Table of Contents

MODELING DREDGE-INDUCED SUSPENDED SEDIMENT TRANSPORT AND DEPOSITION IN THE TAUNTON RIVER AND MT. HOPE BAY, MASSACHUSETTS

J. C. Swanson[1] and T. Isaji[2]

ABSTRACT

A modeling analysis was performed to assess the dredge-induced suspended sediment transport and deposition from a proposed dredging operation in Mt. Hope Bay and the Taunton River, located in southeastern Massachusetts. The dredging is necessary to maintain and deepen an existing nearly 11 km long Federal Channel to allow liquid natural gas tankers to reach a terminal proposed for Fall River. The ultimate goal of the analysis was to determine if the proposed dredging plan that included equipment restrictions and continuous dredging would be protective of aquatic species during periods of particular environmental concern (spawning, fish passage, etc.). The analysis employed a strong science-based approach that included a field program and the use of computer models to determine the environmental effects of the dredging project.

SSFATE (Suspended Sediment FATE) is a model jointly developed by the U.S. Army Corps of Engineers Engineer Research and Development Center and Applied Science Associates to estimate the water column suspended sediment and bottom deposition pattern resulting from dredging operations. The model was developed to provide a consistent estimate of the transport and fate of the portion of dredged material lost during dredging. The model requires specification of circulation in the area of interest, either from direct measurements or hydrodynamic model output; the type of dredging technology used, and the loss rate and vertical distribution of initial material release. Using a random walk procedure, the model tracks representative particle classes as they disperse in the water column and settle to the bottom. Model output includes water column suspended sediment concentrations and bottom deposition thicknesses.

The SSFATE model was applied to three representative sites along the channel in Mt. Hope Bay and the Taunton River, simulating both maintenance (fine grain) and parent (native, coarse grain) materials for different bucket dredge technologies. Bucket cycle, loss rates, and physical dredged material properties were conservatively modeled assuming continuous dredging at forecasted optimum dredge production rates. Results at the different locations were inter-compared. Using these conservative assumptions for model inputs, it was found that locations in Mt. Hope Bay and the Taunton River did not exhibit any significant levels of either water column concentration or deposition thickness. However, when dredging parent material at the turning basin adjacent to the terminal site; some potential effects to winter flounder eggs due to sediment deposition may be of concern, necessitating operating restrictions during the period of winter flounder spawning.

Keywords: Dredging, modeling, suspended sediment, transport, deposition

INTRODUCTION

A Liquefied Natural Gas (LNG) import terminal has been proposed for a site adjacent to the Taunton River in Fall River, MA. In support of this terminal, the existing federally-authorized navigation channel and turning basin require maintenance and improvement. Applied Science Associates, Inc. (ASA) assessed the water quality and biological effects of the dredging-induced suspended sediment using state-of-the-art computer simulation models. The purpose of the study was to determine what effects, if any, the elevated suspended sediment levels and subsequent bottom deposition caused by the proposed dredging would have on the biological communities in Mt. Hope Bay and the Taunton River using model simulations at multiple locations within the dredging limits focusing on biologically-important times of the year. The study included four principal components:

1. A field program component to characterize the physical regime in the Taunton River near the proposed terminal.

---

[1] Principal, Applied Science Associates, Inc., 70 Dean Knauss Drive, Narragansett, RI 02882, USA, Tel: 401-789-6224, Fax: 401-789-1932, Email: cswanson@appsci.com.

[2] Senior Scientist, Applied Science Associates, Inc., 70 Dean Knauss Drive, Narragansett, RI 02882, USA, Tel: 401-789-6224, Fax: 401-789-1932, Email: tisaji@appsci.com.

2. A hydrodynamic modeling study designed to characterize water circulation in Mt. Hope Bay and the Taunton River including tidal effects and river flow.
3. A sediment transport study that simulated the release of sediments to the water column during dredging operations. This model predicted water column concentrations and bottom deposition patterns.
4. A sediment dosing study to evaluate the biological effects of the sediment concentrations and deposition patterns on critical life stages of biological species inhabiting areas adjacent to the dredging sites.

The primary focus of this paper is the discussion of the hydrodynamic and sediment transport studies (2 and 3) with short descriptions of the field program and biological effects studies (1 and 4).

Study Area Description

Mt. Hope Bay, straddling the boundary of Rhode Island and Massachusetts, is the northeast component of the Narragansett Bay system, connecting to the East Passage of Narragansett Bay through Bristol Ferry and to the Sakonnet River at Sakonnet. Mt. Hope Bay is a shallow estuary, with seventy percent of the bay less than 6 m deep at mean low water. Mt. Hope Bay has a total surface area of 35.2 km^2, a mean depth of 5.73 m, and hence a total volume of 2.02 x 10^8 m^3 (Chinman and Nixon, 1985). Tidal fluctuations in Mt. Hope Bay range from 1.0 m at neap tide to 1.68 m at spring tide with a mean range of 1.34 m. There is little amplitude or phase difference throughout the bay for the important tidal constituents: semi-diurnal (M2, S2, N2), diurnal (O1, K1), and the M4 harmonic (Spaulding and White, 1990). The propagation of a tidal signal from Mt. Hope Bay is evident 33 km up the Taunton River (MAEOEA, 2000). The Taunton River is the largest source of freshwater flow into Mt. Hope Bay averaging 29.7 m^3/s (Ries, 1990). This flow varies seasonally, with monthly mean values ranging from a low of 9.4 m^3/s for August to a high of 59.2 m^3/s for March (Ries, 1990). The river extends south from its headwaters in the Town of Bridgewater, MA for 67 km to its mouth at Mt. Hope Bay near Fall River, MA (Figure 1).

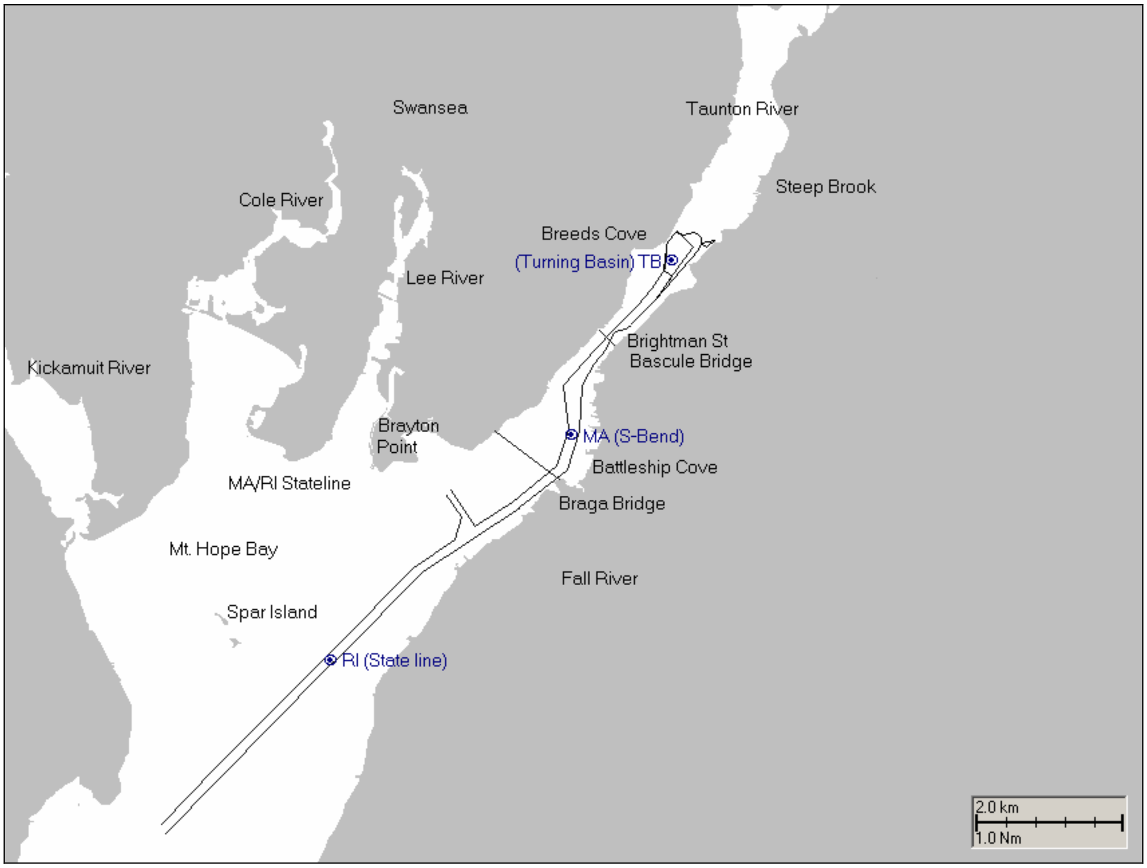


Figure 1. Location of the study area in Mt. Hope Bay and the Taunton River. The Federal Channel and proposed turning basin improvement are outlined. The three modeled dredging sites (TB, MA and RI) as well as names of places, rivers and bays in the vicinity are also shown.

Channel Dredging

The Mt. Hope Bay – Fall River Harbor Channel, a federally-authorized navigation channel, extends from southern Mt. Hope Bay upstream into the Taunton River and is commonly referred to as the Federal Channel. The Federal Channel design dimensions are predominantly 120 m wide with expansion to 150 m wide north of the Braga Bridge, a discreet constriction to 30 m wide at the existing Brightman Street Bridge and terminating at the Turning Basin near the proposed terminal. Records indicate that portions of the channel were last known to be dredged in the 1970s to 10.7 m below Mean Lower Low Water (MLLW).

To allow for transit of tankers to reach the proposed terminal the Federal Channel is to be deepened to -11.3 m MLLW. The existing turning basin at the terminal site will be expanded and deepened to -12.5 m to allow for ship maneuvering and docking under any tidal condition. The total estimated volume of both fine grain maintenance sediment and coarse grain parent material to be dredged is approximately 2.6 million yd^3 (2.0 million m^3) including an allowance for overdredging.

FIELD PROGRAM

The purpose of the field program was to acquire sufficient data with which to calibrate the hydrodynamic model. The field program consisted of a measurement study in the Taunton River adjacent to the proposed terminal and acquisition of additional data from several National Oceanographic and Atmospheric Administration (NOAA) Physical Oceanographic Real-Time Systems (PORTS) stations in the vicinity. The field survey was conducted 30 April through 30 May 2003 with a deployment of two water quality instruments (YSI 6600), one near the surface of the water column and the other near the bottom, at the Turning Basin to monitor water temperature, salinity, dissolved oxygen (DO) and turbidity. An Acoustic Doppler Current Profiler (ADCP) (RDI 600 kHz Workhorse) was deployed in the Turning Basin station to measure currents and water level. Additional data was obtained from NOAA PORTS stations in the area: water level, water temperature and salinity data were obtained from the Fall River WL station; wind data from the Borden Flats station; and velocity data from the Fall River ADCP station. The locations of the various stations are shown in Figure 2. These data were processed and analyzed to determine important characteristics:

- tides are predominantly semidiurnal (M2) with a range of 1.3 m,
- currents exhibit little vertical structure and are semidiurnal with a maximum speed of approximately 68 cm/s at the Turning Basin and 62 cm/s at the PORTS Fall River location at the mouth of the Taunton River,
- some temperature and salinity stratification occurs during the neap portion of the spring-neap cycle but is broken down during spring tides,
- DO levels are typically higher at depth (averaging 11.7 mg/L) than at the surface (averaging 10.1 mg/L),
- turbidity levels are low averaging 3.5 NTU at the surface and 2.4 NTU at depth.

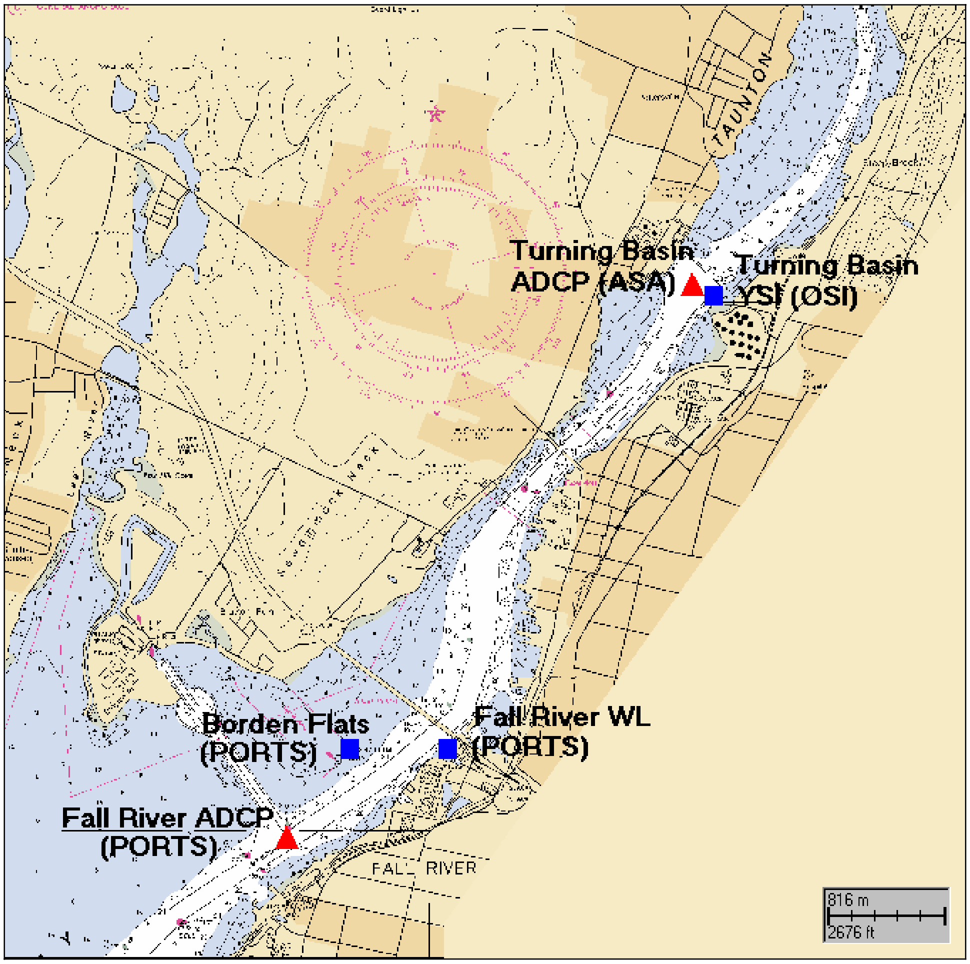


Figure 2. Map showing instrument deployment locations from field survey and nearby NOAA PORTS stations. ADCPs are shown as triangles while other instrument sets are shown as squares.

WQMAP HYDRODYNAMIC MODEL

ASA has developed and applied evolving versions of sophisticated model systems (Swanson 1986, Spaulding et al. 1999) for use in studies of coastal waters for more than two decades. WQMAP, as the model system is known, uses a three dimensional boundary fitted finite difference hydrodynamic model most recently documented by Muin and Spaulding (1997a and b). The model has undergone extensive testing against analytical solutions and has been used for numerous circulation and water quality studies. Some applications particular to dredging studies in the northeastern United States include water quality impacts of dredging and disposal operations in Boston Harbor (Swanson and Mendelsohn 1996); dredged material plume predictions for the Providence River and Harbor Maintenance Dredging Project (Swanson et al. 2000); simulations of sediment deposition from jet plow operations in New Haven Harbor (Swanson et al. 2001); and simulations of sediment transport and deposition from jet plow and excavation operations in the Hudson River (Galagan et al. 2001).

WQMAP Model Application

The grid system used in the boundary-fitted coordinate model system is unique in that grid cells can be aligned to shorelines to best characterize the study area. In addition, grid resolution can be refined to obtain more detail in areas of concern. This gridding flexibility is critical in representing the waters of the Taunton River and Mt. Hope Bay, where geometry is highly variable and complex.

The domain of the hydrodynamic model for this application included the Taunton River, Mt. Hope Bay, the Sakonnet River, portions of the Providence, Kickamuit, Cole and Lee Rivers, and Narragansett Bay as far south as

Newport, RI. Figure 3 shows the large variation in cell size across the model domain. The southern boundary of Narragansett Bay and the Sakonnet River served as an open boundary condition. Cell sizes ranged from in excess of 700 m at the open boundary to ~20 m in the Taunton River where variations in bathymetry and shoreline geometry are complex.

The bathymetry data used in the model was taken from the historical hydrographic survey data CD-ROM set (NGDC 1998), a 1998 USACE survey and from a series of high resolution surveys taken in 2002 by NOAA of the Taunton River. The use of grid refinement together with the high resolution bathymetry data allows the channel and turning basin to be very well defined.

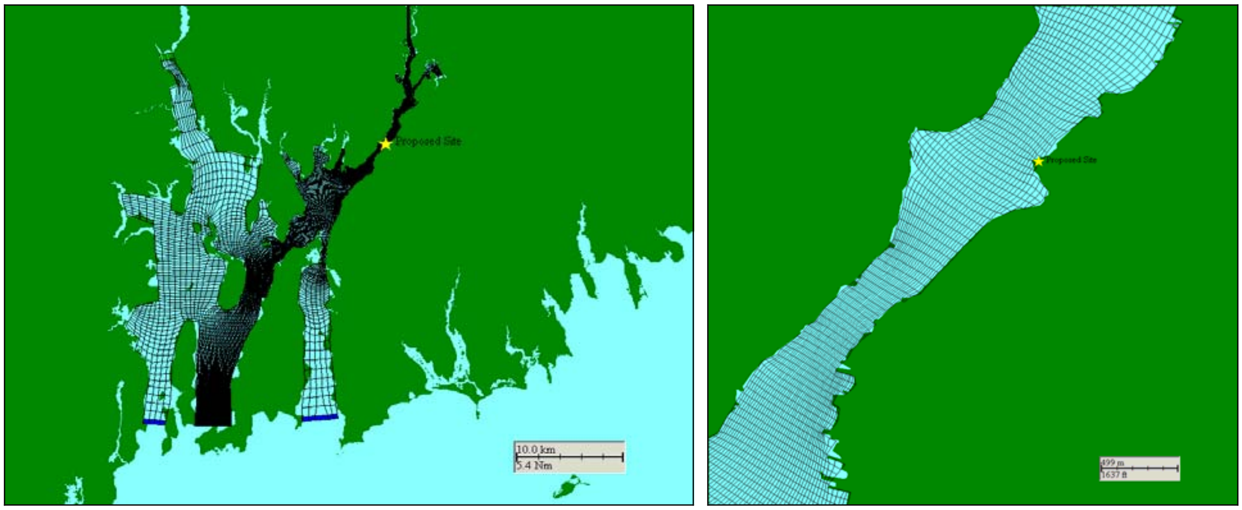


Figure 3. Hydrodynamic model grid for Narragansett and Mt. Hope Bays including the Taunton River (left frame). Hydrodynamic model grid for the lower Taunton River (right frame). The advantages of the boundary-fitted coordinate model system, including grid refinement and boundary conforming cells, are demonstrated here.

WQMAP Model Input

Tidal Boundary

For model calibration, elevation was prescribed at the open boundary using surface elevation data record for this period from the Newport PORTS station in Newport, RI. The raw 6 minute data was filtered using a 3-hour low-pass filter for use in the model. No amplitude or phase adjustments were made at the three entrance locations to Narragansett Bay because the historically-measured differences are less than 1 cm and 2 minutes, respectively. Since the model was driven by actual time series data with a 6-minute time step the small phase differences are masked. The model was not run in baroclinic mode, based on field program results, so there was no need to provide temperature or salinity boundary condition information. The purpose of having the model open boundaries at the entrances to Narragansett Bay was to capture the double flood phenomena that can occur in Mt. Hope Bay (Spaulding and White, 1990).

Surface Wind Stress

Wind data used for model calibration was obtained from the NOAA PORTS Borden Flats station. This station is located approximately 4.0 km from the proposed site. The raw six-minute data (wind speed and direction) was subsampled to one hour intervals using cubic splines and low-pass filtered with a three hour filter for use as input in the model.

River Flow

For the model calibration, data from a series of USGS stream flow gages in the Taunton River watershed was used to model freshwater flow into the Taunton River. The flow data from gages located on the Taunton, Threemile and Segreganset Rivers, were combined and then scaled according to the surface area of the watershed accounted for by these gages to obtain an estimate freshwater flow near the mouth of the Taunton River (Ries, 1990). These data were then filtered with a 3-hour low-pass filter for use in the model. There was no freshwater flow from the Cole River included in the model because it is only 2.7% of the flow in the Taunton River (Ries, 1990) and has no appreciable effect on circulation in Mt. Hope Bay or the Taunton River. No other Narragansett Bay freshwater flow was included in the model either. (Pilson, 1985) estimated that a mean total of only 105 m^3/s enters all of Narragansett Bay. This contrasts to a tidal prism based flow rate of approximately 25,000 m^3/s, thus indicating that the effects of freshwater flow are negligible compared to tidal forcing for this water body.

WQMAP Model Calibration

The hydrodynamic model was calibrated using data obtained from the field program. The hydrodynamic model simulated circulation in the Taunton River and Mt. Hope Bay for the period from 2 – 29 May 2003 using the model inputs described above. Simulated elevations compared well with observations at the Turning Basin ADCP station and the Fall River WL PORTS station. Statistical analysis of the simulated and observed time series at the Turning Basin ADCP station yielded a correlation coefficient of $r = 0.9652$. A similar analysis of the Fall River WL PORTS station gave $r = 0.9989$.

Observed and simulated velocities were rotated to the principal axis of flow (i.e., 42.0º clockwise from true north for the Turning Basin ADCP station, 68.5º clockwise from north for the Fall River WL PORTS station), roughly parallel to the channel, for comparison. Velocities are then compared in terms of flows along and across the channel. Both near-bottom and near-surface velocities compared well for both locations. A quantitative comparison of currents from the hydrodynamic model to observations from both ADCPs (Turning Basin and Fall River) was conducted for the calibration period. This analysis revealed that the hydrodynamic model, without baroclinic effects, was in excellent agreement with the observational data. Model currents were correlated with observed currents with correlation coefficients in the range of 0.7 to 0.8 at both the Turning Basin and the Fall River sites. Furthermore the root mean square (RMS) errors between model currents and observed data were small at both locations, with RMS errors of only 10-15% of the total range in velocities. This level of agreement between model and data falls well within accepted standards of practice (McCutcheon et al., 1990) and argues against the importance of baroclinic effects at this particular location.

WQMAP Model Results

Tide, River and Wind Conditions

An analysis of the field observations and hydrodynamic simulations confirmed that the major force driving circulation in the Taunton River and Mt. Hope Bay is the astronomical tides. Since the purpose of the SSFATE simulations was to predict the distribution of dredged sediments under typical circulation conditions, the particular periods of such simulations were not determined *a priori*. The approach taken here was to develop a set of circulation scenarios that reflect the most likely conditions. These scenarios were comprised of three tidal conditions (spring, mean and neap) and three river flow conditions (high, mean and low).

Tidal conditions were created using just the semidiurnal M2 constituent period (repeating every 12.42 hr), since that period is dominant, to create the surface elevation boundary condition at the open boundary. The amplitude of the M2 constituent, as determined by tide statistics from NOAA National Ocean Service for Newport, RI, was scaled to approximate the neap, mean and spring tidal conditions. Freshwater was assumed to flow into the Taunton River at three constant rates of 59.1 m^2/s, 29.7 m^3/s and 9.4 m^3/s. These correspond to the mean March flow (high), mean annual flow and mean August flow (low), respectively, in the Taunton River as determined by Ries [1990]. Wind forcing was not included in these runs because of its small effect on currents in the river.

The model runs are idealized circulation scenarios, and are not meant to precisely simulate an actual period of time. The currents used in the runs are meant to be representative of typical spring, mean, and neap tide and high, mean and low river flow conditions. While these currents are based on a successfully calibrated model, the tidal and river forcings used in the model scenarios are generic and the resulting currents can not be compared directly to observational data from any particular period.

Example Circulation Results

An example of the hydrodynamic model results representing spring tidal conditions at mean river flow are shown as contours of current speeds during maximum flood in the lower Taunton River for surface and bottom layers (Figure

4). Results show a decrease in the magnitude of velocities from the surface layer to the bottom for all tidal forcing conditions (e.g., left frame vs. right frame). At a given depth, spring forcing results in the greatest velocities while neap forcing results in the smallest velocities.

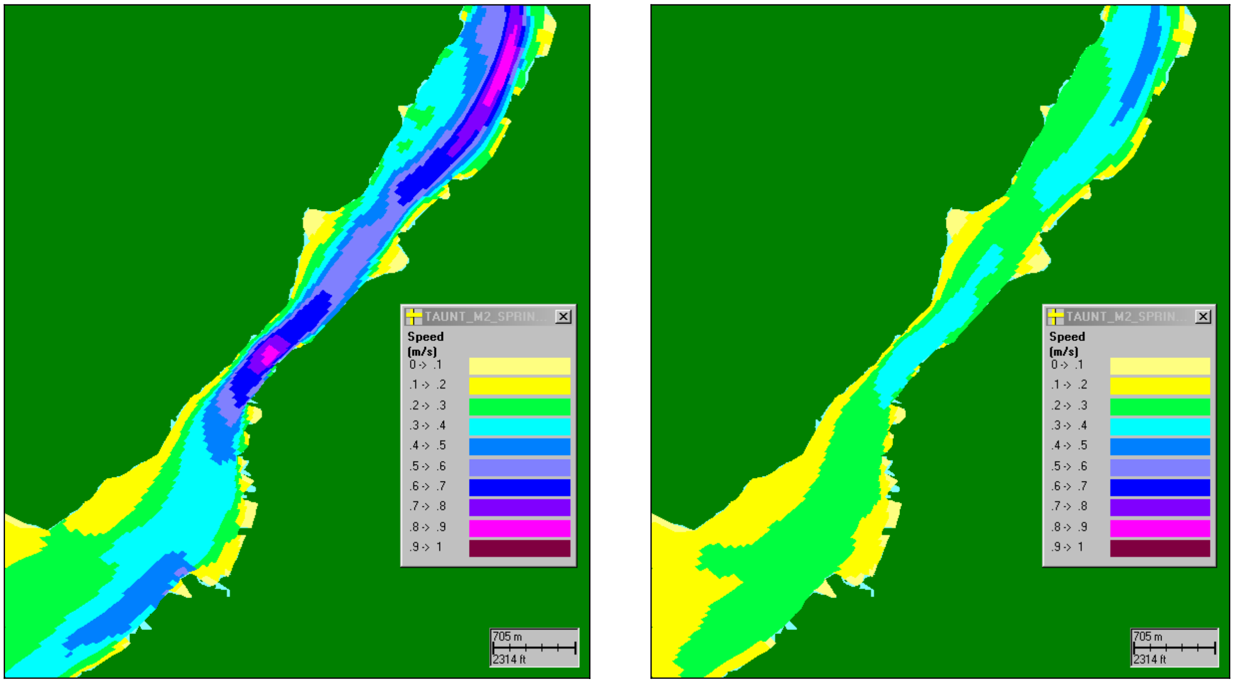


Figure 4. Surface (left frame) and bottom (right frame) speed contours in the lower Taunton River during maximum flood for spring forcing.

SSFATE DREDGING MODEL

SSFATE Model Description

For this application, SSFATE, a model jointly developed by ASA and the U.S. Army Corps of Engineers (USACE) Environmental Research and Development Center (ERDC) was used to simulate the sediment suspension and deposition from dredging operations. It has been documented in a series of USACE Dredging Operations and Environmental Research (DOER) Program technical notes (Johnson et al. 2000 and Swanson et al. 2000), at the World Dredging Conference (Anderson et al. 2001) and the Western Dredging Association Conference (Swanson et al., 2004), and a number of ASA technical reports demonstrating successful application to dredging and cable burial operations.

SSFATE (Suspended Sediment FATE) computes suspended sediment distributions and deposition patterns resulting from dredging operations and contains the following features:

- Ambient currents can either be imported from a variety of numerical hydrodynamic models.
- Computational model predicts the transport, dispersion, and settling of suspended sediment released to the water column during dredging using a random walk procedure.
- Model simulates suspended sediment source strength and vertical distribution from mechanical (e.g., clamshell) or hydraulic (e.g., cutterhead, hopper) dredges and water jet trenchers.
- Multiple sediment types or fractions can be simulated simultaneously.
- Model output consists of concentration contours in both horizontal and vertical planes, time series plots of suspended sediment concentrations, and the spatial distribution of sediment deposited on the sea floor.
- Sediment particle movement and concentration evolution can be animated over Geographic Information System (GIS) layers depicting sensitive environmental resources and areas.

Depending on the resolution of the numerical grid employed, SSFATE can make predictions close to the dredging operation; however, the processes modeled are not near field effects of bucket activities but far field (~25 m [80 ft]) effects in which the mean transport and turbulence associated with ambient currents dominate. A particle-based model predicts the transport and dispersion of the suspended material. Particle advection is based on the simple relationship that a particle moves linearly with a local velocity, obtained from the hydrodynamic model, for a specified model time step. Particle diffusion is assumed to follow a simple random walk process.

The particle model allows the user to predict the transport and fate of classes of settling particles, e.g., sands, silts, and clays. The fate of multi-component mixtures of suspended sediments is predicted by linear superposition. The particle-based approach is extremely robust and independent of the grid system. Thus, the method is not subject to artificial diffusion near sharp concentration gradients and is easily interfaced with all types of sediment sources.

In addition to transport and dispersion, sediment particles also settle at some rate through the water column to the bottom. Settling of mixtures of particles, some of which may be cohesive in nature, is a complex but predictable process with the different size classes interacting, i.e., the settling of one particle type is not independent of the other types. In addition, the clay-sized particles, typically cohesive, undergo enhanced settling due to flocculation. These processes have been implemented in SSFATE and are based on previous USACE studies (Teeter, 1998).

At the end of each time step the concentration of each sediment class as well as the total concentration is computed on a dynamic numerical grid. The size of all grid cells is the same, with the total number of cells increasing as the suspended sediment moves away from the dredging source to encompass the plume. The settling velocity of each particle size class is computed along with a deposition probability based on shear stress. Finally the deposition of sediment from each size class from each bottom cell during the current time step is computed and the calculation cycle begins anew. Deposition is calculated as the mass of sediment particles that accumulate over a unit area.

Estimation of Source Strength

Most of the sediment release from clamshell bucket dredging operations takes place when the bucket penetrates the river bottom. Additional sediment escapes as the bucket is raised through water column; when sediment overflows from the bucket, overlaying water is vented, and sediment from the side of bucket is washed off. Dredging losses estimated from total suspended solids (TSS) concentrations observed in past mechanical dredging operations (Hayes and Wu, 2001) are shown in Table 1.

Table 1. Sediment loss from mechanical dredging operations (from Hayes and Wu, 2001, Table 2).

Locations	Loss (%)	Scow Overflow	Bucket Type	Source
Thames River	0.88	Yes	Open	Bohlen et al (1979)
St. Johns River	0.16	Yes	Open	Collins (1995)
St. Johns River	0.10	Yes	Closed	Collins (1995)
Black Rock Harbor	0.28	Yes	Open	Collins (1995)
Calumet River	0.25	Yes	Open	Hayes, et al (1988)
Boston Harbor	0.66	No	Open	Hayes et al. (2000)
Boston Harbor	0.22	No	Closed	Hayes et al. (2000)

Reported values vary significantly as various individual project conditions must be considered (e.g., operational factors, sediment physical characteristics). Also the sediment loss can not be measured directly, but must be estimated based on observations at some distance from the bucket. To obtain the best estimate, the TSS observation is collected as close to the bucket as possible and contributions of water overflowing the scow must be considered. The sediment losses ranged from 0.16% to 0.88% for an open bucket and from 0.10% to 0.22% for a closed bucket.

The sediment losses cited above for the Boston Harbor Study (Hayes et al., 2000) were determined representative and expected to be the most equivalent to the proposed dredging. Hayes and Wu (2001) report that during the dredging operations monitored the bucket removed approximately 0.6 m of surface silt and 0.3 m of stiff virgin clay. It was assumed that the sediment would be similar to surface sediments in the Taunton River and Mt. Hope Bay since this stiff clay would fall as clumps and not generate significant free clay particles entering the water column. Therefore, for the dredging required for this project, the sediment loss of 0.22% for closed bucket and 0.66% for open bucket from the Boston analysis were selected since no scow overflow existed, both open and closed buckets were examined, bucket size (26 yd^3) was roughly similar to the one planned in this project, and both projects have roughly equivalent sediment characteristics.

Actual TSS strength (sediment release rate) used as model input is a function of the bucket dredge production (based on bucket cycling operating continuously at an optimum daily production rate that reflects dredge cut, water depth, physical sediment properties and dredge repositioning), the density and solid fraction of the sediment and the loss rate,

Sediment release rate = (production) x (solid fraction) x (loss rate) x (sediment density)

Table 2 lists each parameter for the designated sites that were selected for characteristic dredging operation and sediment type. The Turning Basin is located adjacent to the proposed terminal site at the upstream terminus of the Federal Channel, the Massachusetts Channel (S-bend) is located between the Braga and Brightman Street Bridges and the RI Channel is located at the state line between Rhode Island and Massachusetts (Figure 1). The buckets included both closed and open types with two different sizes, 15 and 26 yd^3, closed (0.22%) and open (0.66%) bucket loss rates plus a worst case of 1.32%, production rates, from 2000 to 10000 yd^3/day based on the project dredging plan (C2D, 2003) and solid fractions based on measurements. A request for a higher loss rate was made by state and federal agencies charged with reviewing the project so a value of 2.0% was also evaluated even though the observed range for open bucket loss rates (Table 1) is much lower. In addition, new observations taken in Chesapeake Bay by the U.S. Army Corps of Engineers and reported at the 2004 Western Dredging Association Conference (Swanson, et al., 2004) reinforce the use of a lower open bucket loss rate, in that case, of 0.5%.

Table 2. Release rates used in SSFATE modeling.

Dredge Site	Bucket	Loss Rate (%)	Production (yd^3/day)	Solids (%)	Release Rate (kg/sec)
Turning Basin (Surface)	Closed – 26 yd^3	0.22	10000	31.8	0.164
	Open – 15 yd^3	0.66	5800	31.8	0.287
	Open – 26 yd^3	0.66	10000	31.8	0.497
	Open – 26 yd^3	1.32	10000	31.8	0.994
	Open – 26 yd^3	2.00	10000	31.8	1.506
Turning Basin (Native)	Open – 15 yd^3	0.66	4000	68.7	0.429
	Open – 26 yd^3	0.66	7000	68.7	0.744
	Open – 26 yd^3	1.32	7000	68.7	1.487
	Open – 26 yd^3	2.00	7000	68.7	2.253
MA Channel (S-bend)	Closed – 26 yd^3	0.22	4000	26.1	0.054
	Open – 26 yd^3	0.66	4000	26.1	0.161
	Open – 26 yd^3	1.32	4000	26.1	0.322
	Open – 26 yd^3	2.00	4000	26.1	0.488
RI Channel (Stateline)	Closed – 15 yd^3	0.22	2000	27.9	0.029
	Open – 15 yd^3	0.66	2000	27.9	0.086
	Open – 15 yd^3	1.32	2000	27.9	0.172
	Open – 15 yd^3	2.00	2000	27.9	0.261

One of the major factors that control TSS concentration is how fast the sediment settles out from water column. In general, coarser materials have higher settling velocities and finer sediments (0-75 micron, clay and silt) take longer to settle out. By examining distributions of sediment type for the site, basic settling characteristics can be estimated. In the SSFATE model, the sediment distribution is represented with five distinct size classes outlined below in Table 3. These differ from other physical descriptions and classification methods used in other portions of the dredging and disposal effort but are required for this modeling effort.

Table 3. Sediment class sizes used in SSFATE.

Class	Size (micron)	Name
1	0-7	Clay
2	8-35	Fine silt
3	36-74	Coarse silt
4	75-130	Fine sand
5	>130	Coarse sand

Figure 5 shows fraction distributions of sediment type and solid fractions averaged over the dredge reaches. Data from and locations of the original core samples that make up these averages can be found in C2D (2003). The bulk sediment physical analytical results detailed only the total percentage of silts; however, for the purposes of this modeling effort, the silt percentage was evenly split between fine and coarse silt as required for model input.

The range of fine grain (silt and clay) surface sediments for dredging operations in Boston Harbor as reported in ENSR (2001) was 53% to 95%. Most of the stations (10 of 12) stations ranged from 69% to 95%. The range for surface sediments in the Taunton River and Mt. Hope Bay (Figure 5) ranged from 67% to 93%. Since the sediment grain size distributions are similar, the Taunton River and Mt. Hope Bay dredging release rates were assumed to be similar to Boston Harbor release rates (0.22 to 0.66%). To be conservative in the analysis the loss rate was doubled to 1.32% and some runs used the overly conservative loss rate value of 2.00%.

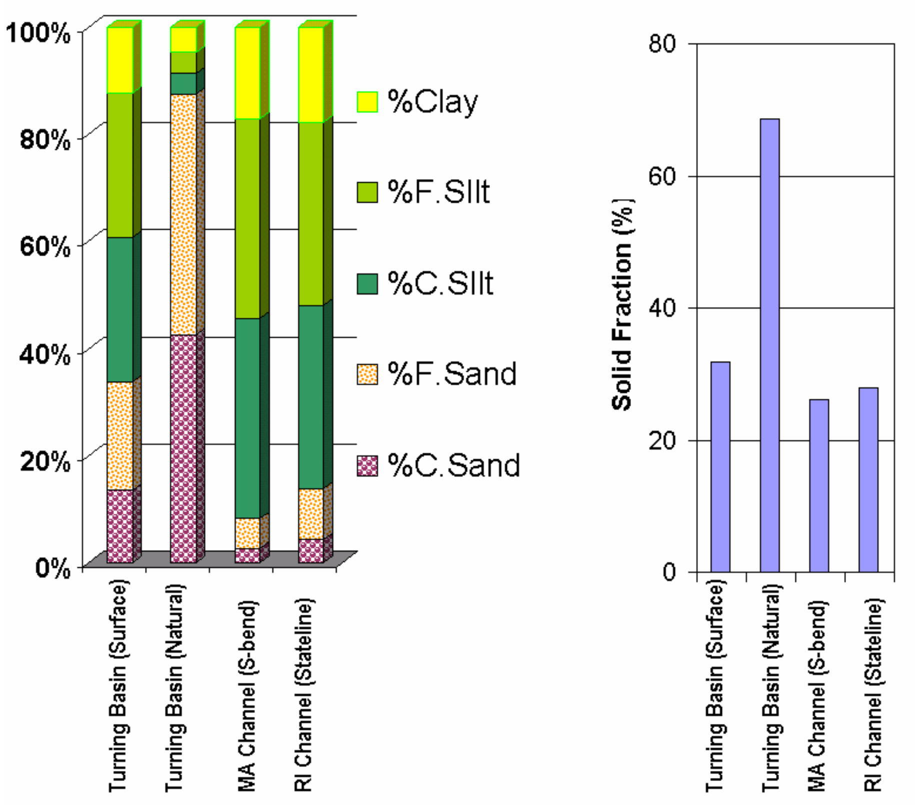


Figure 5. Sediment grain size distributions (left frame) and solid fractions (right frame) at the proposed dredge areas.

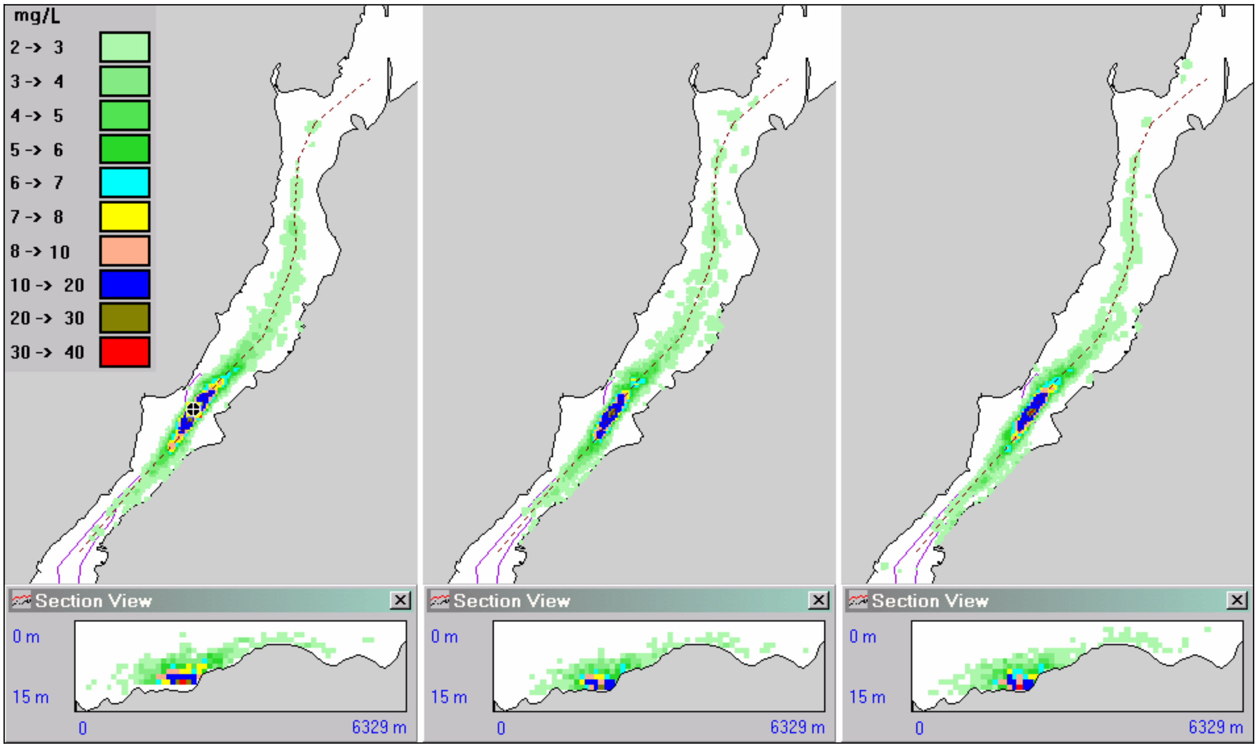
SSFATE Modeling Results for Different Tides and River Flow

SSFATE model simulations that represent clamshell dredging were conducted for various flow conditions and the range of dredge loss rates discussed in the previous section. The environmental flow conditions were a combination of tidal ranges (neap, normal and spring) and river discharges (low, normal and high).

Four dredging sites: Turning Basin (Surface), Turning Basin (Native), MA Channel (S-bend) and RI Channel (Stateline), were selected to represent typical sediment types and associated dredging operations (Figure 1). For brevity, not all sites are presented here since results are similar among the sites relative to the environmental flow conditions. Instead the Turning Basin (Surface) site results with a loss rate of 0.66% from a 19.9 m^3 (26-yd^3) open bucket are shown as illustrative of the SSFATE results.

TSS concentration distributions due to clamshell dredging became quasi-steady state after several tidal cycles (~2 days) but the simulations were run for a total of seven days conservatively assuming continuous optimum dredge production. TSS concentration is a strong function of the local flow speed with highest TSS during slack tide and lowest TSS during maximum flood or ebb flows. The instantaneous concentrations are significantly smaller than the maximum TSS concentrations presented here. The dredge is assumed to remain in one place and the maximum concentrations are determined as the highest concentration at any location in the water column over the simulation run with the dredge in that one location when evaluated at hourly intervals over a seven-day period. The numerical results are presented in excess of background or ambient TSS concentrations, taken as 11 mg/L from a combination of the analysis of the river water used in the elutriate analyses (C2D, 2003) and past dry and wet weather TSS measurements (Boucher, 1991; Turner et al., 1990). The subsequent biological effects analyses used the actual SSFATE hourly output.

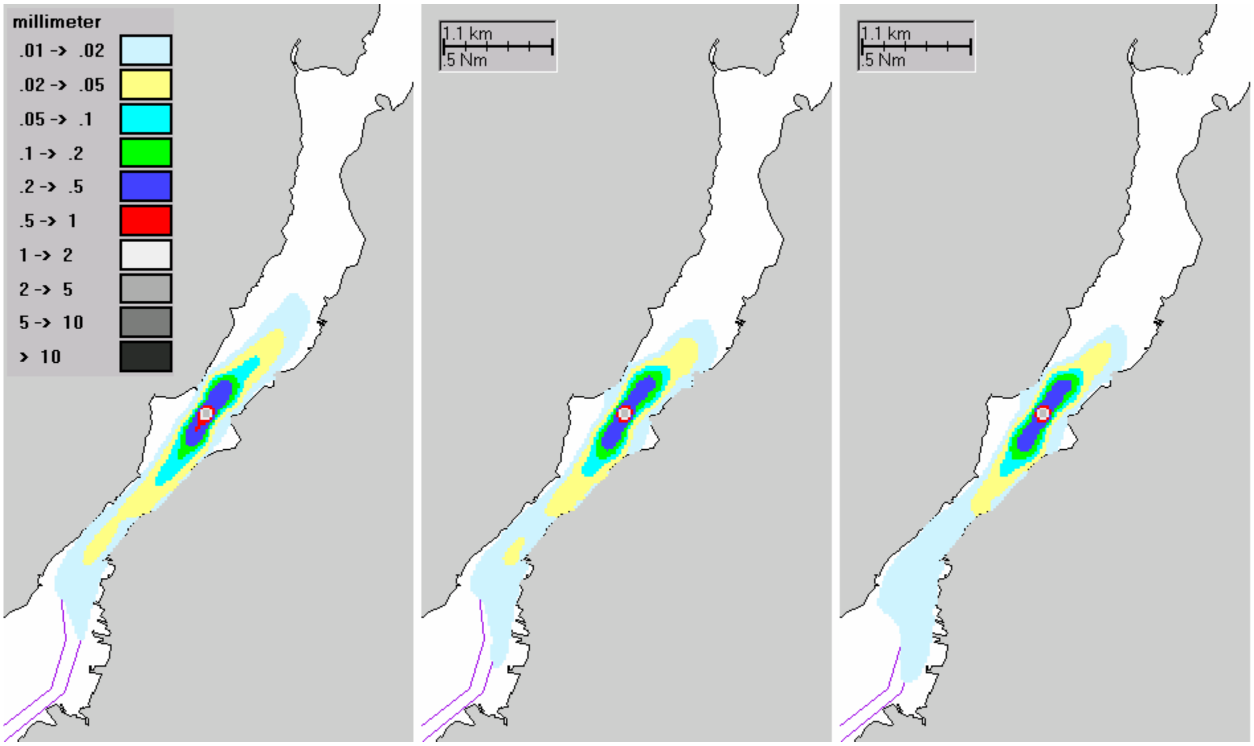
Figure 6 shows the maximum excess TSS concentration (in mg/L) for the Turning Basin (Surface) site for three representative environmental conditions. Each frame in Figure 6 shows a plan view and an along-river vertical section view. The excess TSS concentrations are shown as color coded contours according to the legend shown, ranging from 2 to 40 mg/L. The mean tide / mean river flow results (left frame) show a relatively small, elongated area centered at the site. Spring tide results in similar elongated areas with little difference between low and high river flows. All cases show that the maximum concentration is found at a location close to the sediment surface (river bottom) at approximately 30 mg/L dropping to 5 mg/L within 500 m up and downstream of the site.



Mean tide/Mean river **Spring tide/High river** **Spring tide/Low river**

Figure 6. Maximum excess suspended sediment water column concentration for the Turning Basin (Surface) site with 0.66% loss rate and 26 yd^3 open bucket. The section views are made along the dotted line shown. Left frame: mean tide with mean river flow, Center frame: spring tide with high river flow, Right frame: spring tide with low river flow.

Figure 7 shows the thickness of sediment deposition on the bottom (in mm) at the end of the 7-day simulation for native material dredging at the Turning Basin. The sediment deposition thickness presented in the figures in this section are based on the mass of particles only and do not include the fluffing effects of entrained water since the water content is unknown. Although the rate of deposition becomes quasi-steady state like the water column TSS concentration, bottom deposition (sediment thickness) grows linearly as time progresses. The bottom deposition contours are shown as color coded contours according to the legend shown, ranging from 0.01 mm to greater than 10 mm. It should be noted that this is a log scale extending over two orders of magnitude. The smaller thicknesses (< 0.1 mm), although predicted by the model, are insignificant. The SSFATE deposition results show an elongated area centered at the site because most of the material is coarse grain and quickly falls out of the water column. The mean tide / mean river flow results (left frame) show a relatively small, elongated area centered at the site similar to the water column concentrations. Spring tide results in similar elongated areas with little difference between low and high river flows (center and right frame, respectively). All cases show that the maximum deposition is approximately 5 mm surrounding the dredging site dropping to 0.2 mm within 500 m up and downstream of the site.



Mean tide/Mean river **Spring tide/High river** **Spring tide/Low river**

Figure 7. Thickness of sediment deposition on bottom after seven days for the Turning Basin (Surface) site with 0.66% loss rate and a 26-yd^3 open bucket. Left frame shows mean tide with mean river flow, center frame shows spring tide with high river flow and right frame shows spring tide with low river flow.

SSFATE Modeling Results for Different Dredging Sites

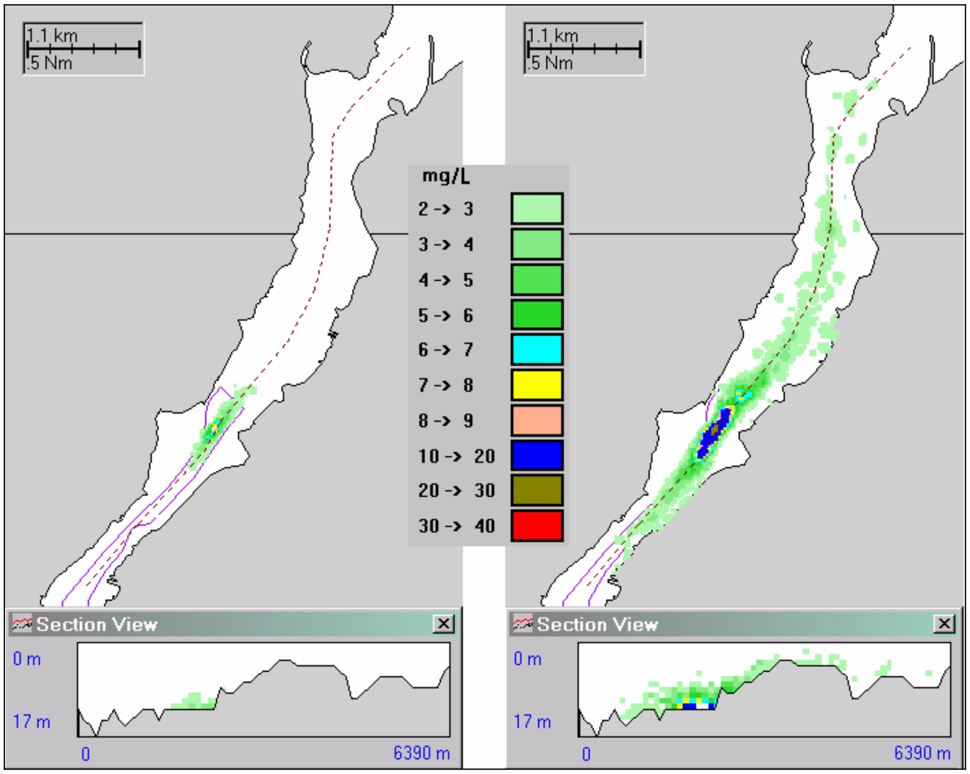
This section shows representative results for the different dredging sites. For purposes of comparison the same environmental flow conditions, spring tide with high river discharge, which resulted in the largest area affected, are shown. A constant loss rate of 0.66% for an open bucket was selected for graphical presentation of bottom area affected. All sites presented used a 19.9 m^3 (26-yd^3) open bucket except for the RI Channel (Stateline) site, which used a 11.5 m^3 (15 yd^3) bucket. The Turning Basin cases are presented together first followed by the MA and RI channel cases.

Results at Turning Basin Site

As explained above TSS concentration distributions due to mechanical dredging became quasi-steady state after several tidal cycles (~2 days). The maximum TSS concentrations presented here are the maximum instantaneous

Table of Contents

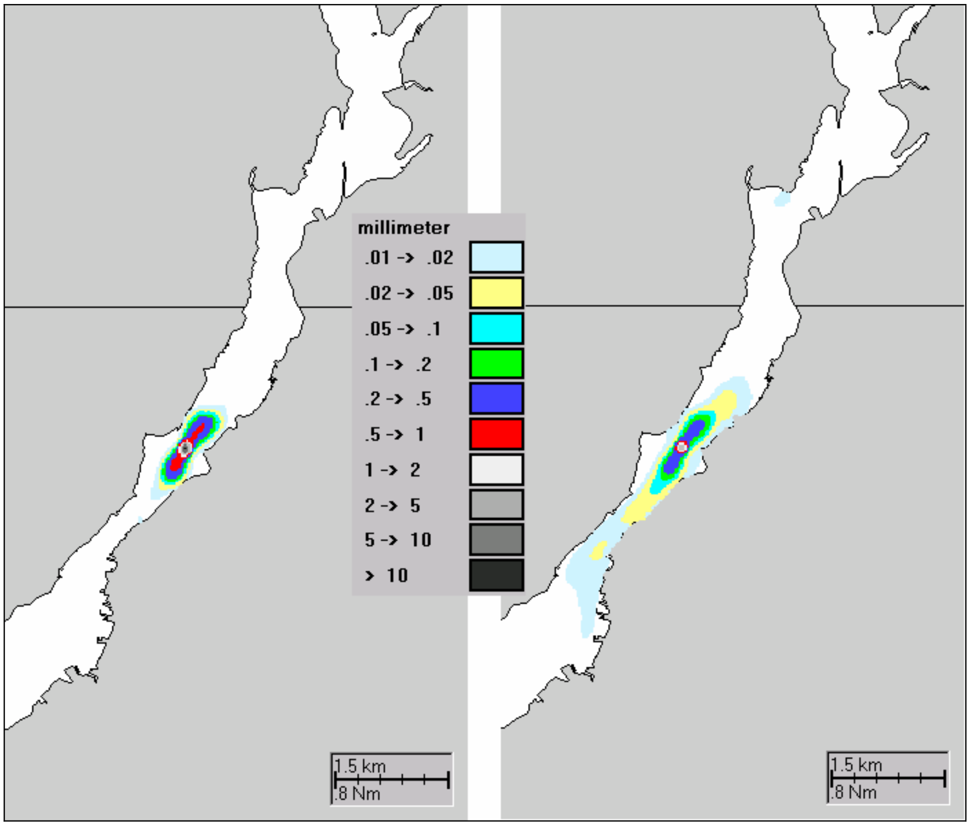
concentrations that occur at a particular cell in the SSFATE model grid. They are in excess of background or ambient TSS concentrations, taken as 11 mg/L from analysis of the site water used for elutriate analyses. Figure 8 shows the maximum excess TSS concentration (in mg/L) in plan view and an along river vertical section view for the Turning Basin native sediments in the left frame and the Turning Basin surface sediments in the right frame. The excess TSS concentrations are shown as color coded according to the legend shown, ranging from 2 to 40 mg/L. The release rate for the surface (river bottom) material was 0.497 kg/s while that for the native material was 50% higher, at 0.744 kg/s. The native material results show a relatively small, elongated area centered at the site because most of the material is coarse grain and quickly falls out of the water column. The surface, fine grain material results show a larger elongated area. Both cases show the maximum concentration is close to the river bottom.



Native **Surface**

Figure 8. Maximum excess suspended sediment water column concentration for Turning Basin dredging with 0.66% loss rate and 26 yd^3 open bucket. The section views are made along the dotted line shown. The left frame shows the sub-surface native material results and the right frame shows the surface material results.

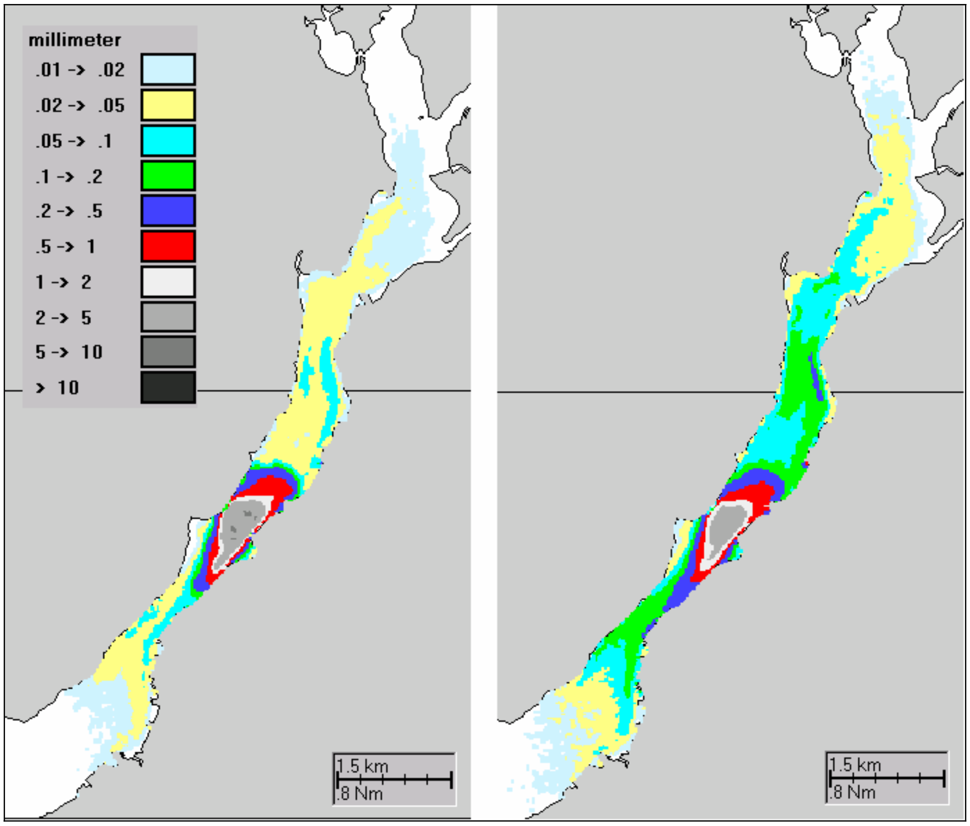
Figure 9 shows the thickness of sediment deposition on the bottom (in mm) at the end of the 7-day simulation for both the native (left frame) and surface (right frame) sediments at the Turning Basin. Although the rate of deposition becomes quasi-steady like the water column TSS concentration, bottom deposition (sediment thickness) grows linearly as time progresses. The bottom deposition contours are shown as color coded according to the legend shown, ranging from 0.01 mm to greater than 10 mm. The native material results show a relatively small, elongated area centered at the release site because most of the material is coarse grain and quickly falls out of the water column. The surface, fine grain material results show a larger elongated area at small thicknesses. The native material results show greater thicknesses nearest the release site.



Native **Surface**

Figure 9. Thickness of sediment on the bottom after seven days deposition at the Turning Basin. The sub-surface native material results are shown in the left side of the frame and the surface material results are shown in the right side of the frame.

Figure 10 shows the thickness of sediment deposition on the bottom (in mm) at the end of a 57-day simulation for the native materials and a 70-day simulation for the surface materials at the Turning Basin based on the estimated dredging duration developed in the dredging program (C2D, 2003), again assuming continuous optimum daily dredge production throughout the entire simulation period. These simulations were different from the 7-day simulations in that the actual dredging location was moved in an east west pattern from north to south in the proposed Turning Basin to better simulate actual conditions in this relatively confined area. The resulting deposition patterns are somewhat wider across the river as a result. Both the native coarse grain material results (left frame) and the surface fine grain material results (right frame) show an area centered over the dredging footprint that is somewhat elongated. Total thicknesses are greater than the 7-day results because the simulation is 57 or 70 days long and sediment continues to accumulate over the period. The surface, silty material results show a larger area at small thicknesses compared to the native, coarse material results.



Native **Surface**

Figure 10. Thickness of sediment deposition on bottom after 57 days at the Turning Basin (Native) site (left frame) and 70 days at the Turning Basin (Surface) site (right frame) with 0.66% loss rate and a 26-yd^3 open bucket.

The effect of different loss rates on bottom deposition was also examined. Figure 11 shows the areal extent of 21-day bottom deposition above a threshold (0.5 mm) for waters less than 5 m for a range of loss rates. The duration, thickness and water depth are related to winter flounder egg development. Figure 11 shows the areas for loss rates of 0.66, 1.32 and 2.00% for a 19.9 m^3 (26 yd^3) bucket as well as a 0.66 % loss rate for a 11.5 m^3 (15 yd^3) bucket in shades of gray. The blue areas indicate water depths less than 5 m. Deposition is primarily localized in the area just upstream of the turning basin. The dredge production was conservatively assumed to be continuous at a rate of optimum daily production.

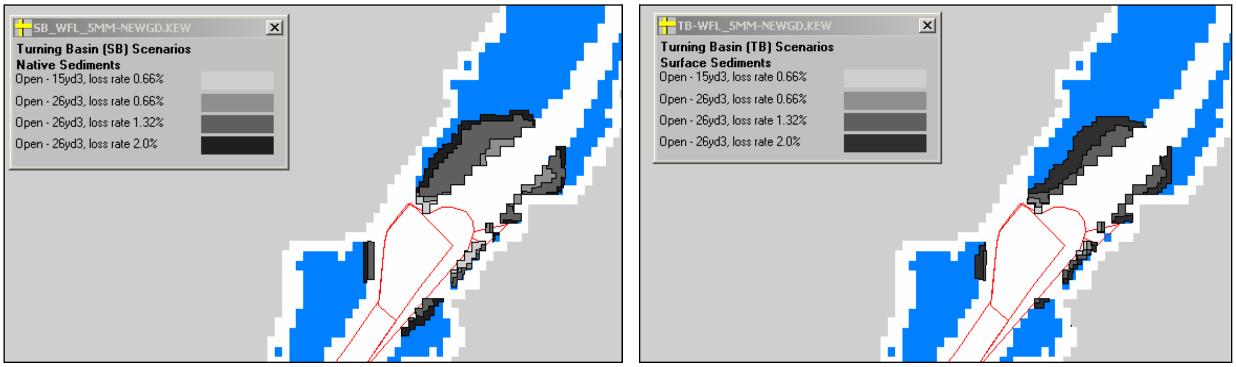
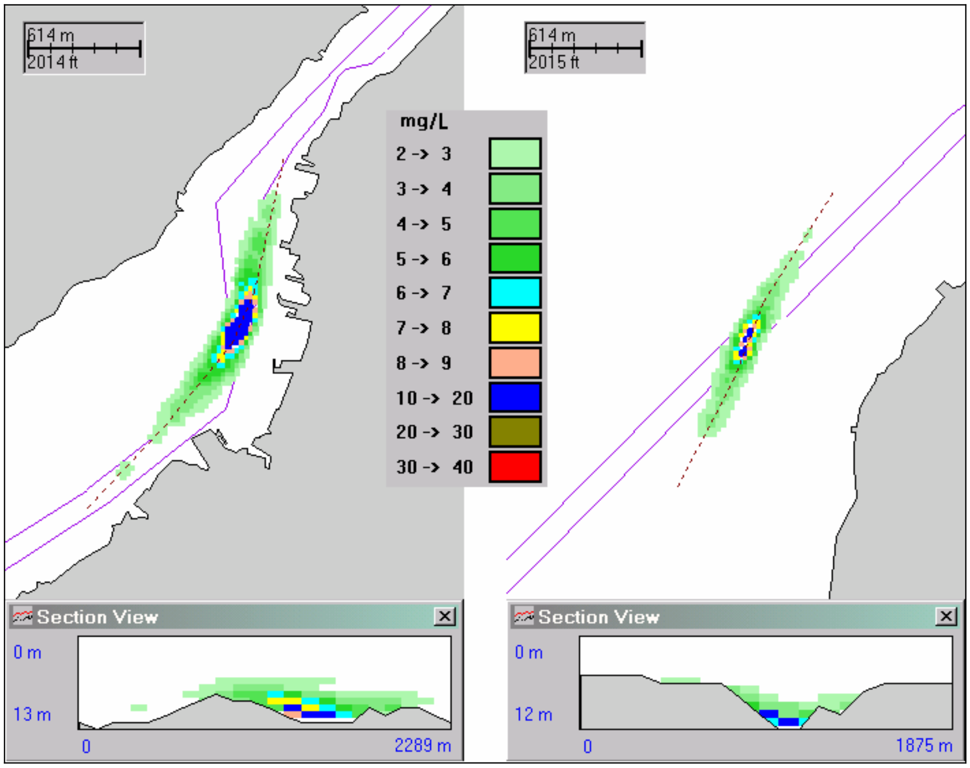


Figure 11. Bottom deposition areas for the Turning Basin site for Native sediments (left frame) and Surface sediments (right frame). The larger areas in blue show water depths less than 5 m.

Results at the Navigation Channel Sites

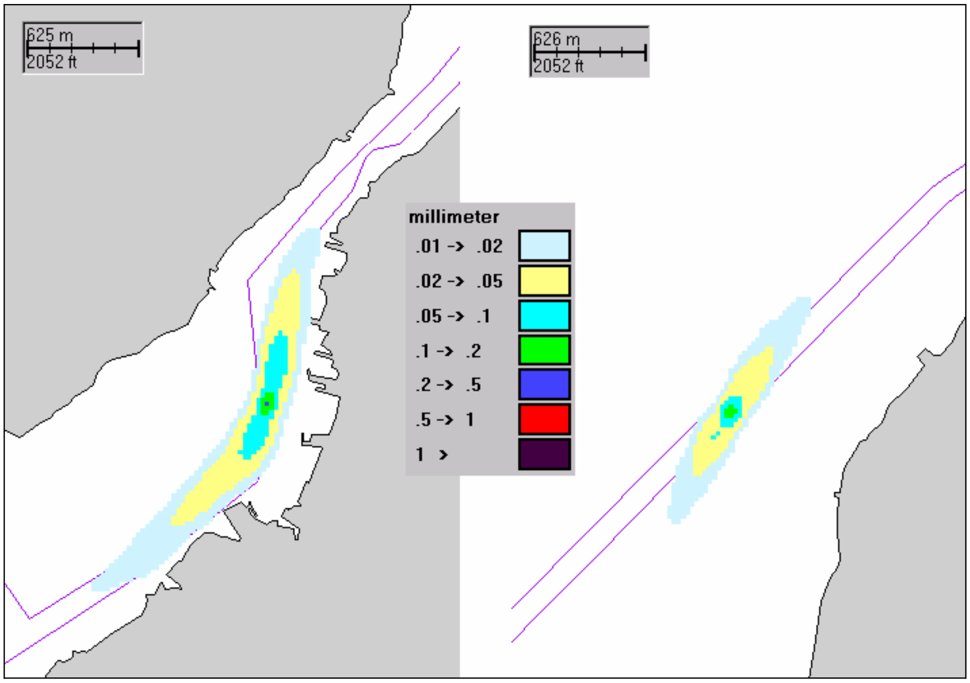
Figure 12 shows plan view and vertical section views of the maximum excess TSS concentration in mg/L for the two navigation channel sites: MA Channel (S-bend) site and RI Channel (Stateline) site. The excess TSS concentrations are shown as color coded according to the legend shown, ranging from 2 to 40 mg/L. The release rate for the MA Channel (S-bend) was 0.161 kg/s while the release rate for the RI Channel (Stateline) was 47% lower, at 0.086 kg/s due to the smaller bucket and a lower dredge production rate. The MA Channel (S-bend) results (left frame) show a curved, elongated area centered at the site consistent with the direction of water flow there. The RI Channel (Stateline) results (right frame) show a smaller elongated area with the axis of the area aligned with the flow direction. Similar to the turning basin results, both cases show that the maximum concentration is close to the bottom.



MA Channel (S-bend) **RI Channel (Stateline)**

Figure 12. Maximum excess suspended sediment water column concentration for navigation channel dredging with a 0.66% loss rate and a continuous optimum dredge production. The section views are made along the dotted line shown. The left frame shows the results at the MA Channel (S-bend) site using a 26 yd3 open bucket and the right frame shows the results for the RI Channel (state line) site using a 15 yd3 bucket.

Figure 13 shows plan views of the thickness of sediment deposition on the bottom (in mm) at the end of the 7-day simulation for both the MA (S-bend) and RI (Stateline) sites. Although the rate of deposition becomes quasi-steady state like the water column TSS concentration, bottom deposition (sediment thickness) grows linearly as time progresses. The bottom deposition contours are shown as color coded according to the legend shown, ranging from 0.01 mm to greater than 10 mm. The MA Channel (S-bend) results (left frame) show a deposition area similar in shape to the water column concentration area, again consistent with the direction of water flow there. The RI Channel (Stateline) results (right frame) also show a deposition area similar to the water column concentration area, again with an orientation consistent with the axis of the flow direction.



MA Channel (S-bend) **RI Channel (Stateline)**

Figure 13. Thickness of sediment deposition on the bottom after seven days at the Massachusetts Channel (left frame) using a 26-yd^3 open bucket and at the Rhode Island Channel (right frame) using a 15-yd^3 open bucket, both using a continuous optimum dredge production with a 0.66% loss rate.

The effect of different loss rates on bottom deposition at these sites was also examined. However there was no area that experienced a 21-day bottom deposition above a threshold (0.5 mm) for waters less than 5 m.

BIOLOGICAL EFFECTS ANALYSIS

The biological effects analysis was designed to determine if any species or life stages of those species inhabiting the area might be affected by either the predicted water column concentrations or bottom deposition patterns. The evaluation was performed in a stepwise manner:

> First, a screening analysis was performed to determine if the minimum effects threshold would be exceeded in the habitats occupied by the species and life history stage for any duration of exposure. If concentrations in the water or thickness on the bottom never exceed the minimum threshold for the species and life stage over any time period, consideration of duration of exposure was unnecessary.
>
> Second, for exposures greater than the minimum threshold, duration of exposure was evaluated to estimate a potential effects area. Both lethal and sublethal effects were evaluated.

The minimum effects concentration in the water column (including background) for any species was not exceeded at any time in all the SSFATE scenarios examined. Thus, in none of the scenarios examined were lethal or sublethal effects levels exceeded in the water column. This also infers that anadromous fish migrating up and down the Taunton River would not have sublethal or lethal effects from suspended sediment concentrations caused by the dredging. The migration of these fish will also not be blocked, as the sediment plume will not extend across the entire cross-section of the river. In the worst-case single hour, the threshold of concern for behavioral effects on migrating fish (20 mg/L) only extends less than 25% across the river.

For deposited sediments, the minimum effects thickness was exceeded for only one species and life history stage (winter flounder eggs) for selected modeled scenarios at a discreet time of the year (January through April) in discreet areas (not widespread). For all other species and life stages, there would either be no exposure (i.e., no demersal life stage in the area where dredging-related suspended sediments would settle) or the exposure would not exceed levels of concern. These model results were subsequently incorporated into the proposed project dredging plan.

CONCLUSIONS

A modeling analysis was performed to assess the dredge-induced suspended sediment transport and deposition from a proposed dredging operation in Mt. Hope Bay and the Taunton River, located in southeastern Massachusetts. Two models were used: a hydrodynamic model (WQMAP) to predict the circulation in the area and a sediment transport model (SSFATE) to predict water column concentrations and bottom deposition patterns from dredging operations.

A field program was conducted to provide information for calibration of the hydrodynamic model. The tides were found to be predominantly semidiurnal (M2) as were the currents, which exhibited little vertical structure. Slight temperature and salinity stratification occurred during the neap portion of the spring-neap cycle but was completed broken down during spring tides so that the flow could be considered barotropic.

The WQMAP hydrodynamic model was applied in a three dimensional mode to Mt. Hope Bay and the Taunton River and successfully calibrated to data. The model was then run for a series of different tidal regimes (neap, mean and spring) and river flows (low, mean and high) to establish a range of velocity conditions for the sediment transport model (SSFATE).

The SSFATE model was applied to test sensitivity to the range of environmental conditions. All cases showed a relatively small, elongated area centered at the site with the maximum concentration close to the sediment surface (river bottom) at approximately 30 mg/L dropping to 5 mg/L within 500 m up and downstream of the site. In a similar manner, all cases showed that the maximum deposition was approximately 5 mm surrounding the dredging site dropping to 0.2 mm within 500 m up and downstream of the dredge.

The SSFATE model was then applied to three representative sites: at the Turning Basin in the lower Taunton River and two representative channel locations in Mt. Hope Bay and the Taunton River. The SSFATE model simulated both maintenance (fine grain) and parent (native, coarse grain) materials for different clamshell bucket dredge technologies (sizes and configurations) and production rates. Bucket loss rates from other studies were evaluated for use in this application and values of 0.22% for closed bucket and 0.66% of open bucket chosen. Additional loss rates of 1.32 and 2.00% were also evaluated, in response to agency requests, although they were considered very conservative. Furthermore, the modeling conservatively assumed continuous, consecutive optimum daily dredge production rates over multi-day simulation period. Sediment characterization (grain size distribution and solids fraction) was developed from analysis of sediment cores. The modeling results indicate that the channel locations in Mt. Hope Bay and the Taunton River did not exhibit significant levels of either water column concentration or deposition thickness; while, when dredging parent material at the Turning Basin adjacent to the proposed terminal, some potential effects to winter flounder eggs due to sediment deposition may be of concern during a portion of the year necessitating operating restrictions.

REFERENCES

Anderson, E., B. Johnson, T. Isaji and E. Howlett. (2001). "SSFATE (Suspended Sediment FATE), a model of sediment movement from dredging operations." Presented at *WODCON XVI* World Dredging Congress, 2-5 April 2001, Kuala Lumpur, Malaysia.

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

C2D, (2003). "Dredging Program, A focused compilation of the environmental planning factors affecting the dredging and subsequent upland reuse to support navigational shipping requirements", Concept 2 Delivery, Inc., December 2003.

Chinmen, R.A. and S.W. Nixon. (1985). "Depth-area-volume relationships in Narragansett Bay", NOAA/Sea Grant Marine Technical Report 87. Graduate School of Oceanography, The University of Rhode Island.

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.

ENSR (ENSR Marine & Coastal Center), (2001). "June 2000 benthic survey of Boston Harbor Navigational Improvement Project confined aquatic disposal (CAD) cells". Prepared for Massachusetts Coastal Zone Management, September 2001.

Galagan C., Swanson, C., and T. Isaji. (2001). "Simulations of Sediment Transport and Deposition from Jet Plow and Excavation Operations for the Cross Hudson Project", Prepared for Environmental Science Services, Inc. Wellesley, MA. ASA Project 99-063.

Table of Contents

Hayes, D. and P.-Y. Wu. (2001). “Simple approach to TSS source strength estimates”. *Proceedings of the Western Dredging Association Twenty-first Technical Conference and Thirty-third Annual Texas A and M Dredging Seminar Special PIANC Session* / Texas A and M University, Center for Dredging Studies, pg-303, Jun, 2001.

Hayes, D., T. Borrowman and D. Averett. (2000). “Near-field turbidity observations during Boston Harbor bucket comparison study”. *Proceedings of WEDA XX*, Providence, RI.

Hayes, D., T. McLellan and C. Truitt. (1988). “Demonstration of innovative and conventional dredging equipment at Calumet Harbor, Illinois”. Miscellaneous Paper EL-88-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Johnson, B.H., E. Anderson, T. Isaji, and D.G. Clarke. (2000). “Description of the SSFATE numerical modeling system”. DOER Technical Notes Collection (TN DOER-E10). U.S. Army Engineer Research and Development Center, Vicksburg, MS. http: //www.wes.army.mil/el/dots/doer/pdf/doere10.pdf.

MAEOEA (Massachusetts Executive Office of Environmental Affairs). (2000). Massachusetts Watershed Initiative, Annual Report. Boston, MA.

McCutcheon, S. C., Z. Dongwei, and S. Bird, (1990). “Model calibration, validation, and use, Chapter 5 in Technical Guidance Manual for Performing Waste Load allocations”. In: Book III: Estuaries, Part 2: application of estuarine waste load allocation models, J.J., Martin, R.B. Ambrose, and S. C. McCutcheon (eds.), US Environmental Protection agency, Office of Water, March 1990.

Muin, M. and M. L. Spaulding, (1997a). “A three dimensional boundary fitted coordinate hydrodynamic model”, *Journal of Hydraulic Engineering*, Vol. 123, No. 1, January 1997, p. 2-12.

Muin, M. and M. L. Spaulding, (1997b). “Application of three-dimensional boundary fitted circulation model to Providence River”, *Journal of Hydraulic Engineering*, Vol. 123, No. 1, January 1997, p. 13-20.

NGDC (National Geophysical Data Center), (1998). GEOphysical Data System for Hydrographic Survey Data, National Ocean Service, Ver. 4.

Pilson, M.E.Q., (1985). “On the residence time of water in Narragansett Bay”. *Estuaries*, Vol. 8, p. 2-14.

Ries, K. G. (1990). “Estimating surface-water runoff to Narragansett Bay, Rhode Island and Massachusetts”. U. S. Geological Survey Water Resources Investigations Report 89-4164, Providence, RI.

Spaulding, M., D. Mendelsohn and J.C. Swanson. (1999). “WQMAP: An integrated three-dimensional hydrodynamic and water quality model system for estuarine and coastal applications”. *Marine Technology Society Journal*, Vol. 33, No. 3, pp. 38-54, Fall 1999.

Spaulding, M.L. and F.M. White. (1990). “Circulation dynamics in Mt. Hope Bay and the lower Taunton River. Coastal and Estuarine Studies”, Vol. 38, R.T. Cheng (Ed.), *Residual Currents and Long-Term Transport*, Springer-Verlag, New York.

Swanson, C., C. Galagan, T. Isaji and H.-S. Kim. (2001). “Simulations of sediment deposition from jet plow operations in New Haven Harbor”. Draft Final Report to Environmental Science Services, July 2001, 13p.

Swanson, J. C. (1986). “A three dimensional numerical model system of coastal circulation and water quality”. Ph. D. Thesis, Dept. of Ocean Engineering, University of Rhode Island, Kingston, RI.

Swanson, J. C. and D. Mendelsohn, (1996). “Water quality impacts of dredging and disposal operations in Boston Harbor”. *Proceedings of the North American Water and Environment Congress 96*, sponsored by ASCE, Anaheim, CA, 22-28 June 1996.

Swanson, J.C, Isaji, T., Clarke, D., and Dickerson, C., (2004). “Simulations of dredging and dredged material disposal operations in Chesapeake Bay, Maryland and Saint Andrew Bay, Florida”. Presented at *WEDA XXIV / 36th TAMU Dredging Seminar*, July 7-9, 2004, Orlando, Florida.

Swanson, J.C., T. Isaji, M. Ward, B.H. Johnson, A. Teeter, and D.G. Clarke. (2000). “Demonstration of the SSFATE numerical modeling system”. DOER Technical Notes Collection (TN DOER-E12). U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/dots/doer/pdf/doere12.pdf.

Teeter, A.M. (1998). “Cohesive sediment modeling using multiple grain classes, Part I: settling and deposition”. *Proceedings of INTERCOH 98 - Coastal and Estuaries Fine Sediment Transport: Processes and Applications*, South Korea.