MONITORING OF SEDIMENT PLUMES GENERATED BY THE SUBAQUEOUS DISPOSAL OF DREDGED MATERIAL

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ABSTRACT

The monitoring efforts performed as part of the Disposal Area Monitoring System (DAMOS) have shown the physical, chemical, and biological impacts associated with the subaqueous disposal of dredged material are typically minor and limited to the seafloor within a disposal site. Increased scientific emphasis has now been focused on examining the impacts of dredged material disposal to conditions within the water column. In the Spring and Summer of 2004, the US Army Corps of Engineers, New England District conducted a series of monitoring surveys over the Rhode Island Sound Disposal Site (RISDS) to evaluate the behavior of sediment plumes resulting from dredged material placement. The objectives of the surveys were to track the extent and concentration of each sediment plume for a three to four hour period following the disposal event at RISDS, and to assess the acute toxicity of these plumes to marine organisms.

Six individual sediment plumes generated by the disposal of maintenance material dredged from the federal navigational channel within the Providence River were monitored. Prior to each disposal event, sediment samples were collected from the split-hull disposal barge for geotechnical and geochemical characterization. Following each placement event, a survey vessel continually profiled the water column with a conductivity, temperature, and depth (CTD) probe, as well as a series of water sampling bottles to measure turbidity and systematically obtain hydrocasts. A transmissometer interfaced with the CTD provided data pertaining to suspended particulate concentrations, while water sampling bottles were triggered on demand to obtain hydrocasts within the densest portion of the plume. Discrete water samples were collected at various time intervals during each survey period and retained for TSS and toxicity analyses. A second survey vessel supporting the survey operations was equipped with a downward-looking broadband acoustic Doppler current profiler (ADCP) to examine acoustic backscatter within the water column, providing information related to the relative concentration of the entrained sediments comprising the plume.

Keywords: Acoustic Doppler current profiler, Barge disposal, disposal site, turbidity, toxicity.

INTRODUCTION

In accordance with the environmental monitoring plan associated with the Providence River and Harbor Maintenance Dredging Project, two planned sediment plume tracking and assessment surveys were completed over the Rhode Island Sound Disposal Site (RISDS) in April and September 2004. The survey efforts were sponsored by the Disposal Area Monitoring System (DAMOS) Program and represents the first comprehensive dredged material disposal plume assessment project performed in New England waters. The current Providence River and Harbor Maintenance Dredging Project involves the dredging of approximately 2.1 million cubic meters of suitable maintenance material (material that meets the ocean disposal testing requirements) to be placed at the recently designated Rhode Island Sound Disposal Site (RISDS).

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When a barge-load of sediment is deposited at an open-water disposal site, the dredged material goes through multiple phases of descent as it settles to the seafloor: convective descent, dynamic collapse, and passive dispersion (SAIC 1988). Although most of the dredged material released from a disposal barge during open water placement operations travel directly to the bottom through the convective descent phase to form a deposit on the seafloor, each disposal event has the potential of creating a disposal plume comprised of sediments that become entrained in the water column. In the relatively shallow water column that exists over RISDS (36 to 39 m depth), the sediment load within each barge falls to the seafloor within 1 to 2 seconds of release. The small percentage of sediments that become entrained in the water column forms a concentrated column of turbid water directly below the disposal barge (SAIC 2004). However, as the disposal plume moves with the water mass over time, suspended sediment particles continue to settle to the seafloor and suspended solids concentrations (turbidity) gradually return to background levels as surrounding seawater dilutes the clouds of entrained material.

As part of the plume tracking and assessment study, sediment plume tracking was conducted for three disposal events in April 2004, as well as three disposal events in the September 2004. During the April 2004 survey (Survey 1), the sediment plumes formed by the subaqueous disposal of sediment dredged from the Sabin Point Reach were monitored to assess their behavior and morphology. The September 2004 survey (Survey 2) was performed to observe the transport, morphology, and relative toxicity associated with plumes formed by the open water disposal of sediments dredged from the lower Fox Point and upper Fuller Rock Reaches of the Providence River federal navigation channel. These sediments were of particular interest to regulators, as the results of geochemical and toxicity testing performed on the in-place sediments prior to dredging determined that these sediments were suitable for unconfined open water disposal with a stipulation that individual disposal events be restricted to 3,000 yd^3 (2,300 m^3). Disposal barges with capacities of 6,000 yd^3 (4,600 m^3) were utilized to transport the smaller volumes of material (2,300 m^3) to the disposal site. The placement of smaller volumes of dredged material by a large capacity disposal barge was expected to result in a relatively dilute sediment plume and minimize any issues associated with acute toxicity in the water column.

The comprehensive plume tracking surveys performed over RISDS in April and September 2004 involved water sampling, turbidity analysis, and plume transport measurements. The primary objectives of this survey were to:

1) track the extent and concentration of the suspended sediment plume during three separate disposal events at the RISDS; and

2) assess the acute toxicity of the sediment plume to marine column organisms.

The 2004 field efforts tested the following predictions:

1) plume total suspended solids (TSS) concentrations at the centroid will decrease to 10 $mg \cdot l^{-1}$ or less within three hours; and

2) water samples collected from the plume centroid will not exhibit toxicity that is significantly different from background conditions at the RISDS within one hour of sediment disposal.

To address these objectives, a variety of vessel-mounted systems, moored sensors, and drifting devices were used to track the plume created by the release of dredged sediment, requiring the acquisition of data on turbidity levels within the sediment plume down-current of the disposal operation during the first few hours after formation. In addition, a water sampling survey was conducted to collect water for total suspended solid (TSS) analysis and water-column bioassays. This paper presents the results of one plume monitoring event from each phase of the sediment plume tracking and assessment study (10 April 2004 and 2 September 2004) performed within RISDS.

METHODS

Both the April and September 2004 plume monitoring surveys utilized identical sampling techniques. Field data collection efforts consisted of sediment plume tracking employing a vessel-mounted acoustic Doppler current profiler (ADCP), optical backscatter sensors (OBS), a high-resolution Conductivity-Temperature-Depth (CTD) profiling system and transmissometer, surface and subsurface current drogues, as well as the collection of hydrocasts for total suspended solids (TSS) and toxicity analysis.

The basic plume-tracking program consisted of a two-vessel sampling operation. One vessel (R/V *Eastern Surveyor*) was primarily responsible for deploying and tracking the current drogues, as well as conducting the periodic water sampling and vertical CTD/transmissometer profiling operations within the sediment plume. The second vessel (M/V *Beavertail*) was responsible for conducting the cross-plume and along-plume vessel-mounted ADCP transects to map the track and lateral extent of the plume, as well as deploy and retrieve a bottom-mounted ADCP mooring and OBS sensor string placed in the anticipated path of the plume.

Figure 1. R/V *Eastern Surveyor* astern of a 6,000 yd^3 (4,600 m^3) immediately following a dredged material placement event at RISDS.

Barge Sampling

Sediment samples for chemical [trace metals and polycyclic aromatic hydrocarbons (PAHs)] and geotechnical (grain size and moisture content) analyses were collected from the individual barge loads of sediment identified for disposal plume tracking operations at RISDS. Representative sediment sub-samples were obtained from the disposal barges by obtaining discrete samples from the bow and stern of the disposal barge on an hourly basis during a four to six hour barge loading process. The selection of a particular barge-load for sampling required coordination between SAIC and the on-site NAE Resident Engineer, and was primarily dependent on anticipated timing of the barge's arrival at RISDS.

A 0.04m^2 Van-Veen sediment grab sampler was used to collect sufficient sediment from the barge to enable bulk chemical and geotechnical analyses of the dredged material. The individual grab samples were composited to create a single representative sub-sample of the material within the disposal barge. The sediment from each barge was placed in a pre-cleaned High Density Polyethylene (HDPE) five-gallon bucket, homogenized, then sub-sampled into a series of pre-cleaned glass jars (500 ml) and held at 4°C during shipment to the analytical laboratories. The geochemical samples were analyzed for polycyclic aromatic hydrocarbons (PAHs), and a suite of trace metals including arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), copper (Cu), nickel (Ni), and zinc (Zn). In addition, sediment samples were also retained for grain size, total organic carbon, and moisture content analyses.

Water Column Currents

SAIC deployed two upward-looking ADCPs moored on one bottom mount during the monitoring project. The array supporting both a 1200 kHz and a 300 kHz ADCP was deployed in close proximity to the work site prior to beginning the plume-tracking operation. The ADCPs were left undisturbed until the plume monitoring operation for each day was complete. The actual placement locations were based on known current patterns, probable disposal locations, and the amount of disposal activity anticipated for each survey day. The temporal sampling objective required rapid (i.e., 1 Hz) sampling by the ADCPs to acquire high resolution data pertaining to near-bottom currents during the relatively brief placement events in order to acquire high-resolution data on plume characteristics during the three to four hour period following material placement. In addition, the data from the ADCPs were used to generate an accurate plot of both the current direction and velocity at different levels in the water column throughout each deployment period.

In addition to the moored ADCPs, surface and subsurface (mid-water and deep-water) current drogues were also used to determine the general speed and direction of horizontal currents at the dredged material disposal location and thus aid in tracking the suspended sediment plumes. Two current-following "holey-sock" drogues were deployed and visually tracked during disposal operations at RISDS to obtain real-time information on horizontal currents at two depths in the water column. These drogues were constructed of a 4.9 m long by 0.6 m diameter cylindrical shape that was made of nylon material and attached to a small surface buoy by a small-diameter, nylon line. The depth of the mid-water drogue was determined based on the depth of the observed pycnocline within the water column from the real-time CTD profile obtained prior to disposal operations on the first day of monitoring. For each deployment, one mid-depth drogue (15 m) and one near-bottom drogue (32 m, approximately 5 m above the bottom) were deployed as a pair and tethered to the surface buoys to facilitate real-time tracking of the lateral movement of the plumes located at mid-depth and/or near-bottom levels. In addition, a single Davis-style surface drifter was deployed at the start of each plume-monitoring event. This drifter remained within the surface waters (1 m) providing an indication of flow within the upper layer. The surface drifter, mid-depth drogue, and deep-water drogue provided a real-time indication of current shear within the water column.

Following deployment, the near-bottom and mid-depth drogues served as reference points for the position of the disposal plume. Accurate DGPS positions of each drogue were obtained at 15-minute intervals as the water-following drogues were transported away from the initial placement site by water column currents. In addition, the majority of the CTD/transmissometer profiles and hydrocasts used to quantify water column turbidity were collected in close proximity to either the mid-depth or near-bottom drogue.

Plume Tracking

Real-time CTD/Transmissometer Profiles

A Seabird Electronics SBE-19® conductivity-temperature-depth (CTD) profiler integrated with a Wet-Labs C-Star, 25 cm path length transmissometer (660 nm wavelength) was mounted within a Seabird (Model SBE-32) Carousel Water Sampler to collect and display vertical profiles of the water column in real-time, and thus aid in deciding on the timing and depth of discrete water sample collection. The SBE-32 Carousel unit was controlled by a Seabird SBE-33 deck unit to facilitate the transmission of real-time CTD data and served as the triggering mechanism for individual water sampling bottles. The CTD profiling system provided real-time display of sensor depth and water column properties (e.g., turbidity, salinity, density, etc.) to facilitate quality control and assurance that monitoring objectives were being met. Real-time viewing of the vertical distribution of turbidity concentration allowed careful selection of the optimum depth for collection of discrete water samples. The real-time data provided by the transmissometer were used to determine the depth, thickness, and maximum turbidity at the centroid of the plume.

The CTD profiling system was also equipped with a bottom-contact switch, which was attached to a small weight suspended approximately 2 m below the level of the water sampling bottles on the Carousel. During each lowering, the CTD descent rate was initially about 0.5 $m \cdot s^{-1}$, but was decreased to approximately 0.1 $m \cdot s^{-1}$ within the lower 5 m of the water column. When the small weight that was suspended beneath the CTD touched the seafloor, this contact was indicated on the real-time display and the CTD operator immediately stopped the downcast. This procedure prevented the CTD from making contact with the seafloor, and thus eliminated unwanted resuspension of bottom sediment, as this would have suspended ambient sediment that would have interfered with measuring the dredged material plume near the seafloor.

The water column profiling surveys followed each disposal plume as it traveled with the ambient currents during the three and one-half hours after each placement event. Water column turbidity measurements were monitored continuously and the centroid of the plume was identified using the Wet-Labs optical beam transmissometer, which measured the amount of light transmitted through the seawater within the 25 cm path length of the instrument. A low value of measured light transmittance represented a relatively high concentration of suspended particulate matter (turbidity) in the water column. Because the main focus of the plume monitoring study was to track the movement and temporal evolution of the suspended sediment plume after release of dredged material from the barge, emphasis was placed on the real-time assessment of numerous vertical profiles of turbidity (percent light transmittance) to determine the optimal location for the collection of water samples.

Moored OBS Arrays

In addition to the real-time turbidity profiling conducted at RISDS aboard the CTD survey vessel, an in-line, vertical mooring with three Seapoint optical backscatter (OBS) sensors (Seapoint Inc. Turbidity Meters) was used to monitor in-situ turbidity levels within the water column at a fixed location near the disposal location. The OBS mooring was deployed prior to the targeted dredged material placement event, down-current of the disposal operation, and in the projected path of the plume to monitor suspended sediment concentrations in the mid-depth and near-bottom levels. The individual OBS sensors were interfaced with a single Dryden R2 data logger and positioned on the mooring to remain at water depths of 13, 18, and 32 m. Based on water depths at the mooring areas, the depth of the lowest OBS sensor ranged from approximately 2 to 4 m above the seafloor, in an attempt to monitor turbidity in the near-bottom plume as it passed the mooring.

The OBS sensors measured the amount of emitted (infrared) light that was reflected back to the sensor. The higher reflection values equated to a greater quantity of suspended particulate material in the volume of water being measured. The R2 data logger acquired turbidity data from each sensor at 10-second intervals throughout the deployment periods. The OBS data presented in this report are stated in terms of Formazin Turbidity Units (FTUs), which provide a relative measure of suspended particulate matter.

Real-time ADCP

In order to track the movement and document changes in the morphology of each of the RISDS sediment plumes, ADCPs were used to log the echo intensity or strength of each acoustic return in decibels (dB) to estimate the amount of particulate matter in the water column. Commonly referred to as acoustic backscatter, the intensity of the acoustic return would provide a relative measurement of the turbidity within various depth levels. Underway ADCP surveys were conducted on each of the three plume survey days with the ultimate goal of characterizing the transport and dispersion of sediment plumes in the water column associated with the placement of dredged material at RISDS.

Underway in-situ measurements of acoustic backscatter and horizontal currents were acquired throughout the water column using a vessel-mounted ADCP on a second survey vessel. A single downward-looking, vessel-mounted ADCP (600 kHz) was used to acquire detailed information on real-time currents (speed and direction) and echo intensity (relative backscatter) in the water column. These data were logged with position and time stamps, as well as evaluated in real-time to assess vertical shear in the water column currents and monitor changes in plume morphology in both time and space. The 600 kHz broadband ADCP was optimal for identifying the boundaries of the plume and centroid (maximum sediment concentration) and providing guidance to the water sampling operations during the final stages of the plume-tracking operation when suspended sediment concentrations were relatively low.

Prior to the RISDS plume monitoring survey effort, a series of predetermined survey lines spaced at 100 m intervals was established over the disposal site to facilitate collecting cross-sectional data from the moving sediment plume (Figure 2). Multiple survey lines were constructed over the disposal site, with lines oriented in various directions (north-south, east-west, northeast-southwest, and northwest-southeast). Data were collected by the vessel mounted ADCP prior to each disposal event to characterize background or reference profiles for backscatter intensity, as well as the speed and direction of water column currents. Upon review of the current data, survey lines running perpendicular to the anticipated direction of plume transport were selected. The backscatter intensities detected within the background profiles were then subtracted from acoustic data collected following the disposal event to yield a residual backscatter that was attributable to presence of plume sediments in the water column. These residual backscatter intensities were represented as acoustic counts, where 1 decibel is equivalent to 2 counts (1 dB=2 counts).

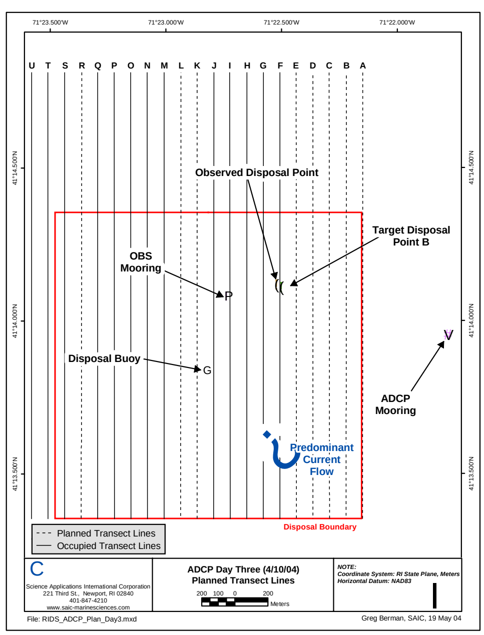


Figure 2. Basemap displaying a subset of the predetermined ADCP survey lanes established over RISDS.

Water Sampling

Total Suspended Solids (TSS)

Using various types of monitoring equipment and survey techniques, the densest portion of each sediment plume, or centroid, was identified and water samples were collected to determine the suspended solids concentration and toxicity. In addition to the in-situ measurement capabilities of the CTD profiling system described above, the electronics of the CTD were interfaced to the Seabird Carousel Water Sampling, which was equipped with six 5-liter Niskin and two 2.5-liter Go-FLO water-sampling bottles to allow hydrocasts to be collected concurrently with the real-time vertical CTD profiles (Figure 3). The vertical CTD profile data gave the on-board scientist the ability to view, in real-time, the turbidity profile and then select the optimum depth for water sample collection (at the depth of highest turbidity in the vertical profile). Horizontal positioning of the CTD survey vessel in the right spatial location within the plume was based upon: 1) real-time assessment of drogue tracks, and 2) constant communication with the roving vessel with the downward-looking ADCP (acoustic backscatter).

Individual Niskin-type sampling bottles were located approximately 1 m above the transmissometer and fired at predetermined time intervals to collect water samples for post-survey laboratory analysis of TSS. Water samples were collected for TSS measurement within the densest portion of the plume 10, 20, 40, 60, 90, 120, 150, and 210 minutes after the dredged material placement event. At each sampling time, three separate 1-liter triplicate samples were drawn from a single Niskin bottle. A minimum of 24 water samples were acquired for TSS analysis during the survey operations. In addition, at least three background samples were collected within 5 m of the seafloor to characterize TSS concentrations in the ambient water prior to the placement event.

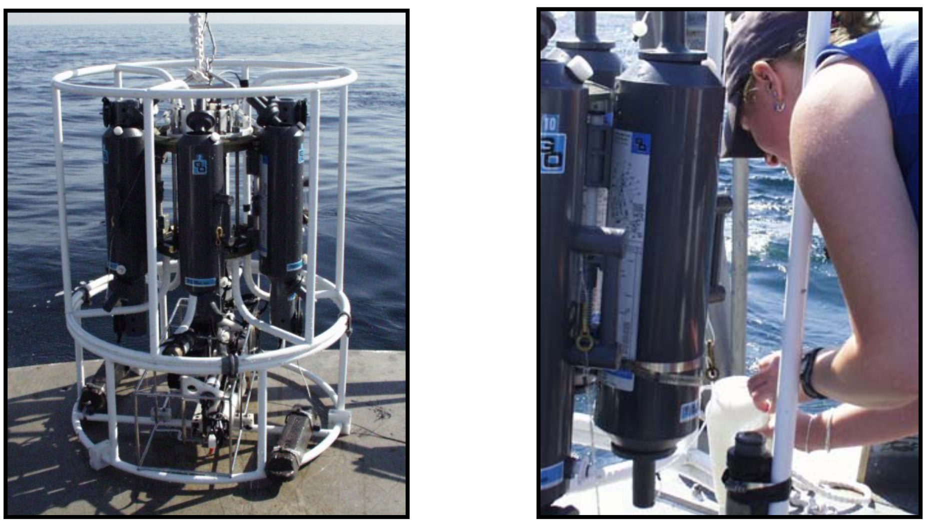


Figure 3. Images of the Seabird SBE32 Carousel unit employed as part of the plume monitoring surveys performed at RISDS.

Acute Toxicity Testing

Concurrent with the collection of samples for TSS determination, water samples were collected to assess acute toxicity within the mixing zone at RISDS during two of the three survey days within each phase of the monitoring program. A pair of 2.5 liter General Oceanics Go-FLO water sampling bottles incorporated into the Carousel system was used to obtain toxicity samples. Toxicity samples were collected prior to the dredged material placement event (background), as well as 40, 60, and 120 minutes following disposal. Four liters of water were obtained at each time interval and composited in a single cubitainer. The water samples were tested using the methodology outlined in the Inland Testing Manual (EPA/USACE 1998). Aquatec Biological Sciences conducted 96-hour water column toxicity testing with mysids (*Americamysis bahia*) and juvenile silversides (*Menidia beryllina*). These tests were conducted with five replicates of 100% field samples with no dilution. Standard measurements including survival and water quality conditions were made at 24-hour intervals and were reported to SAIC.

RESULTS

The abundance of data collected as part of the first plume monitoring survey indicated that the morphology and characteristics of each sediment plume are the products of multiple mechanical and environmental factors associated with the subaqueous disposal of dredged material. Geotechnical characteristics of the material, barge configuration and volume, water column current velocities, and water depth dictate the formation, transport, diffusion, and settlement of sediments entrained within the water column during disposal. This section of the paper presents detailed results for 10 April 2004 (Plume 3) as part of the first phase of monitoring and 2 September 2004 (Plume 2) as part of the second phase of the monitoring relative to the individual disciplines used to characterize elements of plume behavior.

The following subsections offer a synthesis of these data to chronicle the observations made during the course of the surveys. To simplify the presentation of findings, particular emphasis was placed on the attributes of each plume at the 32 m depth interval as maximum turbidity was often detected in the acoustic, optical, and water sample data collected along this near-bottom horizon. In addition, this depth interval corresponded to the depth of the deep drogue and near-bottom current record, allowing strong correlation between the individual data sets.

Phase I – 10 April 2004 (Plume 3)

On the approach to the selected disposal point within RISDS, the loaded 4,000 yd^3 split-hull barge was towed into RISDS from the north, deposited 3,200 m^3 of dredged material from the Sabin Point Reach of Providence River, and then proceeded south while turning to the west to begin its return transit to Narragansett Bay. Based on the cross-sectional acoustic measurements made by the ADCP along North-South axis of the plume (Line F) at five minutes post-placement, the resulting sediment plume was approximately 160 m wide at the surface and nearly 290 m wide near-bottom when initially formed (Figure 4-A). The subsequent survey line (Line G) was completed 100 m to the west (down-current) of the observed disposal location, capturing the sediment plume at ten minutes post-placement. The acoustic profile information indicated a significant extension of the near-surface portion of the sediment plume to the south and west, likely as residual sediments were washed from the open barge as it was positioned for return transit as well as turbulence from the wake of the tugboat, while the near-bottom portion of the sediment plume displayed relatively minor expansion.

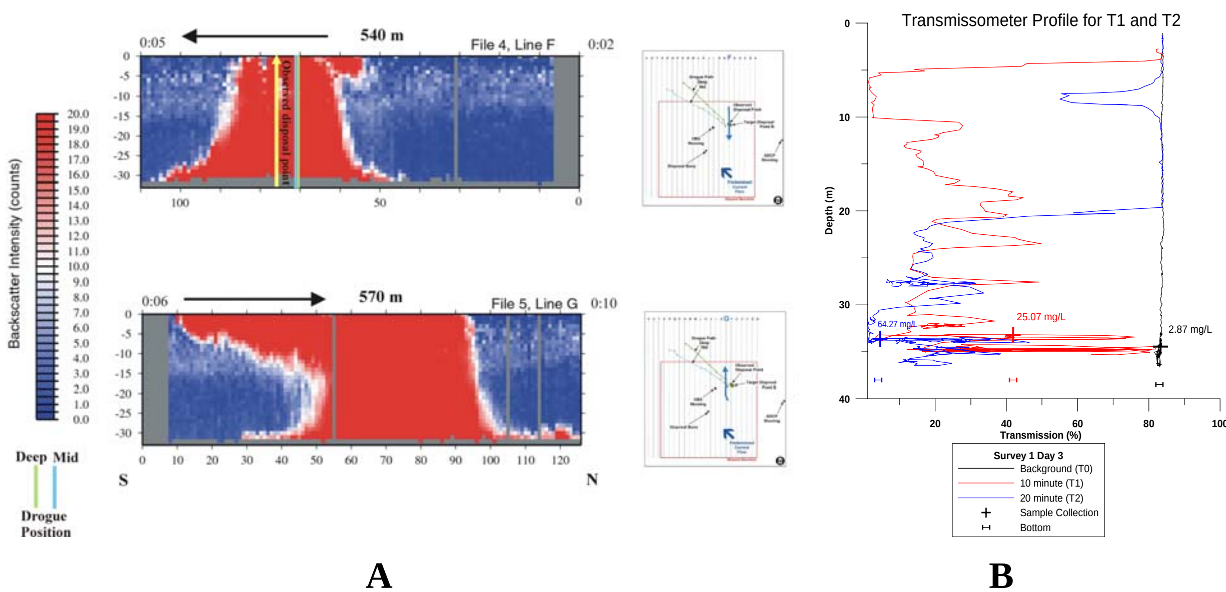


Figure 4. Profile plots of ADCP data collected along Lines F and G (Plume 3) displaying residual acoustic backscatter intensity within the water column to illustrate plume morphology 2 to 10 minutes after the dredged material disposal event at Point B (A). Profile plot of percent light transmission versus sensor depth acquired during CTD sample intervals T1 and T2 during Plume 3 (B).

Utilizing positional information provided by the ADCP data, the CTD/water sampling vessel remained southwest of the current drogue tracks and identified the plume centroid in the lower water column. Water samples for TSS were often collected from the most turbid portion of the plume at levels 3 to 5 m above the seafloor. The near-bottom portion of the sediment plume (32 m depth) displayed the highest backscatter intensity over background levels (relative turbidity) immediately surrounding the observed disposal point, as well as 100 m down-current (to the west). The T1 transmissometer profile and water samples were obtained in an area with a significant amount of suspended particulate matter (which was confirmed by the ADCP data), but given the relatively low TSS value near the seafloor (25 $mg{\cdot}L^{-1}$), the profile and hydrocast were likely collected outside the tightly constrained core of the sediment plume (Figure 4-B). Based on the current meter data, the water mass and initial sediment plume moved approximately 62 m to the northwest during the first ten minutes of the survey.

Between 10 and 23 minutes after the disposal event, the water mass at the 32 m depth interval moved an additional 86 m to the northwest, resulting in 148 m total advection. Acoustic backscatter data appeared to be obtained over the leading portion of the plume as it was advected to the northwest by ambient currents. These data also suggested the presence of two areas of suspended sediments at the 32 m depth interval that were separated by relatively clear water. The formation of two plume features in the water column was attributable to the sediment load within the barge falling to the seafloor as two distinct sediment deposits. The primary plume feature was located west-northwest of the disposal point, while the secondary feature was offset to the southwest. The T2 transmissometer profile and water samples were collected in what appeared to be the central portion of the plume as light transmission was near zero and average TSS was 64 $mg{\cdot}L^{-1}$ (Figure 4-B).

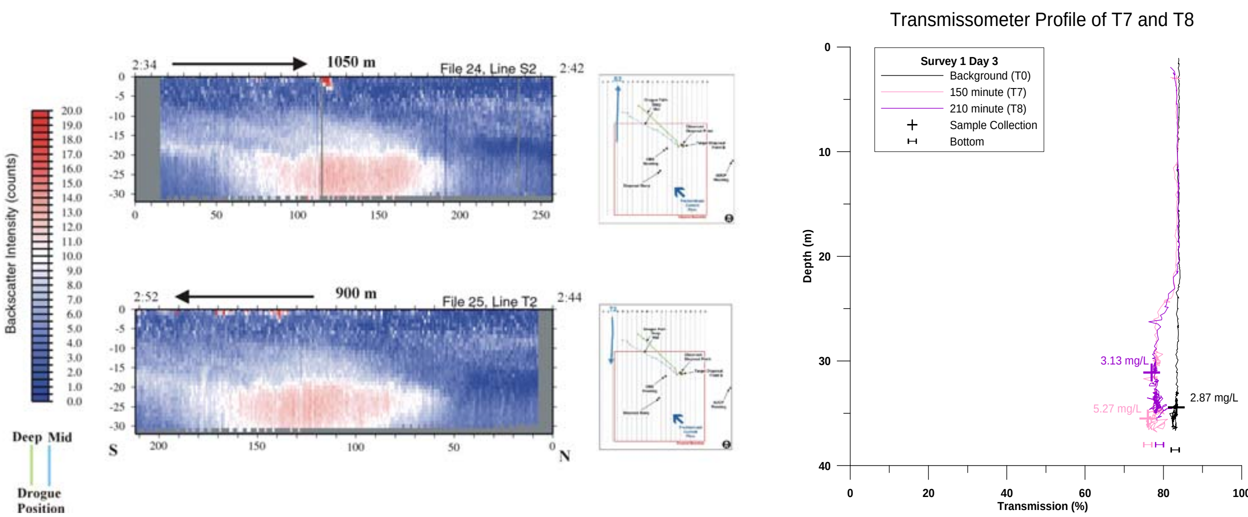
Traveling at an average rate of 11 $cm{\cdot}s^{-1}$, the core of the sediment plume was likely transported over 250 m and broadened substantially during the first 40 minutes of the survey. The T3 profile and TSS samples were obtained approximately 225 m northwest of the original disposal point, which indicated maximum turbidity within the plume existed 6 m above the seafloor (suspended sediment concentration of 45 $mg{\cdot}L^{-1}$). The data obtained via the ADCP prior to the T3 survey indicated some residual turbidity existed near the observed disposal point, with isolated pockets displaying residual backscatter values above 15 counts. Approximately 200 m down current, the near-bottom portion of the sediment plume appeared more coherent, but still existed as two distinct features in the water column. The acoustic data collected along these survey lines confirmed the presence of elevated suspended particulates over the T3 sample location, as well as at the T4 sample location that was occupied 20 minutes later.

After 40 minutes of surveying, near-bottom current speeds began to increase, impacting the transport and dilution rates as the plume mixed with ambient seawater. The T4 samples were obtained 63 minutes post-placement from a location that displayed a concentrated pocket of turbidity according to the acoustic data. The CTD detected a light transmittance values of 50% and greater, while the average TSS concentration from the 32 m depth horizon was 9 $mg{\cdot}L^{-1}$. While these data indicated the T4 profile and water samples were collected from within the plume, they may not be representative of its absolute centroid.

Approximately 90 minutes into the survey, the ADCP record suggested that metrological conditions were impacting the overall morphology of the sediment plume. The stress on the surface waters and resulting short-period waves generated by a winds emanating from the west and southwest opposed the northwest current flow at the surface, preventing migration and concentrating of these entrained sediments near the original disposal point. As water column currents at mid-depth and near-bottom continued to transport corresponding layers of the sediment plume northwest, the surface and near-surface elements of the plume were essentially sheared the from the remainder of the feature. The T5 sampling was completed in proximity to the plume centroid approximately 800 m down-current from the disposal point. The T5 transmissometer profile indicated discrete layers of plume sediments at mid-depth and near-bottom, exhibiting values ranging between 50 to 60%. The replicate-averaged TSS value calculated for the T5 samples was 12.6 $mg{\cdot}L^{-1}$ utilizing waters captured from the 32 m depth interval. Comparisons to the turbidity measured earlier in the survey day indicated a small-scale (3 $mg{\cdot}L^{-1}$) increase in TSS at T5 (90 minutes) relative to the T4 (60 minutes) results. This increase may have been the product of increased particle settlement or minor difference in the location of the water sample relative to the centroid of the plume.

The ADCP vessel later identified the leading edge of the sediment plume on Line Q, approximately 1,250 m northwest of the original disposal point, while the subsequent survey lines provided insight into turbidity closer to the centroid. Ten minutes prior to the T6 sample interval, the near-bottom portion of the plume had been subjected to sufficient advection by ambient currents to transport the turbid water nearly 930 m to the northwest. The centroid of the plume was re-acquired by the ADCP vessel approximately five minutes prior to the T6 sample interval as an isolated pocket of water displaying acoustic backscatter values greater than 15 counts over background. The CTD/water sampling vessel was directed to this location and completed the T6 (120 minute) profile and sample collection. Both the transmissometer profile and TSS data displayed relatively low turbidity levels at the 32 m depth interval despite the strong acoustic signal detected by the ADCP. Minimum light transmittance values of 65% were detected in the CTD profile and an average TSS value of 6 mg·L^{-1} was calculated from the water samples. Two hours after the disposal event, the core of the plume was identified approximately 1,010 m northwest of the observed disposal point in both the acoustic and optical data, which closely aligned with the calculated total advection distance of 1,019 m based on near-bottom current velocities.

For the remainder of the survey day, the most concentrated portion of the sediment plume was detected in the bottom 10 to 15 m of the water column. Only one coherent plume feature was detectable, as the primary plume and secondary plume likely merged to form a single, broad feature that was advected to the west and northwest by ambient currents. Survey lines completed outside the northern and western boundaries of RISDS indicated residual acoustic backscatter intensities between 5 and 15 counts above background nearly three hours post-placement. Estimates of advection based on near-bottom current velocities suggest the core of the sediment plume was transported 1.3 km within 172 minutes. The T7 (150 minute) CTD profile and water samples were obtained from a position approximately 1,300 m down-current from the observed disposal point at a location just outside the northern boundary of RISDS. The transmissometer data indicated a slightly lower light transmittance in comparison to background, indicative of a small-scale elevation in suspended particulates. With a replicate-averaged TSS value of 5 mg·L^{-1}, the water samples were likely acquired within the diffuse plume, but outside the centroid (Figure 5-B).



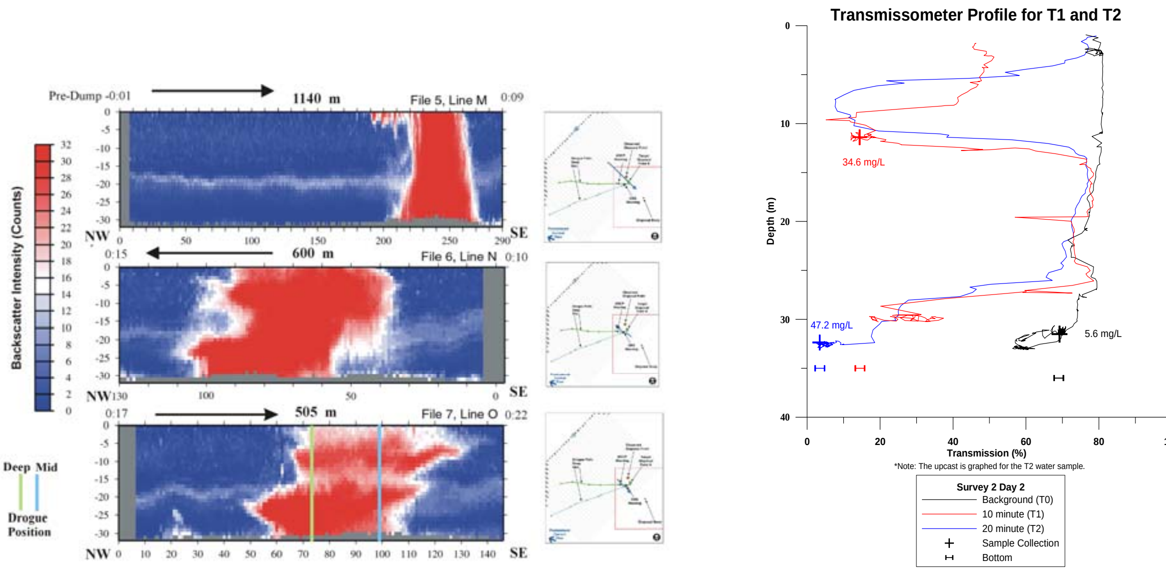
A B

Figure 5. Profile plots of ADCP data collected along Lines O and N (Plume 3) displaying residual acoustic backscatter intensity within the water column to illustrate plume morphology 154 to 172 minutes after the dredged material disposal event at Point B (A). Profile plot of percent light transmission and sensor depth acquired during CTD sample intervals T7 and T8 for Plume 3 (B).

The T8 transmissometer profile and TSS samples were collected 210 minutes after the disposal event from a location that was 175 m north-northwest of the T7 CTD station. Although no acoustic data were obtained during that time period, the ADCP transects completed 40 minutes prior to the T8 sampling event suggested the bulk of the turbid water in the lower half of the water column had moved beyond the disposal site in the form of a broad diffuse sediment plume. The transmissometer profile for T8 was quite similar to that of the T7 sampling event with low levels of particulate matter detected at depths greater than 25 m. However, the replicate averaged TSS value for the T8 samples indicated near-bottom turbidity was essentially at background levels (3 mg·L^{-1}). Given the rate and direction of transport, total advection for the densest portion of the sediment plume was likely 1.6 km northwest of the original disposal point. The recorded position of the T8 samples was 1.4 km northwest of the disposal point; therefore, the transmissometer profile and TSS results were likely characteristic of the trailing edge of the broad and diffuse sediment plume.

Phase II – 2 September 2004 (Plume 2)

A 6,000 yd³ split-hull disposal barge loaded with 2,280 m³ (3,000 yd³) of fine-grained sediment dredged from the Fuller Rock Reach of Providence River was transported to the northwestern quadrant RISDS for disposal. The barge entered the disposal site from the north, stopped at Disposal Point A for the disposal event, and then continued south and eventually turning to the east and north for the return transit. The acoustic backscatter information acquired along the first survey line seven minutes after the disposal event indicated high residual backscatter values throughout the water column, with the initial plume existing as a column of turbidity approximately 160 m wide on the surface and nearly 300 m wide at depth (Figure 6-A).



A B

Figure 6. Profile plots of ADCP data collected along Lines M, N, and O (Plume 2) displaying residual acoustic backscatter intensity within the water column to illustrate plume morphology prior to disposal and 22 minutes after the dredged material disposal event at Point A (A). Profile plot of percent light transmission and sensor depth acquired during CTD sample intervals T1 and T2 for Plume 2 (B).

The T1 (10-minute) transmissometer profile was collected approximately 150 m west-northwest of the observed disposal point and corresponded to an area displaying high residual backscatter values in the ADCP data. The transmissometer record indicated light transmittance was reduced within discrete layers of the water column existing at the surface, mid-depth, and near-bottom. The minimum transmittance value detected (representing maximum turbidity) within the T1 transmissometer profile was 14% at a water depth of 11 m. The water samples obtained from that depth horizon yielded an average TSS value of 34.6 mg·L^{-1}, suggesting the profile was obtained on the periphery of the tightly constrained sediment plume (Figure 6-B).

The water column profile for the T2 (20-minute) sample interval was similar in structure to that of T1, but maximum turbidity was documented near the seafloor. The T2 profile and samples were obtained approximately 200 m west of the observed disposal point and displayed an increase suspended particulate concentrations in both the surface and near bottom layers of the water column relative to T1. An average TSS value of 47.2 mg·L^{-1} was calculated from the hydrocast obtained from a depth of 32 m, which correlated to a minimum transmittance value of 3.5% (Figure 6-B). Based on the near-bottom current velocities obtained by the bottom-mounted ADCP, the water mass carrying the core of the sediment plume was transported 238 m to the west between the time of the disposal event and the end of the T2 sampling event. Given the location of the T2 profile, relative to the calculated transport distance, the data obtained at the T2 interval may be more representative of the trailing edge of the constrained plume sediment plume, rather than its absolute centroid.

The second occupation of Lines M and O suggested the core of the sediment plume had continued to move to the west and northwest in response to the near-bottom currents. The acoustic data indicated that suspended sediment concentrations within the near-bottom element of the plume remained relatively concentrated, as residual backscatter intensities in excess of 15 counts were detected as far as 400 m west-northwest of the observed disposal point 37 minutes following the disposal event. This finding correlated well with the transport distance of 410 m in the near-bottom waters calculated from the current records obtained by the bottom-mounted ADCP.

The T3 (40-minute) profile and water samples were collected approximately 550 m west of the observed disposal point just outside the western boundary of RISDS and displayed a substantial difference in the distribution and concentration of entrained sediments relative to the earlier casts. The transmissometer data indicated waters from the surface to 20 m depth displayed suspended sediment concentrations near background levels, while intervals of turbid water were detected at mid-depth and near-bottom separated by intervals of relatively clear water. Maximum turbidity was detected at approximately 32 m depth (4 m above the seafloor), with the T3 water sample yielding an average TSS value of 29.6 $mg{\cdot}L^{-1}$. The lower TSS value relative to the T2 sample, and the location of the 40-minute profile suggested this profile and water sample were collected 100 m to 150 m ahead of the centroid and were more characteristic of the leading edge of the plume.

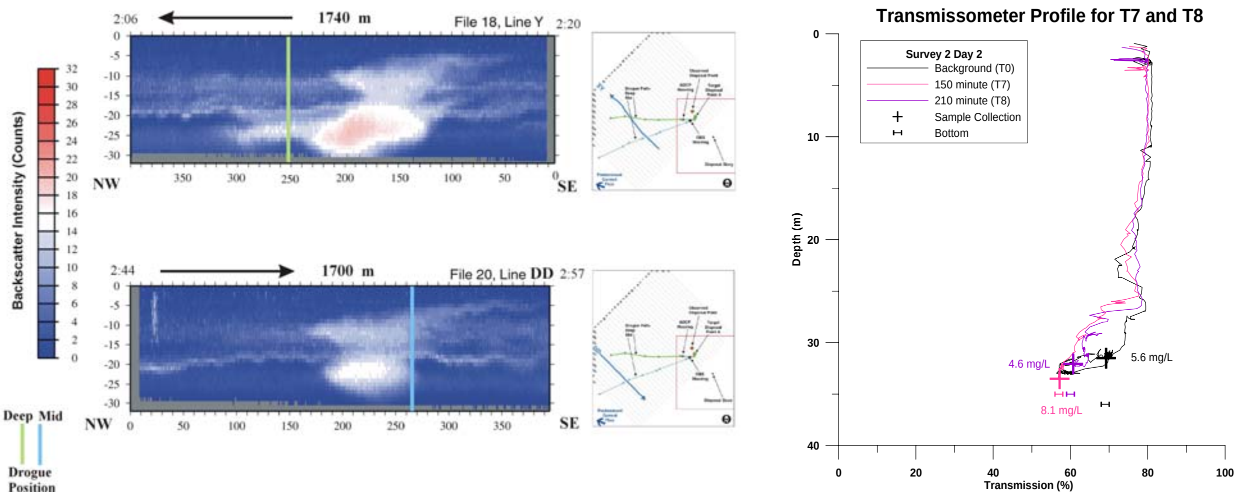
During the 20 minutes that elapsed between the T3 (40-minute) and T4 (60-minute) sampling intervals, the water mass at the 32 m depth interval moved an estimated 315 m west in response to near-bottom currents. The T4 samples were collected 175 m west-southwest of the T3 sample location and 750 m down-current from the observed disposal point. Total calculated advection during the one-hour period following the disposal event was 725 m, suggesting the T4 profile and water sample were closely aligned with the core of the disposal plume. With the exception of an apparent reduction in suspended sediment concentrations, the transmissometer profile obtained during the T4 sampling interval was quite similar in structure to that of T3. The water sample obtained for TSS analysis during the T4 profile was collected from a depth 34 m (approximately 2 m above the seafloor) and yielded an average value of 12.3 $mg{\cdot}L^{-1}$.

The acoustic data collected along Lines U and V, 100 and 200 m down-current from the T4 sample location respectively, detected low residual backscatter values in the 32 m depth interval. These findings suggest the ADCP data re-acquired the leading edge of the sediment plume as it was transported west by the ambient currents. Following the completion of Line V, Line U was re-occupied at the time corresponding to the T5 (90-minute) sampling interval. The acoustic data from the 32 m depth interval detected an area of high residual backscatter with intensities in excess of 15 counts 950 m down-current from the observed disposal location. The size of this plume feature and reduced intensities in the subsequent survey lines suggests the absolute plume centroid was in close proximity to Line U 90 minutes post-placement.

The T5 transmissometer profile and water sample were collected 1,050 m down-current from the observed disposal location 97 minutes post-placement. Despite the high acoustic returns in the ADCP data set, the transmissometer profile depicted a suspended particulate load approaching background levels in both the upper and lower water column. Similar to the transmissometer records from prior casts, percent transmittance values remained near 80% in the top 20 m of the water column. Below 20 m, transmissometer values decreased with depth indicating an increase in suspended sediment concentrations, eventually reaching a minimum transmittance of 50% at 33.9 m depth. However, the increase in turbidity that was documented in the lower water column was much more gradual in the T5 profile relative to the earlier casts. The T5 water sample was obtained from the densest portion of the near-bottom plume element, yielding an average TSS value of 9.1 $mg{\cdot}L^{-1}$, slightly lower than the T4 value. Since it is assumed that both the T5 and T4 sample were collected in close proximity to the plume centroid, the decrease in the average TSS value was indicative of a slow, continuous reduction in suspended sediment load within the centroid due to diffusion and settlement.

The remaining two hours of monitoring captured the slow decay of the sediment plume as turbidity levels within the centroid gradually returned to background conditions. The T6 (120-minute) profile and water sample were collected adjacent to the deep-drogue at a point that was 1,350 m west of the observed disposal point. The transmissometer data indicated a slightly lower transmittance throughout the majority of the water column relative to the T5 profile, indicative of a small-scale increase in turbidity levels. In addition, a relatively distinct increase in turbidity was detected at a depth of 25 m as light transmission values decreased sharply from 76 to 55%, and then rebounded to approximately 70%, which may have been a function of the physical properties of the water column (i.e., density). A transmittance value of 55% was also recorded at a depth of 34 m, approximately 2 m above the seafloor. A water sample obtained from this interval yielded an average TSS value of 6.5 $mg{\cdot}L^{-1}$ suggesting the near bottom element of the plume had degraded somewhat between the T5 (90-minute) and T6 (120-minute) sample intervals.

The acoustic data collected after the T6 sample interval was successful at tracking the progression of the sediment plume as it was advected west and then southwest in response to the counter-clockwise rotation of near-bottom currents that began flowing in a southerly direction three hours after the disposal event. The centroid of the disposal plume was apparently detected within the 32 m depth interval along Line Y 1500 m down-current of the observed disposal position 130 minutes post-placement (Figure 7-A). Residual backscatter values in excess of 15 counts were measured within 75 m wide segment of Line Y, which was bounded on either side by a gradient of decreasing backscatter intensities that eventually returned to background. Based on the current meter data, total advection of the plume centroid was estimated to be 1,400 to 1,500 m to the west, indicating strong agreement with the field observations.



A **B**

Figure 7. Profile plots of ADCP data collected along Lines Y and DD (Plume 2) displaying residual acoustic backscatter intensity within the water column to illustrate plume morphology 126 to 177 minutes after the dredged material disposal event at Point B (A). Profile plot of percent light transmission and sensor depth acquired during CTD sample intervals T7 and T8 for Plume 2 (B).

The T7 profile and water sample were obtained 1,750 m west of the observed disposal location 152 minutes post-placement (Figure 7-B). The T7 transmissometer profile and water samples both indicated only a minor elevation in near-bottom turbidity relative to the background profile. The water sample for the T7 interval was obtained from a depth of 33.5 m and yielded an average TSS value of 8.1 $mg{\cdot}L^{-1}$, which was slightly higher but comparable to the background turbidity value (5.6 $mg{\cdot}L^{-1}$) for the Plume 2 survey (Figure 7-B). No acoustic data were collected in proximity of the T7 sampling position at the time the transmissometer record was obtained to determine its location relative to the centroid. However, the T7 sample interval was completed prior to the southerly rotation in the near-bottom currents. Given the distribution of plume sediments 15 minutes prior to the T7 sample and the consistent direction of flow, the transmissometer record and water sample likely captured a portion of the sediment plume at the 32 m depth interval, but not the absolute centroid.

Following the T7 sampling interval, the sediment plume remained acoustically detectable in the water column as a decreasing mass of turbid water, displaying a discernable centroid approximately 195 minutes post-placement. The acoustic data collected along Line CC documented the core of the plume as an area of turbid water with a moderate acoustic backscatter signature over background (10 to 15 counts). The apparent centroid of the residual plume was documented over 1,800 m west-southwest of the observed disposal point. However, the lateral extent of the plume (perpendicular to direction of transport) appeared to be gradually decreasing from continued dilution at the periphery, resulting in a reduction in acoustic backscatter intensity.

The T8 transmissometer profile and water sample were collected over 2.1 km west of the observed disposal point 212 minutes post-placement. The transmissometer record displayed suspended sediment concentrations analogous to background in the upper water column, as well as remnant turbidity near-bottom (Figure 7-B). A hydrocast obtained from a depth 32 m yielded an average TSS value of 4.6 $mg{\cdot}L^{-1}$, which was actually lower than the background turbidity values prior to the Plume 2 disposal event (5.6 $mg{\cdot}L^{-1}$). A comparison of the recorded position for the T8 water sample and location of the sediment plume as detected along Line CC indicated the final water sample and transmissometer profile were collected 400 m northwest of the centroid. This offset in position was likely due to the effects of the change in water column current flow three hours post-placement and the continued settlement of material from the upper and mid-water column influencing plume morphology.

CONCLUSIONS

Summary of Findings

The primary objectives of the April and September 2004 studies were to track the extent and concentration of the disposal plume during three separate disposal events at the RISDS during the placement of varying volumes of sediment, as well as to assess the toxicity of disposal plumes to marine, water column-dwelling organisms. A total of six sediment plumes were monitored as part of the study completed at RISDS; three plumes generated by the disposal of maintenance material dredged from Sabin Point Reach and three plumes generated by the disposal of sediments removed from Fuller Rock Reach. The sediment was characteristic of most maintenance material, composed primarily of high water content, unconsolidated estuarine silts and clays.

All study objectives were accomplished within three sequential days of field sampling in April 2004 and another three in September 2004, with each effort yielding accurate and consistent results. Employing a combination of acoustic (ADCPs), optical (transmissometer and optical backscatter), and physical (current drogues and drifters) techniques, all six plumes targeted for monitoring were successfully tracked over a period of three to four hours. Water samples obtained within or near the centroid of each plume at the various time intervals provided sufficient information to follow the decay of each plume over time, as well as to verify a general lack of water column toxicity 40 minutes after the disposal event and any point in time thereafter.

The findings of the April and September 2004 survey efforts demonstrated that sediment plumes generated by the open water disposal of dredged material remain detectable in the water column with remote sensors for a period of three to four hours following an individual disposal event. Multiple acoustic and optical remote sensors were able to define the general plume morphology and relative turbidity levels above background throughout the water column. Total suspended solids measurements from water samples collected at various time intervals during each survey day showed strong agreement with the data obtained by the remote sensors.

When initially formed, the sediment plumes typically existed as a concentrated column of turbid water at the dredged material placement location for a short period (10 to 15 minutes) following the disposal event. Some broadening of the sediment plumes was observed in the surface layers as sediments were washed from the open disposal barge as it was towed away from the primary disposal location. The turbid water comprising the sediment plume was subject to advection by water column currents resulting in broadening and diffusion of the plume throughout the various levels of the water column over time.

The overall morphology of the sediment plume was primarily a function of the behavior of the water column currents over a given time period. The data collected by a bottom mounted ADCP deployed at RISDS during each plume monitoring event detected differences in current velocity and direction at the various depth horizons, resulting in multi-layer and/or divergent flow. The differences in current flow documented within the vertical axis served to stretch or broaden the sediment plume over time. Clear water was continually introduced into the plume during the advection process, resulting in dilution of the turbid water and diffusion of the suspended sediment particles. However, the most turbid, and therefore most persistent element of each sediment plume was usually situated in close proximity to the seafloor. The information obtained over the subsequent 3 to 4 hour survey captured the gradual decay of each sediment plume as advection, diffusion, and particle settlement eventually resulted in the return of background turbidity conditions.

During the three to four hour period between the disposal event and dissipation of the resulting sediment plume, portions of the plume existed in the upper, mid, and lower water column. As anticipated, the highest turbidity values indicative of the centroid of the plume were consistently detected within lower 3 to 5 m of the water column during the monitoring period following each disposal event. Data from the optical and acoustic remote sensors, as well as the discrete water samples, suggested the centroid of each sediment plume remained relatively concentrated for the first 40 to 60 minutes of each survey, followed by a consistent decrease in turbidity. Total suspended solids measurements performed on water samples obtained near the centroid indicated turbidity values in excess of 20 $mg \cdot L^{-1}$ were common in the first hour of the monitoring operation, decreasing with time and returning to background levels of 2 to 5 $mg \cdot L^{-1}$ within 3.5 to 4 hours of an individual disposal event.

The sediment plumes formed at RISDS during the study were the result of dredged material disposal events at pre-determined, target disposal points within the RISDS boundary. These points were selected based upon the results of sediment plume behavior modeling prior to the start of the Providence River and Harbor Maintenance Dredging Project in an effort to maximize the amount of time for the sediment plume to dissipate through particle settlement and dilution prior to leaving the area defined as the “mixing zone” to comply with water quality criteria. In general, regardless of the actual point of disposal, the centroid of each sediment plume studied remained within the disposal site boundary for a minimum of 30 minutes, but commonly resided within the site for one to two hours. Although the TSS data has shown turbidity within this sediment plume was typically of little environmental significance at the time the individual plumes crossed the boundary, refinement of the model calculations used to predict plume behavior at RISDS and the target disposal positions could increase plume residence time and allow suspended sediment concentrations to fully return to background levels prior to leaving the site boundaries.

Modeling efforts and mass balance studies over the past ten years have examined the relationship between grain size distribution and water content of dredged material to the percentage of a particular barge volume that becomes entrained in the water column. While the mechanics dictating the formation of a sediment plume remain relatively constant within the near coastal environment, the concentration and morphology of each plume monitored as part of the RISDS study appeared heavily dependent upon other variables. The configuration of the disposal barge had a noticeable effect on turbidity levels within the initial plume, as well as its overall size and persistence within the water column. In addition, the morphology of the sediment plume over time was directly related to water column currents and the physical properties of the water mass, which impacted transport rate of the suspended sediments and subsequent dilution of the sediment plume over time. From an ecological perspective, variations in these parameters could affect the degree and duration of exposure that pelagic organisms are subjected to environmental contaminants associated with sediments dredged from an industrialized harbor.

Water samples were collected specifically for toxicity analysis at 40, 60, and 120 minutes post-placement during both the April and September 2004 survey efforts. After a 96-hour exposure to waters collected at or near the centroid of the plume, neither the mysid (*Americamysis bahia*) nor juvenile silverside (*Menidia spp*.) test organisms exhibited a lethal response in any of the tests that were run. This was the anticipated outcome for the materials dredged from the Sabin Point Reach in April 2004 given the low levels of contamination detected within the in-place sediments. However, the material dredged from Fuller Rock Reach in September 2004 was restricted to a maximum volume of 2,280 m^3 (3,000 yd^3) for each disposal event due to the results of elutriate testing performed during the characterization of the in-place sediments in 1994. The reduced volume of dredged material was transported to RISDS in 6,000 yd^3 barge that offered a larger areal footprint relative to the smaller capacity 4,000 yd^3 barge that could have been employed. The effects of placing a reduced volume of sediment within a disposal barge offering a larger footprint resulted in the formation of a more dilute sediment plume within the water column upon placement. Therefore there was a reduced potential of toxicity within the sediment plumes generated by material dredged from Fuller Rock Reach.

Assessment of Project Logistics and Field Sampling Techniques

Although the sediment plume monitoring surveys were performed on an ambitious schedule that required tight logistical control, all sampling elements of the field study proved to be operationally feasible. The key to the success of the project was strong logistical planning and coordination between the dredging/sampling operations within Providence River and the survey activity being conducted at RISDS.

Barge Sampling

The sediment sampling that was conducted aboard the disposal barges was a relatively straightforward process requiring coordination between the scientific, engineering, and operational elements in advance of sampling. In general, the process of retrieving sediment samples from the disposal barge provided a good composite sample from each barge load, with minimal interruption of the continuous dredging process. Due to transit time between the dredging area and the disposal site, as well as the unpredictable nature of dredge production efficiency through the course of the evening, multiple barges were often sampled during the evening prior to monitoring operations to provide greater flexibility when attempting to schedule the offshore monitoring operations on the following day. Once it was determined which barge was on a favorable schedule for plume tracking operations, the final homogenizing and sample splits for geotechnical and geochemical analyses were made and sub-samples subsequently shipped to their respective laboratories for analysis.

Current Measurements

Since the morphology, migration, dilution, and particle settlement rate of the sediment plume were a function of water column currents, accurately determining the direction and magnitude of these currents was a critical element of the monitoring operation. The methodology employed as part of this study offered strong redundancy in current measurements from the three independent measurement systems (current-following drogues, underway ADCP, bottom mounted ADCP).

The current following drogues were relatively simplistic, but provided very useful real-time information on currents for the scientific crews on both survey vessels (ADCP and CTD). Since multi-level, divergent flow was documented within the water column during several of the survey days, the sediment plume tended to expand and become dilute at the surface and mid-depth. When deployed immediately following the disposal event, the drogues and drifters consistently remained with the densest portion of the sediment plume at their respective depth intervals (surface, mid, deep) and served as visual markers for the CTD profiling and acoustic interrogation with the ADCP.

The bottom-mounted ADCP provided useful Eulerian (fixed position) time series data on currents throughout the water column for the 3 to 4 hour duration of each plume study. The information collected with the bottom-mounted ADCP provided a continuous, high-resolution digital data set that offered insight into the behavior of the plume, as well as confirmed the observations made by the underway ADCP and drogue tracks regarding multi-level, divergent current flow.

The primary function of the underway ADCP was to assess acoustic backscatter in the water column prior to and following the disposal event to document plume morphology and transport. In addition, the ADCP provided real-time current profile data that were used prior to each disposal event to aid in determining the likely path of the plumes as they were advected away from each disposal point.

Vertical Profiling of Density and Optical Turbidity

The CTD profiling system was quite useful in the plume monitoring program, acquiring accurate and high-resolution data for each vertical profile. The data from the CTD were monitored in real-time, generally allowing profiles to extend to within 1 to 2 m of the seafloor. However, when ocean swell was encountered the depth of profiling was limited to 3 to 4 m above the seafloor (to prevent equipment impact with the bottom and subsequent resuspension).

The transmissometer that was also integrated within the CTD package provided better resolution than an integrated OBS sensor and was the preferred instrument for sediment plume tracking. The real-time data from the transmissometer provided useful data for making instantaneous judgments on vessel position relative to the depth and location of the plume centroid. The increased resolution of the transmissometer enabled the detection of small-scale changes in water column turbidity that was necessary to distinguish the centroid from the periphery of the sediment plume.

Collection of Discrete Water Samples in the Plume Centroid

The Carousel water sampler functioned as expected for the duration of the survey operation, reliably firing Niskin and GO-FLO bottles upon electronic command from the vessel laboratory. All bottles closed properly upon firing, and no samples had to be recollected. The multi-bottle sampler was a critical component to the success of the survey operation given the rapid sampling that was required during the first hour of each survey (sample intervals T1, T2, T3, and T4). By integrating the seawater sampling device with the real-time vertical profile CTD data, there was a high degree of confidence that the hydrocast was acquired within the proper time interval and the desired height above bottom.

Vertical Profiling of Acoustic Backscatter along Transects

The primary purpose of the vessel-mounted ADCP was to collect acoustic backscatter information from the water column and provide a cross-sectional view of the sediment plume over RISDS. Similar methodology has been used in plume studies performed within dredging areas and dredged material disposal sites, with varying degrees of success (Land and Bray 2000). In general, use of the 600 kHz ADCP at the open water dredged material disposal site provided useful spatial information on settling and lateral transport of the plumes.

In addition, a 1200 kHz ADCP was used in tandem with the 600 kHz system primarily to provide high-resolution data during the later stages of the plume monitoring surveys when sediment concentrations in the water were expected to dissipate and acoustic backscatter levels diminish. However, due to the density layering within the water column and signal attenuation, the higher-frequency, but weaker, outgoing acoustic pulses of the 1200 kHz system were unable to penetrate beyond mid-depth. As a result, these data were only valid for the top 13 to 15 m of the water column, yielding an incomplete profile of the sediment plume.

A series of survey lines aligned perpendicular to the projected direction of plume transport was occupied with the vessel-mounted ADCP to best capture the leading edge, core, and trailing edge of each plume monitored as part of the study conducted at RISDS. Since the process required collecting data over the acoustically detectable margins of the plume, the length of the survey lines increased with distance from the initial disposal point as the turbid plume broadened with time. As the core of the plume was identified in the real-time ADCP record, its position relative to the current-following drogues was relayed to the water-sampling vessel to aid in directing the CTD profiling operations in obtaining profiles and hydrocasts from the centroid.

One unanticipated finding with regards to the use of underway ADCPs for plume characterization was the impacts associated with the density structure of the water column on the quality of the acoustic data used to characterize plume morphology. During the April 2004 survey, the acoustic data collected to assess background conditions within the ambient water column yielded substantially higher backscatter intensities within at mid-depth (10 to 20 m water depth). Although these results suggested the presence of a significant turbidity layer in the water column prior to dredged material disposal activity, there were no corresponding deflections in the transmissometer record during background water column profiles. Based upon the findings of similar surveys conducted in support of turbidity monitoring, it was theorized that the banding effect was driven by changes in seawater density within the mid-water column (Flagg and Smith 1989). Despite the existence in what would traditionally be described as a well-mixed water column, the high resolution CTD data revealed many small-scale, but sharp vertical density gradients that may have acted as reflectors of the acoustic signal transmitted by the ADCP. The acoustic returns associated with these density micro-layers were indistinguishable from backscatter related to suspended particulate matter in the mid-water column. As a result, once the raw background backscatter signal was removed from the cross-sectional data collected as part of the April 2004 survey efforts, the effects of the strong acoustic signature associated with the water column density gradient tended to obscure the morphology of the sediment plume at mid-depth.

Conversely, the data collected during the September 2004 survey efforts did not display the same banding effect at mid-depth despite the presence of a stratified water column. Individual acoustic reflectors yielding strong increases in raw backscatter intensities were detected at depths corresponding to well-defined pycnoclines within the water column. However these were discrete features with thicknesses of 0.5 to 1 m and did not have any adverse impacts on the determination of residual acoustic backscatter intensities.

Moored Measurements of Optical Turbidity

The moored OBS array was deployed for each of the three disposal plume tracking events to measure changes to water column turbidity at three levels in the water column during plume passage. The instrument string was deployed following conversations with the approaching tugboat and a determination of the target placement location for the load of interest. The array was placed in the predicted path of the sediment plume based on background current measurements made with the vessel-mounted ADCP. The OBS mooring collected reliable data during each of deployment, with the time-series of turbidity data useful in evaluating relative turbidity and transport rates in the mid-water column (13 and 18 m depth), as well as near-bottom (32 m depth). The distance between the OBS mooring location and the target disposal point varied between survey operations, providing information on either near-field and far-field impacts to water clarity.

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