod Bay Disposal Site in 2010 provides a recent example of confirmatory monitoring within the DAMOS Program. The Cape Cod Bay Disposal Site is located within the waters of Massachusetts approximately 15 km southwest of Provincetown, Massachusetts. It was selected as an open-water site in 1990 in response to an increase in dredging needs at many regional harbors due to a steady rise in population and recreational boating activities on Cape Cod (Battelle, 1990). The 1.9 x 1.9 km site is relatively flat with an average depth of approximately 30 m and includes an area that historically received dredged material (Wellfleet site in Figure 1). Since its selection, the site has received nearly 800,000 m^3 of dredged material targeted at three locations across the site (mounds A, B, C in Figure 1). Similar to many other open-water sites in New England, the long-term management strategy incorporates the formation of an outer berm constructed of individual disposal mounds. Ultimately, the resulting central depression area will provide additional capacity and easier logistics for potential future projects that require capping.

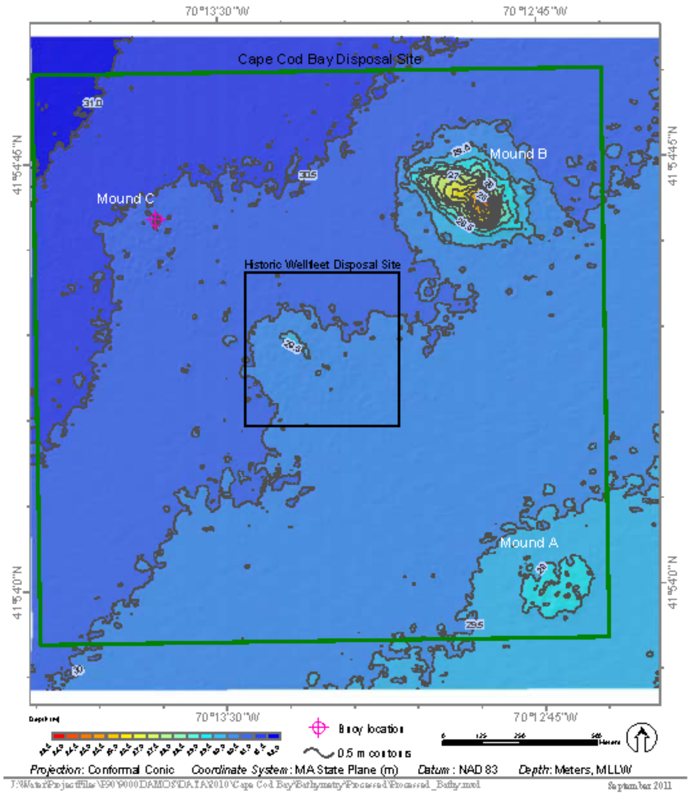


Figure 1: September 2010 bathymetry of the Cape Cod Bay Disposal Site showing the area of historically recorded disposal (Wellfleet site), previously targeted areas of the site (mounds A and B), and the active area of placement (mound C)

The 2010 confirmatory survey at the site was performed to document changes in the seafloor topography and to track the biological recovery of the previously formed and now inactive mounds A and B and the recently active mound C (Figure 1). Comparison of the 2010 bathymetry with a previous 2003 survey confirmed the stability of the older mound A and identified the beginning of formation of mound C from more recent disposal. Although there was no change in the overall footprint of older mound B, the bathymetric comparison identified some redistribution of material near the peak of this large mound that rose approximately 6 m above the surrounding seafloor that was attributed to storm-induced transport at this exposed site (Figure 2). Sediment-profile images from all three mounds showed advanced successional stages of biological communities identical to those of surrounding reference areas (Figure 3). Plan-view imaging was also included in the 2010 survey; this technique provides broader bottom coverage (important where patchiness of the benthic community may be prevalent), and it is now included in many DAMOS confirmatory surveys. The plan-view imagery further supported the full benthic recovery of the disposal mounds (Figure 4).

Based on the bathymetric findings of the 2010 survey, future placement of material at the site will be distributed over a wider area rather than directed to a specific target point to promote the formation of broader mounds and limit the potential for storm-induced redistribution of placed material. Based on the biological recovery of the site, future confirmatory surveys would only be required following future placement of larger quantities of material at the site. The full survey report is available at the DAMOS website as contribution #188 (AECOM, 2012a).

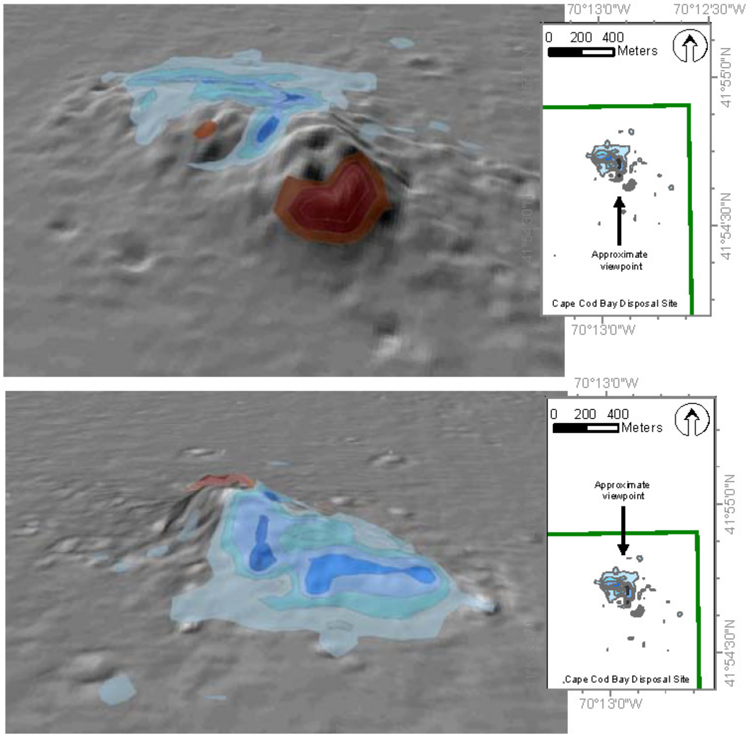


Figure 2: Oblique views of vertically exaggerated 2010 bathymetry of mound B at the Cape Cod Bay Disposal Site highlighting potential areas of sediment transport between the 2003 and 2010 surveys

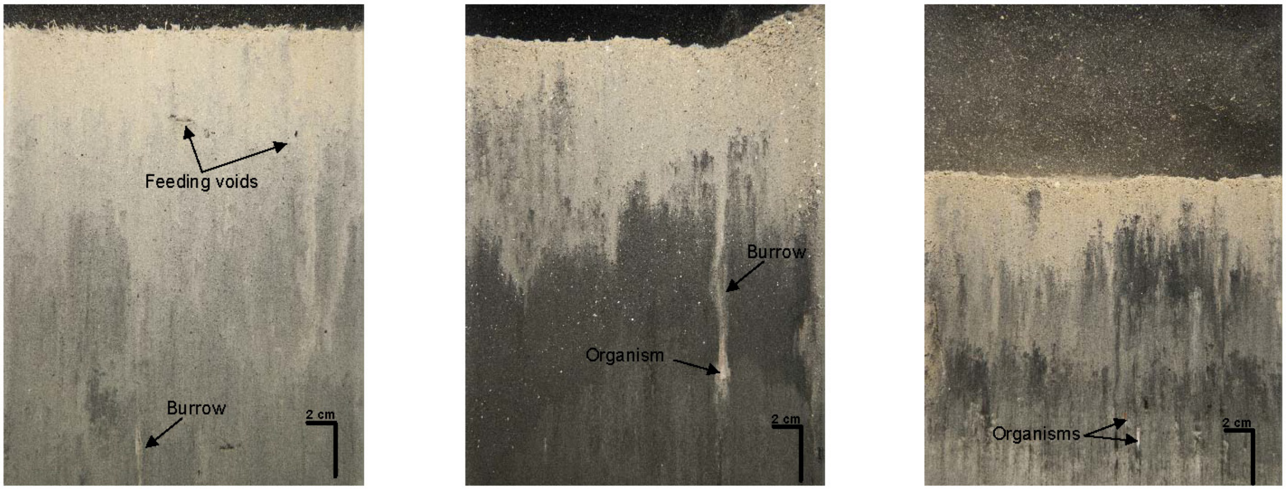


Figure 3: Sediment profile images from illustrating evidence of advanced successional stages. Mound A station (left) shows dense Stage 1 surface tubes overlying two Stage 3 feeding voids and a deep oxidized burrow. Mound B station (center) shows a large-bodied Stage 3 organism with associated oxidized burrow within the reduced dredged material at depth. Mound C (right) shows dredged material layering with several larger-bodied organisms in the subsurface layers.

Figure 4: Plan-view image from mound C at the Cape Cod Bay Disposal Site station showing a crab, juvenile flatfish, burrow opening, and extensive organism tracks

Focused Studies of Historic Uncapped Disposal Mound

Several experimental capping projects were conducted in the waters of the Central Long Island Sound Disposal Site in the late 1970s and the early 1980s to determine the feasibility and effectiveness of using level-bottom capping to isolate contaminated dredged material. The site is located approximately 11 km south of New Haven Harbor, Connecticut and averages 20 m in depth. This general location has been utilized for the disposal of sediments dredged from surrounding harbors for at least 70 years, with many disposal features apparent in the site bathymetry (Figure 5).

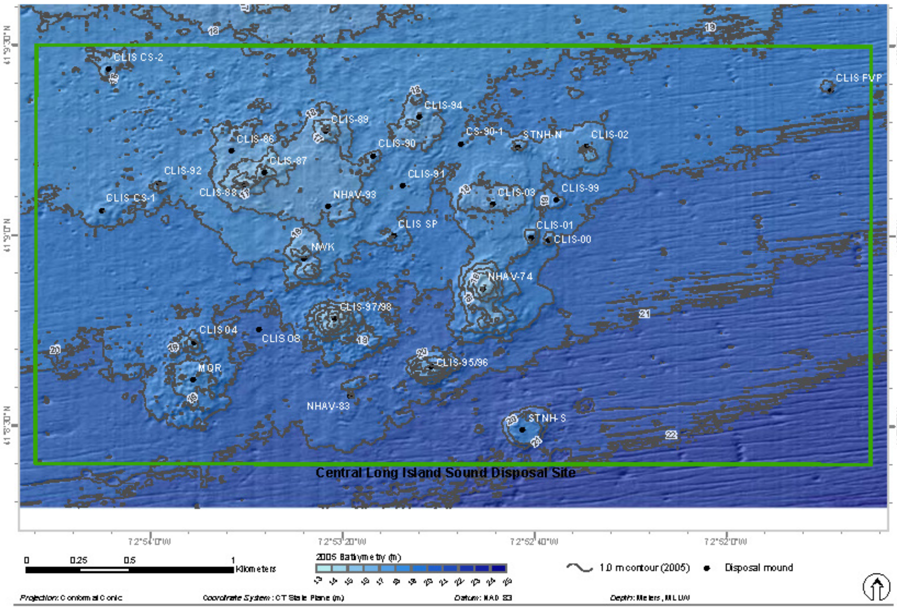


Figure 5: Bathymetry of the Central Long Island Sound Disposal Site from a 2005 survey with accentuated relief highlighting the named dredged material disposal mound locations

For the experimental work, six mounds were formed with dredged material assessed unsuitable for unconfined placement because of elevated contaminant or biological toxicity levels. Five of the mounds were capped with coarse- and/or fine-grained material suitable for unconfined open-water placement (STHN-N, STNH-S, MQR, CS-1, and CS-2 in Figure 5), and one mound was allowed to remain uncapped for study (FVP in Figure 5). The experimental mounds were the focus of multiple followup investigations that are reported in the DAMOS contribution series. The most recent survey of two of the capped mounds was performed in 2004 and included collection of cores documenting the long-term integrity and successful performance of the caps on STNH-N and CS-2 (see DAMOS contribution #165 [ENSR, 2005]).

The uncapped FVP mound was created in the northeast corner of the disposal site as part of the U.S. Environmental Protection Agency/Corps of Engineers Interagency Field Verification of Testing and Predictive Methodologies for Dredged Material Disposal Alternatives Program, known simply as the Field Verification Program (FVP). This program ran from 1982 to 1988 with the objective of field-verifying existing test methods for predicting the environmental consequences of dredged material disposal under aquatic, wetland, and upland conditions (Peddicord, 1988).

The FVP mound was created in 1982 to 83 from the placement of 55,000 m^3 of material dredged from Black Rock Harbor in Bridgeport, Connecticut. The dredged material contained elevated concentrations of both organic and inorganic constituents and demonstrated both chronic and acute effects in biological testing (Myre and Germano, 2007). The mound was intentionally left uncapped to verify monitoring techniques for identifying adverse effects of placing this type of material on the seafloor. The mound has shown a wide range of benthic community responses during monitoring, from an initial classic primary successional recovery (Scott et al., 1987) to episodes of retrograde succession following extreme environmental conditions (i.e., storm events, excessive algal blooms, and hypoxia) experienced by the overall area (Parker and Revelas, 1988; Morris, 1997).

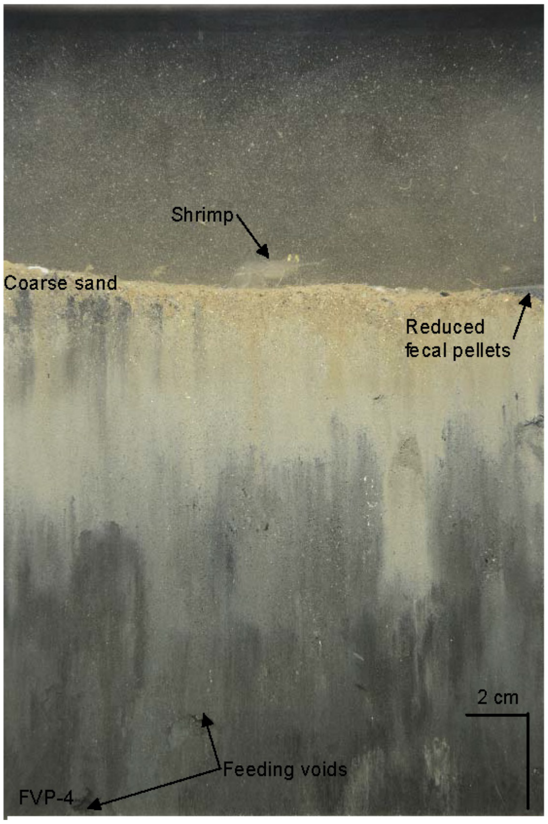


Figure 6: Sediment profile image of FVP mound station, showing traces of burrowing throughout the approximately 2-cm apparent redox potential depth and feeding voids that resulted in an advanced successional stage designation. Shrimp, coarse sand (some reduced) and reduced fecal pellets are apparent on surface.

Given that the mound has remained physically stable and isolated from other disposal activities at the site, its location in a generally depositional, biologically active area also made it ideal for study of monitored natural recovery of impacted sediments. A focused study was performed in 2011 to assess the stability of the mound and the recolonization status over the central portion of the mound where deposition rates were expected to be lowest. The 2011 multibeam bathymetry was compared with previous data and confirmed the physical stability of the FVP mound nearly 30 years following its formation. Sediment-profile imaging revealed that after nearly 30 years of natural deposition and reworking of the sediment by both physical and biological processes, the mound now supported an advanced successional status that was biologically indistinguishable from the reference areas (Figure 6). The full report on this survey will be available on the DAMOS website as contribution #192 in late 2012 (AECOM, 2012b).

Focused Study of Confined Aquatic Disposal (CAD) Cells

As our understanding of the processes at work in open-water placement of dredged material increased and we developed a successful record of managing impacts at open-water sites, DAMOS Program studies have shifted in later years to evaluate new dredged material disposal approaches, such as confined aquatic disposal (CAD) cells. The use of constructed CAD cells (Figure 7) increased over the past two decades as an effective method of disposal of dredged sediments that had contaminant or biological toxicity levels that precluded unconfined open-water placement (Fredette 2006), with cells constructed in six New England harbors over that time period.

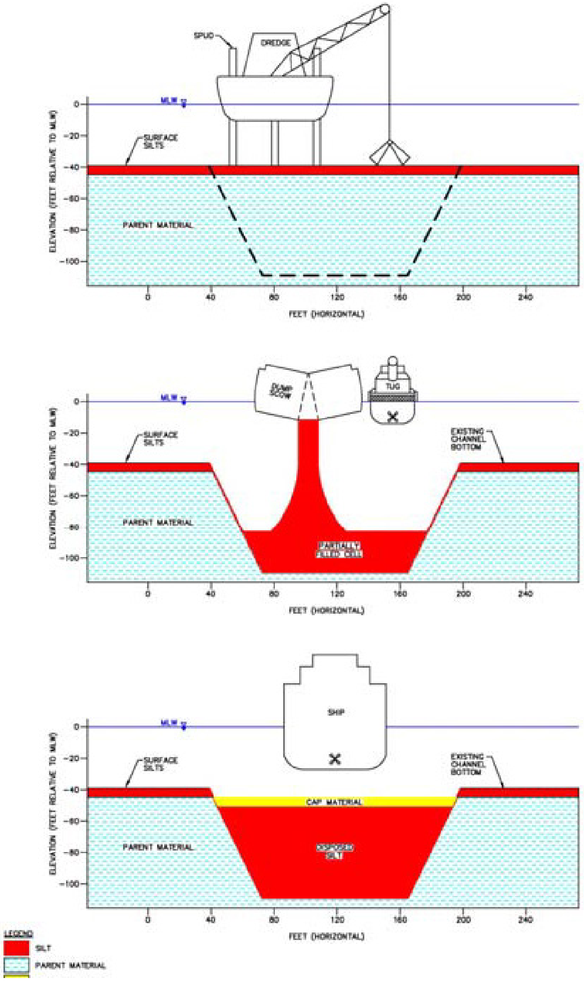


Figure 7: Schematic of construction, filling, and completion of a CAD cell located beneath a navigable channel

Beginning in 1997, a total of 11 CAD cells have been constructed in Boston Harbor; nine of the cells were constructed between 1997 and 2000 in the upper reaches of the harbor as part of the Boston Harbor Navigation Improvement Project (BHNIP), and two additional cells were constructed as part of a separate maintenance-dredging project in 2008. The BHNIP marked the first major use of CAD cells in the United States. Given the scale of the project and the innovative use of CAD cells beneath the footprint of the navigable channel, there were a number of environmental concerns related to release of contaminated sediment during and following placement into the cells. As a result, the state-issued Water Quality Certification contained multiple conditions requiring monitoring of disposal into the cells as well as capping of the cells with a 1 m layer of well-graded sand to isolate the disposed material from the overlying water column and reduce scour potential.

The BHNIP was successfully completed in two phases, and a summary of the environmental monitoring during the project can be found in ENSR (1997, 2002). Monitoring during performance of the BHNIP was carried out as part of the project with DAMOS Program input, and DAMOS assumed the role of longer-term monitoring following project completion, with a focus on cell stability and the integrity of the cap at sequestering the contaminated sediment within the cell. A 2004 confirmatory survey, incorporating bathymetry, sediment-profile imaging, and towed video, revealed the cells as stable and biologically similar to the surrounding harbor area, but the imaging was unable to detect the sand cap that had been documented as intact and at the surface of the completed cells (ENSR, 2007). This was attributed to enhanced deposition of fine-grained material on top of the cap within the cells, which are substantially deeper than the surrounding harbor bottom.

As a follow up, a focused DAMOS survey was performed in 2009 incorporating bathymetry, sub-bottom profiling, and the collection of shallow cores over a subset of the CAD cells to better resolve the cap and deposition over the cells. The bathymetry survey confirmed the continued stability of the cells as depressions below the harbor bottom (Figure 8).

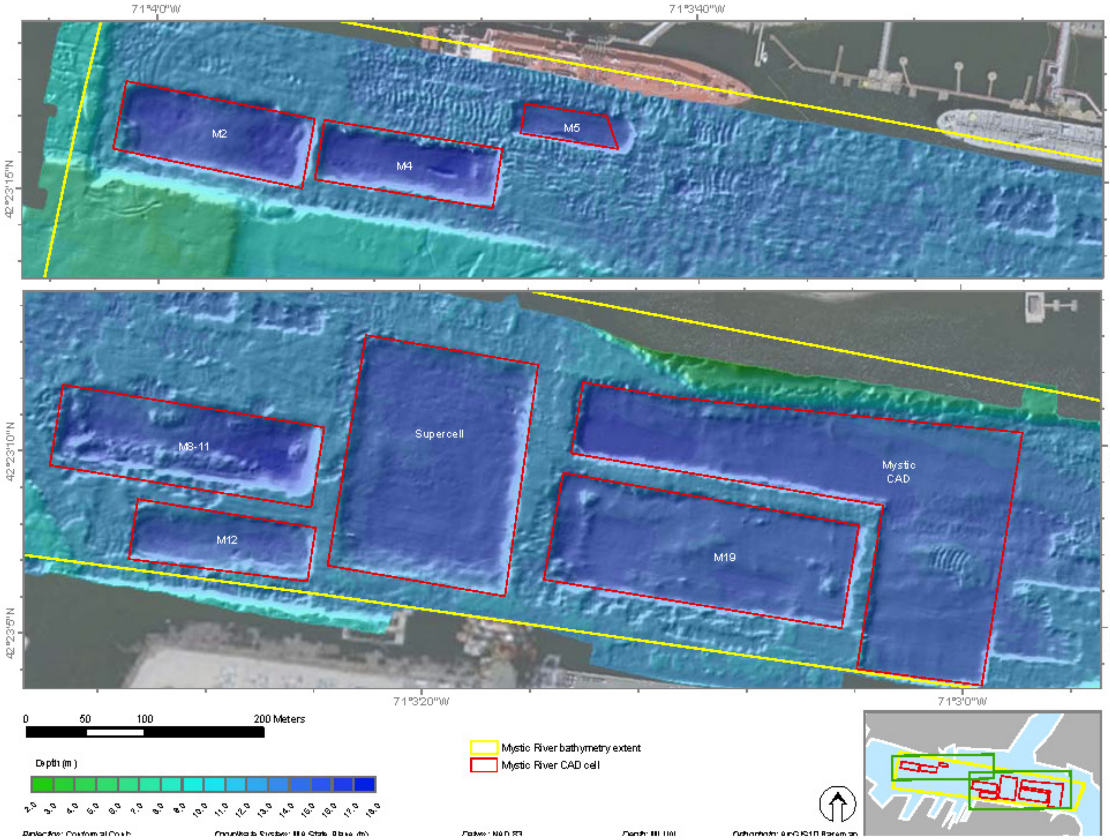


Figure 8: November 2009 bathymetry of the Mystic River in Boston Harbor with accentuated relief highlighting the individual CAD cells that remain deeper than the surrounding harbor

The sub-bottom profiling was able to resolve the intact cap layer below the newly deposited surface layer, indicating the long-term stability of the material within the cells (Figure 9).

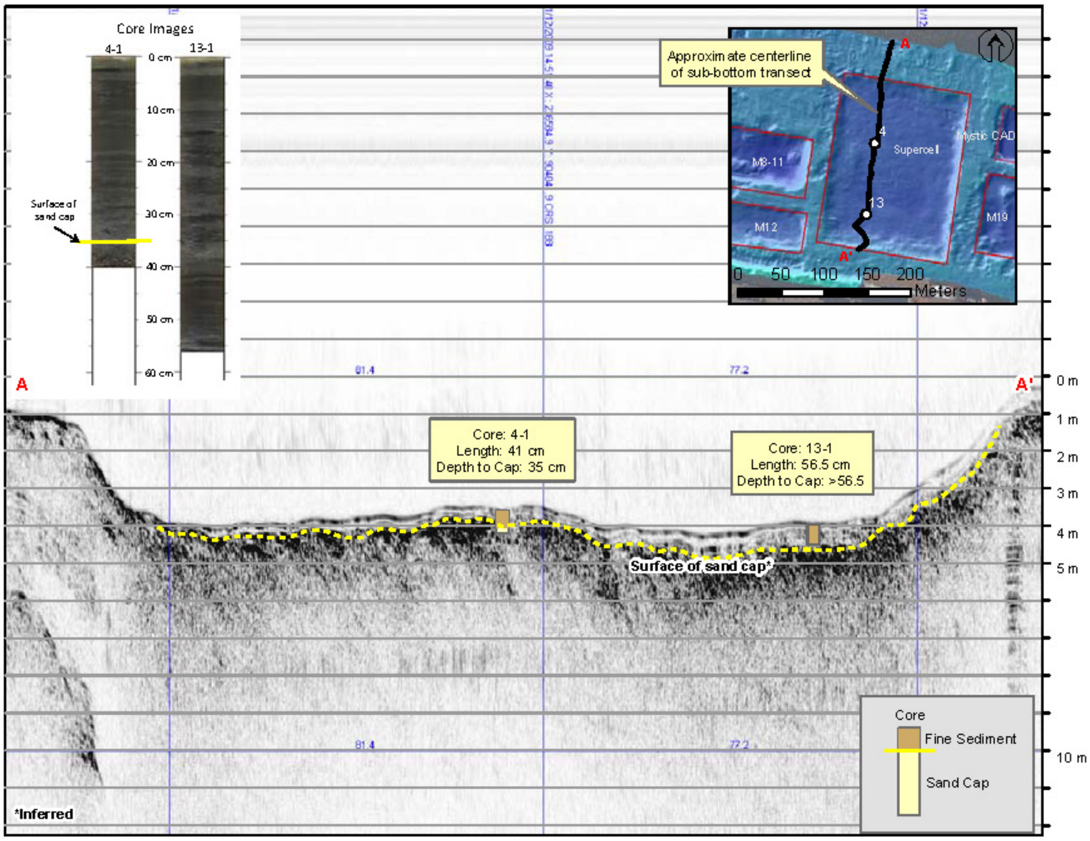


Figure 9: Sub-bottom profile line across the Supercell CAD in the Mystic River with inset of core photographs

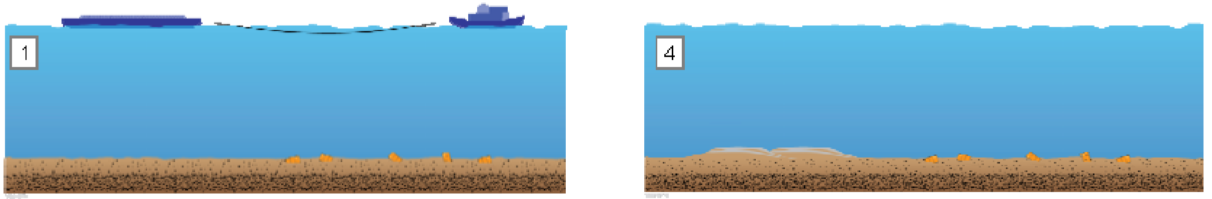
In addition, the sub-bottom profiling, together with the collection of shallow, minimally disturbed cores, confirmed the expectation of enhanced deposition, with rates of 2+ cm/yr estimated over these cells. This deposition, coupled with an observed shallow biological mixing depth and evidence of limited physical disturbance, indicate that by the time the cells had consolidated sufficiently to allow effective placement of the sand cap (with consolidation ranging from 1 to 2 m depending on the initial cell depth and filling history), sequestration of the material within the cells was already taking place through natural deposition. It was concluded that future CAD cell projects should take into account the physical and biological environment in which the cell is placed as well as the characteristics of the dredged material being placed in deciding if a constructed cap is required and, if so, what material type and thickness of cap are acceptable. All these factors should be weighed against expected environmental and project costs.

The full report on this investigation is contribution #186 (USACE 2012a), and a summary of other New England CAD cells can be found in contribution #185 (USACE 2012b) at the DAMOS website.

Focused Study Evaluating Deep Water Capping Techniques

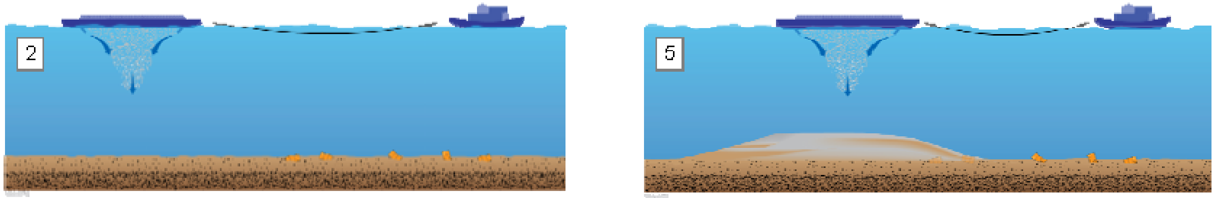
Capping of dredged material at open-water disposal sites (termed level-bottom capping) has a long history in New England, even pre-dating DAMOS. Multiple surveys have evaluated the status of capped mounds in Long Island Sound, and four DAMOS contributions have been specifically devoted to capping demonstrations or overviews (#95, #98, #123, #147). Successful capping has been demonstrated from the shallower waters of Long Island Sound (20 m), to the moderate water depths at the Portland (Maine) Disposal Site (65 m), and to the deeper waters at the Massachusetts Bay Disposal Site (90 m).

As an extension of these investigations, a DAMOS study is currently being completed that focused on identifying techniques for minimizing placement impacts of cap material on the ambient bottom in deeper waters using split-hulled scows (Figure 10). The motivation for this study is the potential capping of a portion of the historic Industrial Waste Site (IWS) in Massachusetts Bay using glacial deposit material generated from an improvement project in Boston Harbor. The IWS, located approximately 31 km (19 miles) from Boston Harbor, received a range of material from the 1940s up until 1976 including, at various time periods, hazardous wastes, munitions, and low-level radioactive wastes in addition to dredged material and construction debris (Wiley et al 1992, NOAA 1996). Although previous studies have not identified significant sediment contamination or environmental risk at the site, they did identify thousands of waste containers scattered across the seafloor (NOAA 1996). Given uncertainty on the contents and expected integrity of the containers, a long-term pro-active goal is to cap the portion of the IWS with the highest density of identified containers on the seafloor. Constraints on capping include the scale of the effort (target area covers 3.5 km^2) and concerns about disturbing/releasing wastes when cap material is dropped through the 90 m water depth over the site.



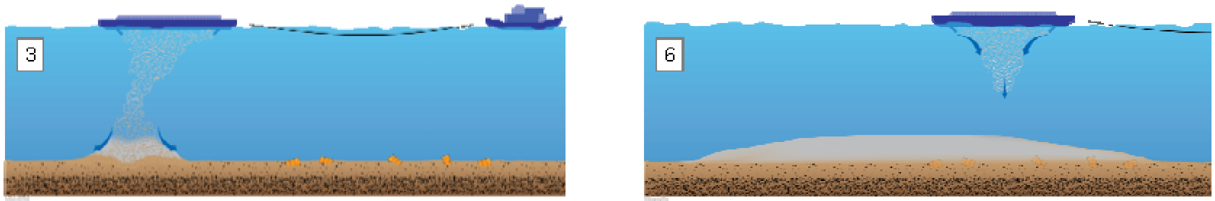
Towed disposal barge approaching the target capping area

Disposed material settles into a defined feature adjacent to the target capping area



Barge releases material adjacent to target capping area

Subsequent disposals form mound that spreads over the target capping area



Disposed material reaches the bottom

Direct disposal over the target capping area, occurs only after creation of a protective berm

Figure 10: Conceptualization of low-impact capping approach using split-hulled scow and staged placement

The recent capping demonstration was performed in comparable water depths to the IWS in a relatively undisturbed portion of the existing Massachusetts Bay Disposal Site just south of the IWS. The project was conducted using material dredged from the construction of a CAD cell in Boston Harbor in 2008. The technique involved highly targeted placement of multiple loads of material using standard disposal from split-hulled scows to build a berm of cap material over a specifically selected initial deposit area. As the berm increased in height with additional material placement, material was expected to spread out laterally with limited disturbance of the adjacent ambient sediment. Once a sufficient thickness of material covered the adjacent limited disturbance area, additional material was directly placed allowing the capping to proceed laterally across the site (Figure 10). The study involved multiple series of placement events followed by collection of bathymetric data, sediment profile imaging, sub-bottom profiling, and selective coring. The project clearly demonstrated that material could be placed with high accuracy using standard disposal techniques in this water depth (Figure 11). Data on assessment of impacts to ambient sediments are currently being evaluated, with preliminary results indicating a scale of approximately 1 m for displacement of or mixing with ambient sediments. A summary report of this work is expected in late 2012 as DAMOS contribution #193.

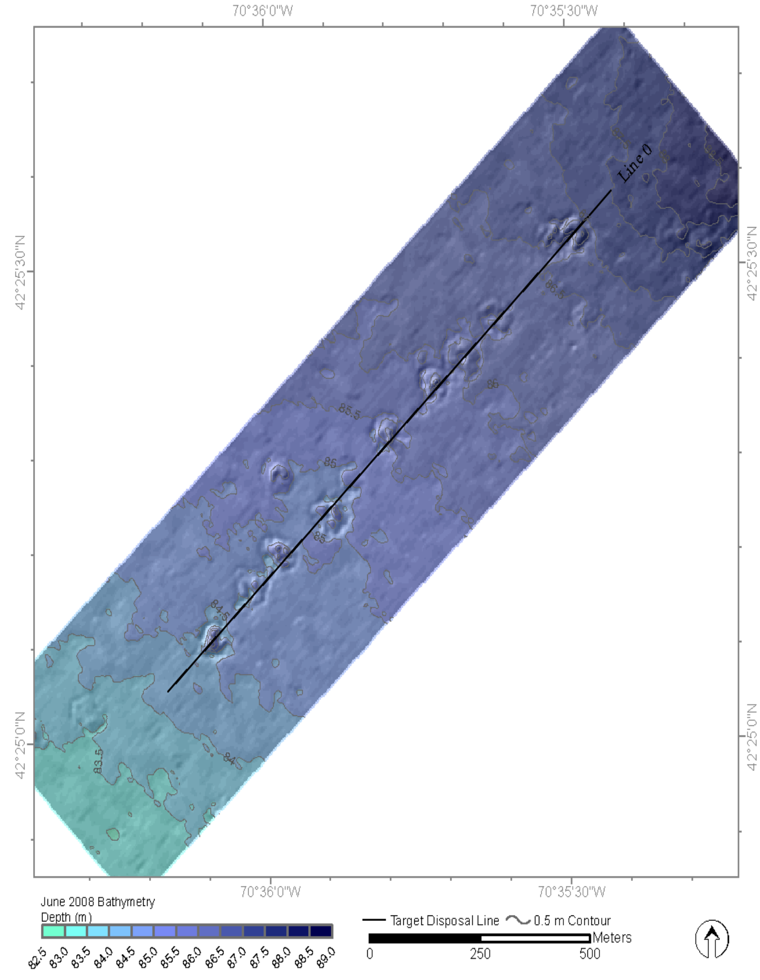


Figure 11: Bathymetry with accentuated relief clearly showing individual scow disposal features along a target line of the cap demonstration area

PERSPECTIVES GOING FORWARD

In the 20-year review of the DAMOS Program (Fredette, 1998), it was noted that the philosophical goal of DAMOS or any similar monitoring program should be to sufficiently address environmental questions and concerns such that the program can be substantially reduced or discontinued altogether. In many respects, DAMOS has reduced various efforts and approaches and discontinued some aspects of monitoring. Other monitoring elements have been replaced with more cost-effective screening or remote-sensing techniques. This has allowed the program to address new aspects of disposal site monitoring not envisioned at its start (such as the use of CAD cells), while operating on a level funded budget with substantially fewer real dollars than during the first decades of the program's existence. Going forward, continued budgetary constraints are certainly expected for all types of environmental monitoring, but by partnering with states and other Federal agencies, we can build off our existing understanding of dredged material disposal and prioritize data needs for future monitoring. Additionally, ongoing advances in technology, such as the national program for electronic tracking of dredging and disposal operations, greater resolution capabilities of acoustic remote sensing tools, and the ability to easily share existing data, allow us to more effectively manage dredged material disposal sites and streamline monitoring. Demonstrating success of CAD cells as well as continued documentation of the long-term success of cap sites will likely remain important elements of the program given the limited ability to implement other dredged material disposal strategies such as shoreline or upland confined disposal facilities (CDF) along the highly developed New England coastline. It can also be envisioned that with climate change the potential increased frequency or severity of storms impacting the New England region may require additional site stability assessments. Climate change and sea level rise may also drive a need to use greater volumes of dredged material beneficially in nearshore land protection schemes, and the DAMOS Program can play a critical role in designing and assessing success of such projects.

ACKNOWLEDGEMENTS

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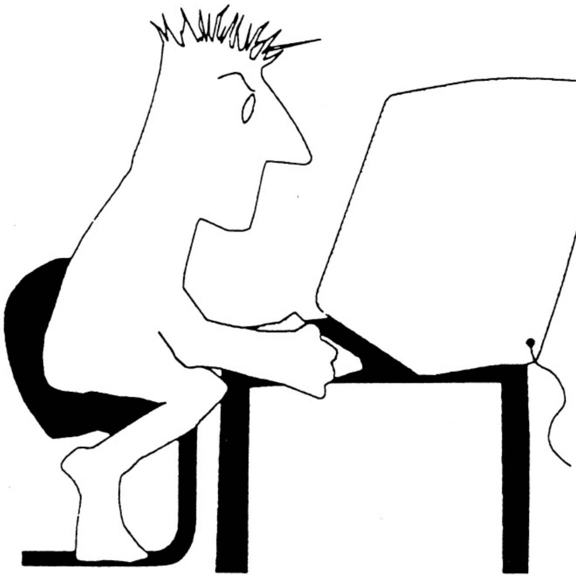

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