SUSPENDED SEDIMENT PLUMES ASSOCIATED WITH NAVIGATION DREDGING IN THE ARTHUR KILL WATERWAY, NEW JERSEY

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ABSTRACT

The Port Authority of New York/New Jersey and the New York District of the US Army Corps of Engineers, in coordination with other state and Federal agencies, have begun an extensive navigation channel deepening program known collectively as the Harbor Deepening Project. Regulatory agencies have identified sediment resuspension during the dredging process as a primary environmental concern. Consequently, monitoring of mechanical dredging operations in the Arthur Kill Waterway, New Jersey, was undertaken as part of a concerted effort to characterize the spatial and temporal dynamics of suspended sediment plumes under conditions typical of the deepening project. Plumes created during removal of overlying maintenance sediments by a 13.8 cubic meter (18 cu yd) capacity environmental Cable Arm® bucket were surveyed to determine their dispersion patterns from a location near the confluence of the Arthur Kill Waterway and Newark Bay during flood and ebb tides. Monitoring efforts included deployment of optical backscatter sensors (OBS) for time series records of turbidity and acoustic Doppler current profiler (ADCP) surveys to map acoustic signatures of the sediment plumes. Estimates of total suspended solids (TSS) concentrations were derived from acoustic backscatter data. OBS data indicated that ambient turbidities were generally less than 8 nephelometric turbidity units (NTU) in the upper portion of the water column, decreasing to 3 NTU at a depth of 8 m. Sensors deployed in central axis of plume movement indicated that average turbidities exceeded background by 15 NTU at approximately 30 m down-current and 11 NTU at 50 m. Maximum turbidities exceeded background by as much as 74 NTU in short duration "spikes" at the innermost sensors. Elevated turbidities ranging from 25 to 50 NTU above background occurred in pulses less than 30 minutes in duration. Maximum TSS concentrations measured acoustically at a distance of 10 m from the source were approximately 300 mg/L. TSS concentrations 100 m down-current from the source generally did not exceed 120 mg/l. These values are consistent with the results of gravimetric analyses of water samples taken within the plume, which ranged from 100 to 190 mg/l less than 60 m from the source. TSS concentrations decreased to 50 mg/l or less at a down-current distance of approximately 150 m, and to 20 mg/l at 350 m from the source, indicating rapid settling of the plume. ADCP plume signatures with concentrations less than 10 mg/l above background were detectable as far as 620 m from the source. Plume trajectories were generally confined to the basin of the navigation channel, with no evidence of excursion beyond the channel side slopes. Some variation in both turbidity and TSS concentrations at comparable depths and distances from the source between sampling events was noted, attributed to short-term variation in dredge production rates. Results support a finding that management practices applied to the dredging operation effectively ensured minimal release of sediment to the water column and generation of spatially confined plumes with generally low internal TSS concentration gradients.

Keywords: Turbidity, mechanical dredge, environmental bucket

INTRODUCTION

To remain competitive in a rapidly changing global marketplace, ports nationwide must be able to accommodate the newest generation of deep-draft commercial ships. Recognizing the need for continued improvement of harbor navigational channels, the Port Authority of New York/New Jersey (PANY/NJ) and the New York District of the US Army Corps of Engineers (USACE) have undertaken an extensive navigation channel deepening program known collectively as the Harbor Deepening Project (HDP). A major concern raised by regulatory agencies during the coordination of the HDP has been potential detrimental environmental impacts of sediments resuspended during the dredging process. Consequently the conduct of dredging during the HDP is subject to management practices

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intended to minimize resuspension, thereby minimizing risks to the environment. Management practices include environmental windows (i.e. constraints on the seasonal timing of dredging operations), equipment selection options (e.g., mechanical rather than hydraulic dredges, closed rather than open buckets), and adherence to operational measures (e.g., limitations on bucket hoist speeds). Application of various management practices can inflate the cost of dredging, and the effectiveness of many management practices in achieving meaningful reductions in sediment resuspension remains speculative. To address knowledge gaps concerning the spatial and temporal scales of suspended sediment plumes, field monitoring of plume dynamics induced by dredging as conducted in the HDP has been initiated.

During dredging operations, some sediment is invariably resuspended into the water column. In many cases, this suspended sediment is evident as visible surface turbidity plumes in the vicinity of the dredge operation. Potential impacts of sediment resuspension and subsequent deposition on aquatic organisms and their habitats have been a persistent concern of regulatory agencies, particularly where dispersion of sediment-bound contaminants may occur. The scale of the HDP has therefore generated concerns for both short and long-term consequences of sediment resuspension in the harbor system. To address critical aspects of these concerns, an understanding of dispersion of resuspended sediment from dredging sources is required. Although many previous studies have examined the spatial and temporal scales of dredging-induced plumes, the multiplicity of factors that govern dispersion patterns (e.g., geotechnical properties of the *in situ* sediments, type and size of the dredge plant, production rate of the dredge, site bathymetry, local hydrodynamics) site-specific studies can provide useful insights in support of assessments of likely impacts.

Because suspended sediment plumes are dynamic rather than static phenomena, varying over large areas in short periods of time, particularly when driven by tidal forces, characterizing plumes can present a difficult challenge. Data collected at subjectively determined points in time at fixed locations are insufficient to assess dredge plume structure. However, advanced acoustic technologies offer advantages in capturing data at appropriate spatial and temporal scales to allow more accurate interpretation of plume dynamics. This study entailed plume characterization during the removal of sediments from the North of Shooters Island Reach (Figure 1) of the Arthur Kill (AK) waterway navigation channel by a 13.8 cubic meter (18 cubic yard) capacity environmental Cable Arm® bucket, from the Dredge *Michigan*, operated by Donjon Marine Company, Inc. (Figure 2).

Figure 1. Study site indicating location of Shooters Island in relation to Newark Bay. (Map courtesy of Google Earth)

Figure 2. The Dredge *Michigan* using a Cable Arm® environmental bucket in the Arthur Kill Waterway. The shoreline of Shooters Island is in the background.

METHODS

Current Structure and Suspended Sediment Plume Acoustic Signatures

An RD Instruments 600-kHz Mariner Workhorse Series acoustic Doppler current profiler (ADCP) was used to collect current velocity, direction, and acoustic backscatter data. Navigation data received from a differential Global Positioning System were collected synoptically and integrated during data post-processing. Acoustic backscatter data were analyzed using Sediview Software provided by Dredging Research Ltd. The Sediview Method (Land and Bray 2000) derives estimates of suspended solids concentration for each ADCP data bin. This process requires collection of a field data set consisting of water samples, analyzed gravimetrically, that represents the full TSS concentration gradient occurring at the study site. These "groundtruth" data are used to calibrate the acoustic backscatter data. Water samples are collected at known locations within the insonified portion of the water column, so that individual gravimetric samples can be directly compared with acoustic estimates of concentration for the same unit volume of water. All ADCP surveys were similarly designed, with roughly parallel transects established perpendicular to the channel's long axis at distance intervals selected to capture the entire spatial extent of fully developed plumes. Data were recorded in horizontal and vertical bins of predetermined sizes to optimize plume resolution.

Water Sampling

One hundred water samples were collected using a Niskin-type 2.2 L water sampler. Water samples were processed gravimetrically for TSS (mg/L) and optically for turbidity measured in nephelometric turbidity units (NTU) using standard laboratory procedures (EPA-600/4-79-020, March 1983 and subsequent revisions).

Optical Turbidity

D&A Instrument Company optical backscatter sensors (Model OBS-3A) capable of measuring turbidities in the 0 to 1,000 NTU range were used in this study. Ten OBS units were deployed at depths ranging from 0.5 to 9.5 meters during each monitoring event to capture both ambient and internal plume data.

RESULTS

Current Structure

Depth-averaged current vectors indicated a generally uniform vertical flow patterns during the flooding tide. Vector headings indicated that flows were predominantly to the west into the AK during the flooding tide, with current velocities ranging from 0.32 to 0.40 m/sec. During the ebbing tide, flows were vertically mixed. At the northern terminus of each transect, current flows were typically to the west (0.34 m/sec) except in the upper 1 to 2 meters of the water column. At the southern end of each transect, flows (0.28-0.30 m/sec) were generally to the east.

Acoustic Concentration Data Calibration

In this study, 100 water samples ranging in TSS concentration from 5.2 to 190 mg/L produced a robust calibration, although the number of samples at the upper end of the concentration gradient was somewhat limited. In Figure 3 the entire population of gravimetric measurements derived from water samples and acoustic estimates derived from ADCP backscatter data are arranged in rank order. For these data the relationship between gravimetric and acoustic measures had a relatively high degree of correspondence, although acoustic estimates of concentrations tended to be slightly higher than gravimetric concentrations in the 20 to 70 mg/L range.

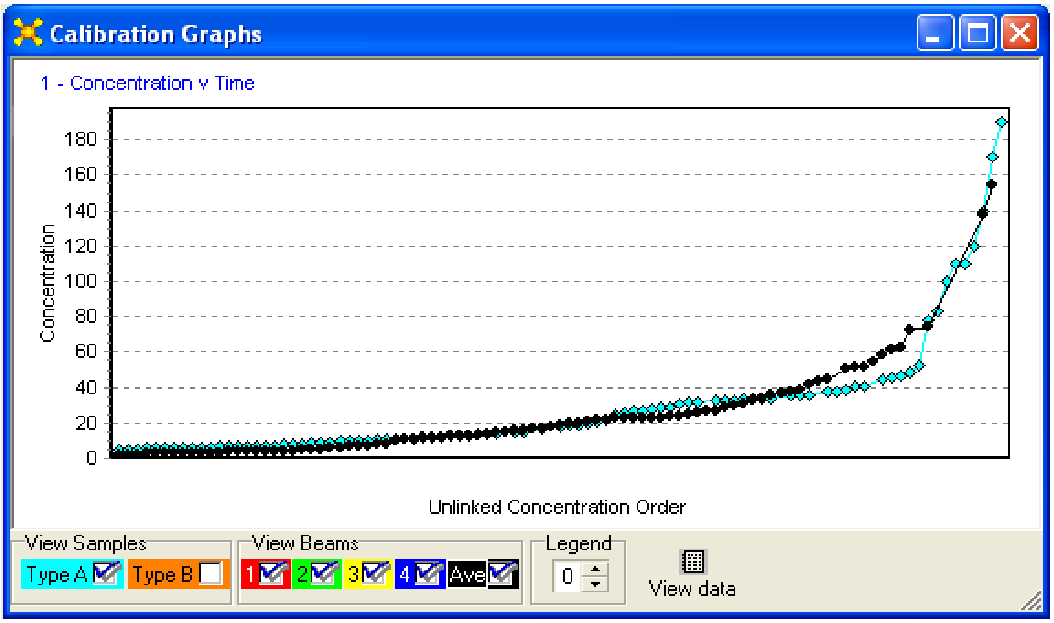

Figure 3. Comparison of gravimetric and acoustic estimates of TSS concentration for the entire population of samples in rank order. Results of gravimetric analysis (TSS) of water samples are represented in blue, whereas TSS estimates derived from ADCP data are in black.

Turbidity

Because optical measures of turbidity are influenced by properties of the sediments in suspension, direct comparison of turbidity and TSS concentration cannot be made without synoptic samples obtained from the same sampled water volume. TSS (mg/L) values determined from laboratory gravimetric analyses and synoptic NTU values measured by the OBS-3A unit affixed to the water sampler display a relatively high degree of correspondence (R^2 = 0.8846). Some scatter is present and can be attributed to the highly variable conditions within the plume where the higher NTU and mg/L values were obtained. Plumes, particularly near the source of re-suspension, are very heterogeneous with larges changes in concentration occurring on very small spatial scales. Turbidity measurements taken at 5 to 15 second intervals by moored sensors at ambient, near-field, and far-field stations during sampling efforts on 20, 22 and 23 June are summarized in Table 1.

Table 1. Summary of turbidity values recorded during flood and ebb tidal cycles.

Station Description	Depth	20 June 2006 (NTU)			22 June 2006 (NTU)			23 June 2006 (NTU)		
		Dist.	Mean	Range	Dist.	Mean	Range	Dist.	Mean	Range
Station 1 Up-current Ambient	< 1							540	8.7	7.1-9.5
	2-3				350	5.2	4.8-5.7	540	4.4	3.7-5.8
	4-5	150	7.0	6.3-10.7	350	3.3	2.6-4.1	540	4.3	3.4-5.0
	7-8	150	7.4	5.9-13.8	350	2.6	2.3-3.7	540	2.2	1.3-3.6
	>9	150	7.0	5.1-13.5						
Station 2 Down-current Near-Field Plume	< 1							60	7.5	6.6-11.0
	2-4	63	9.1	5.5-14.6	60	6.8	2.4-26.7	60	4.0	2.2-12.9
	5-7	63	9.4	4.5-34.7	60	5.8	2.5-35.1	60	12.8	1.3-38.7
	>7	63	163	2.4-66.4	60	4.8	1.2-32.7	60	13.2	1.6-56.3
Station 3 Down-current Far-Field Plume	< 1							145	9.2	8.9-9.4
	2-4	160	9.3	4.1-23.4	150	Sensor Failed		145	4.0	3.3-5.4
	5-7	160	13.7	4.9-49.6	150	3.3	2.3-7.1	145	10.4	7.-17.9
	>7	160	18	4.5-57.0	150	2.1	1.0-4.3	145	5.4	3.5-15.2

Ambient Turbidity Conditions

A representative time series record of ambient turbidities during a flooding tide is given in Figure 3. Ambient readings ranged from 1.3 to 13.8 NTU throughout the water column, with a mean turbidity of approximately 7 NTU. In ebbing tide time series data ambient turbidities were highest in the upper portion of the water column (< 2 m), averaging 8.7 NTU on 23 June. Lower average readings occurred on the same date at 2.2 NTU for the sensor deployed at a depth of 8 m. Readings above 10 NTU occurred only once on 20 June when a tug passed close to the moored OBS unit producing a short-lived spike in turbidity, particularly at the two deeper sensors (7.4 and 9.5 m) (Figure 4). This "spike" was considered to be an indication of natural background turbidity because of the obvious linkage to the passage of the tug. If this single event is excluded, turbidity values less than 10 NTU were consistently representative of ambient turbidity conditions throughout the study.

Near-Field During-Dredging Deployment

OBS sensors were deployed during 3 sampling events for durations ranging from 1.5 to 3.5 hours at a distance of approximately 60 m down-current from the bucket at depths of 0.3, 1.7, 3.4, 5.0, 6.5, 8.0 and 9.1 m (not all depths were instrumented in every monitoring event). Highest turbidities occurred during a flooding tide when relatively slow current flows carried the plume to the west. The production rate of the dredge during this flooding tide survey was observed to be relatively high, evidenced by the fact that the dredge completely loaded the barge in about 2.5 hours. Loading times observed on other dates were as long as twelve hours. Nevertheless, it should be noted that based on the daily inspection logs the overall production rates were relatively low on the monitoring dates as compared to rates achieved earlier in the dredging project (see Table 2). Current vectors during ebbing tides varied considerably from westerly (northern terminus of transect) to easterly (southern terminus) with mixed flows in the middle reach of the channel. Therefore it is possible that the plumes deviated from a path that would carry them through the fixed buoy stations during portions of the OBS unit deployments.

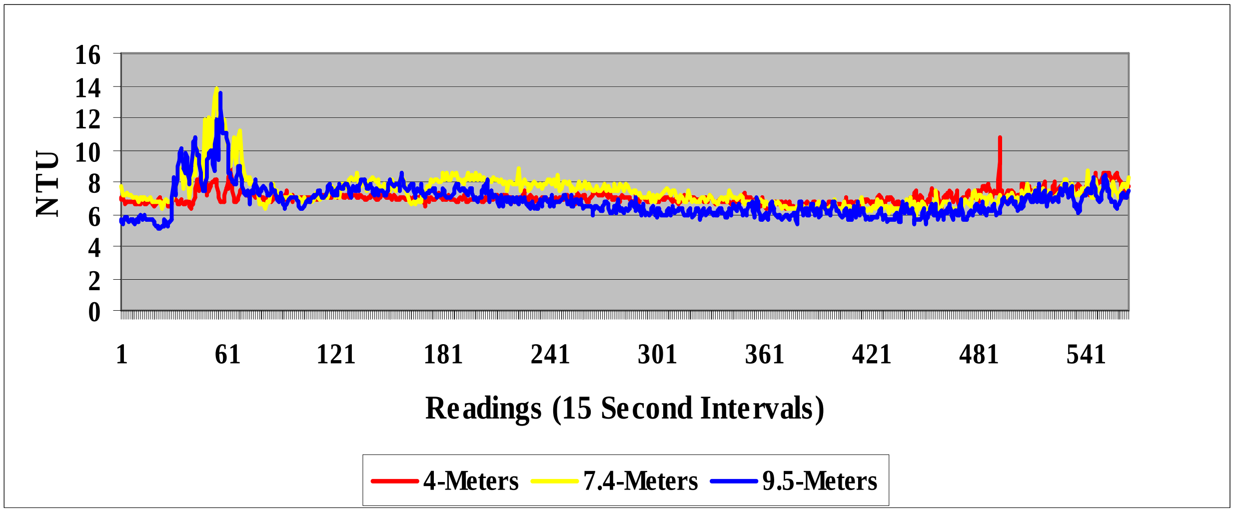

Figure 4. Ambient turbidity measured at depths of 4.0, 7.4 and 9.5 m at a distance of 150 m up-current from the dredging operation during a flooding tide on 20 June 2006.

Figure 5 provides time series results for the 60 m near-field station during a flooding tide. Turbidities were lower at the two upper sensors where values ranged from 5.5 to 14.6 NTU (sensor at 2.1 m, mean = 9.1 NTU) and 4.5 to 34.7 NTU (sensor at 3.4 m, mean = 9.4 NTU) respectively. Turbidities rarely exceeded ambient at the uppermost sensor (2.1 m). The highest recorded near-field turbidity occurred at the lower sensor (9.1 m), peaking at 80.7 NTU, or approximately 70 NTU above ambient. Turbidities at water depths of 6.5 m (mean = 16.3 NTU) and 9.1 m (mean = 21.8 NTU) were approximately twice those in the upper water column, indicating that the suspended sediment plume occurred primarily in the lower half of the water column.

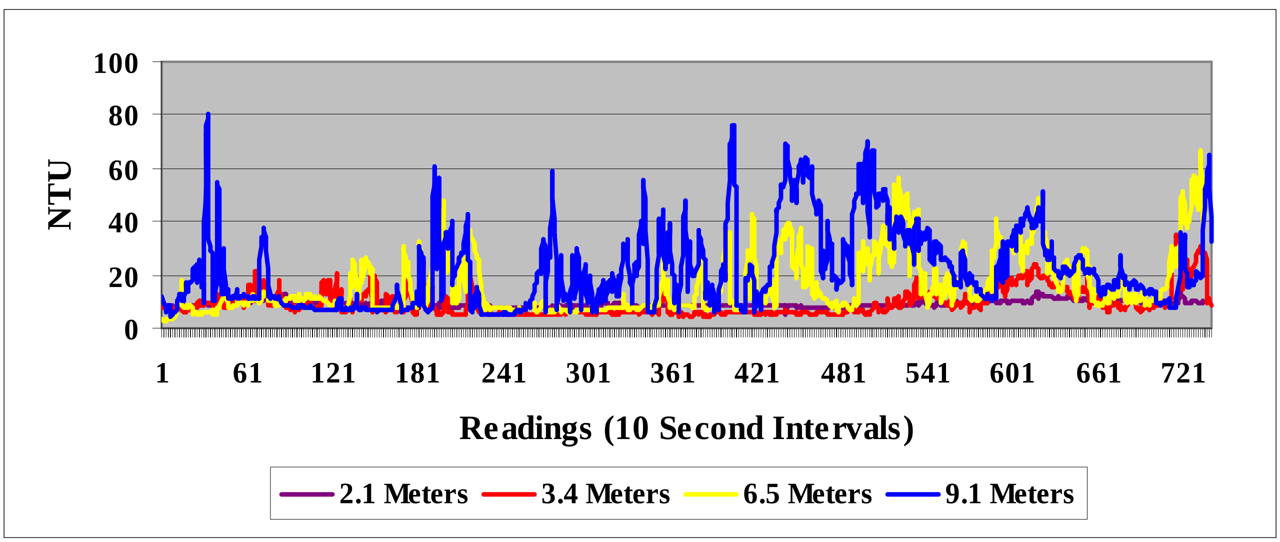

Figure 5. Near-field turbidity measured at depths of 2.1, 3.4, 6.5 and 9.1 m at a distance of 60 m down-current from the dredging operation during a flooding tide on 20 June 2006.

Turbidity at 60 m down-current from the source during an ebbing tide on 22 June peaked at the mid-water sensor at 35.1 NTU, approximately 25 NTU above background. Turbidities differed only slightly between the shallow sensor at a depth of 1.8 m (mean = 6.8 NTU) and the deep sensor at a depth of 8 m (4.8 NTU). Ambient conditions were exceeded by 10 NTU or higher during six time intervals, each persisting no longer than several minutes.

OBS units redeployed in the near-field at 60 m on 23 June during an ebbing tide provided slightly different results. In contrast to the previous day's data, movement of the plume was largely confined to the lower half of the water column, in a manner similar to that observed during the flooding tide. The two sensors located at 0.3 m (mean = 7.5 NTU) and 2 m (mean = 4 NTU) water depth recorded peak turbidities less than 13 NTU, indicating very little sediment movement in the upper water column. Mean turbidities in the mid- (5 m) and lower (8 m) segments of the water column were similar at 12.8 NTU and 13.2 NTU respectively. Peak turbidity occurred at the deep sensor (8m) at 56.3 NTU, approximately 46 NTU above background.

Far-Field During-Dredging Deployment

In comparison with the synoptic near-field data, peak turbidities at the far-field station 160 m from the source fell by as much as 10 (shallow sensors) to 23 (deep sensors) NTU. More turbid waters were found at the deepest sensor (9.2 m) with a peak turbidity of 57 NTU. A time series record of far-field turbidities measured during the flood monitoring event can be found in (Figure 6). Mean turbidities increased with increasing water depth from 9.3 NTU at the shallow sensor (4 m), to 13.7 NTU at the mid-water sensor (6.5 m), and to 18 NTU at the deepest sensor (9.2 m) (Table 1).

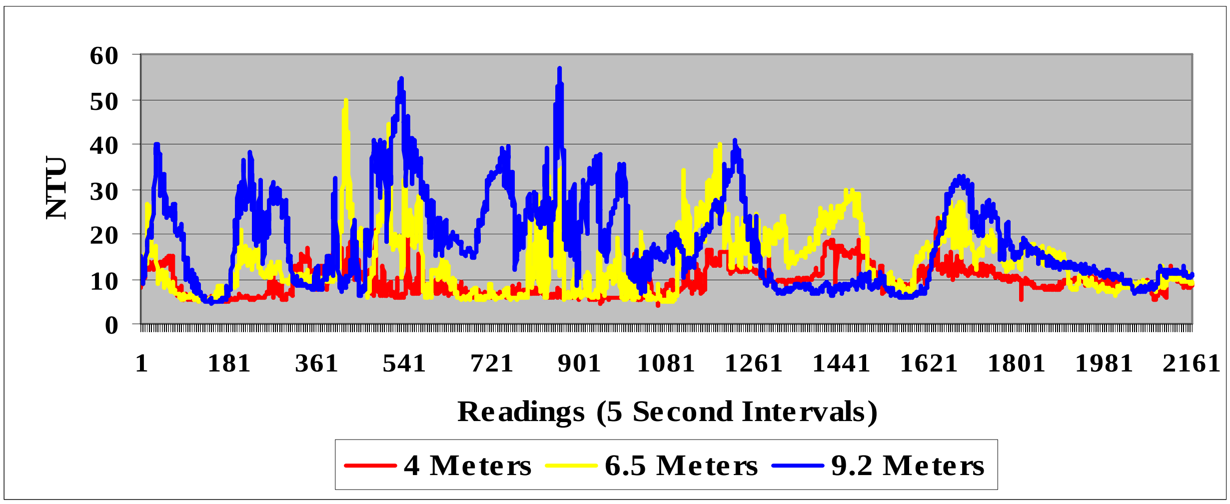

Figure 6. Far-field turbidity measured at depths of 4, 6.5 and 9.2 m at a distance of 160 m down-current from the dredging operation during a flooding tide on 20 June 2006.

At OBS units deployed 150 m down-current from the dredging operation on 22 June during an ebbing tide turbidities were relatively low (< 7 NTU), indicating that the plume was decaying substantially before reaching the sensors at this distance. However, no data were obtained for the upper (1.8 m) sensor due to equipment failure. On the following day at OBS units deployed 145 m down-current from the source during an ebbing tide turbidities remained relatively low. Mean turbidity at the uppermost sensor was 9.2 NTU, within the range of ambient conditions at the site. Maximum turbidity (17.9 NTU) exceeded ambient by 8 to 12 NTU at a depth of 5 m, when compared to the 5 NTU maximum observed at the up-current 5 m sensor. Background readings were also exceeded by 13 NTU at the lower sensor (mean = 15.2 NTU), as compared to the 2 NTU reading measured at the comparable depth at the up-current station.

Bucket Production Rates

Daily dredging inspection logs submitted by the contractor for the Dredge *Michigan* were used to estimate production rates (Table 2). Production rates were calculated simply as the total cubic yards excavated divided by the total hours of active dredging on a given day. Therefore these production rates represent a composite of a very large number of bucket cycles. These rates do not reflect the highly punctuated activity that was observed to characterize the dredging operation over shorter time intervals. Periods of high productivity while the dredge was digging in "new" sections of the cut or where the dredge encountered thicker overburdens of maintenance materials were interspersed with series of bucket cycles in which little sediment was actually removed. The latter probably typified dredging as the bucket approached the depth of refusal, or where the unconsolidated overburden layer was thin. Daily production rates changed substantially during the course of the dredging project, tending to decline from beginning to end. Initially the production rate averaged over 400 cubic yards per hour and stayed above 300 cubic yards per hour through 15 June. From this date forward production rates decreased consistently. By the start of monitoring on 19 June, when both ebb tide surveys (NJEA and NJEB) were conducted, the production rate was 114.8 cubic yards per hour, relatively low when compared to the previous dates. Production rates increased on 20 June to 257.7 cubic yards per hour, during which time the flood survey (NJFD) was completed. This production rate was closer to the average production rate for the entire project. The remaining survey (NJAB) was conducted during a period when the dredge removed only 59.5 cubic yards per hour.

Table 2. Production rates for the Dredge *Michigan* based on daily inspection logs.

Date	Material Removed (Cu. yds)	Hours	Cu. yds/ Hour	Surveys Completed	Date	Material Removed (Cu. yds)	Hours	Cu. yds/ Hour	Surveys Completed
1 June	3,422	8.5	402.6	-	15 June	1,156	3.5	330.3	-
2 June	5,850	13.67	427.9	-	16 June	3,400	14.67	231.8	-
3 June	2,267	5.5	412.2	-	17 June	1,925	13.85	139.0	-
5 June	4,533	13.15	344.7	-	19 June	1,463	12.75	114.8	NJEA & B NJFA & B
6 June	5,083	10.33	492.1	-	20 June	5,025	19.5	257.7	NJFD
7 June	4,250	13.95	304.7	-	21 June	1,157	12.85	90	NJFF NJWS
8 June	4,622	13.67	338.1	-	22 June	565	9.5	59.5	NJAA &B NJWS
9 June	3,178	10.33	307.7	-	23 June	782	14.0	55.9	NJWS

Bucket Cycle Times

In addition to the use of a Cable Arm® environmental bucket, an operational measure to reduce overall sediment resuspension was a 2 ft/sec restriction on the hoist speed of the bucket. This management practice is intended to prevent excessive sediment loss caused by turbulence and washing of sediment off external surfaces of the bucket as well as reduction of rapid changes in hydraulic head as the bucket transits the water/air interface. One outcome of complying with this management practice is to slow down the bucket cycle. In many unrestricted maintenance dredging projects in channels of depths comparable to the AK, an average bucket cycle (i.e. the time elapsed from bucket insertion into the water through descent, impact with the bottom, closure, ascent, slewing over the barge, dumping into the barge, and return to the water's surface) can be 60 sec or less. To examine the bucket cycle sequence as applied in the AK project, a video record was obtained of twenty complete cycles. The video record was then analyzed for time increments for each component of the cycle.

For the observed bucket cycles average elapsed times for each component were as follows: descent = 14.5 seconds, closure = 14.6 seconds, ascent = 22.4 seconds, slewing to barge = 18.3 seconds, dumping = 8.1 seconds, and slewing back to water = 14.1 seconds. The average total elapsed time per cycle was 92.0 seconds. A certain degree of variability in cycle component elapsed times was seen across the 20 cycles selected for evaluation. The shortest cycle was 82 seconds long, whereas the longest was 102 seconds long. The hoist speed restriction demonstrably slowed the pace of the operation. The average duration of the ascent component was 22.4 seconds, which indicates that at 2 feet/second the bucket could traverse 44.8 feet of vertical depth. Given the approximate 45 ft depth of the channel in which the dredge was working, the contractor appeared to be adhering to the 2 feet/second hoist speed restriction.

Sediment Plume Acoustic Characterization

Ambient Conditions

Ambient conditions were consistently below 10 mg/L during each of the sampling efforts. The only departure from this occurred in the lowest 1 m of the water column, where TSS concentrations of up to 15 mg/L were infrequently observed. For the purpose of graphical presentation of plume acoustic signatures in cross-sectional profiles, concentrations < 10 mg/L were considered ambient conditions. All acoustically estimated TSS concentrations > 10 mg/L are herein considered to be attributable to the presence of the dredging-induced plume unless otherwise stated. For example, during one plume characterization survey (NJFD) concentrations above background caused by ship traffic occurred on portions of four transects on the up-current or ambient side of the dredging operation.

Ebb Tide During-Dredging Plume Characteristics

A "3D" depiction of the plume mapped during Survey NJEA is presented in Figure 7. Note that the TSS concentrations are plotted in X and Y coordinates with an exaggerated Z (depth) axis. To examine plume structure in as complete detail as possible a series of vertical profiles were also generated for increasing distances from the dredging operation. Examples at selected distances from the source are given in Figures 7 through 9. Considered in tandem the 3D, plan view, and vertical cross-sectional profiles can be examined to reveal detailed internal TSS concentration gradient structure of the plume at known distances from the source of resuspension. Note that the northern shoal is depicted on the left side of each vertical cross-sectional profile.

Ambient conditions (i.e. acoustically estimated TSS concentrations of 10 mg/L or less) were found throughout the water column on the up-current side of the dredging operation on Survey NJEA with the exception of the parcel of water immediately off the channel bottom in which TSS concentrations intermittently reached 15 mg/L.

On the innermost north (port) transect, passing approximately 10 m lateral to the bucket, TSS concentrations reached as high as 70 mg/L, or approximately 60 mg/L above ambient. Evidence of lateral spreading of the plume at the point of excavation was confined to the lower half of the water column (> 7 m). TSS concentrations up to 20 mg/L above background extended 70 m northward, but were confined to the bottom 3-m of the water column. A passing ship earlier in the survey on this side of the dredge plant is likely to have contributed some portion of the suspended sediment evident on this transect. Detection of plume-derived suspended sediment south of the dredge was not possible until the plume emerged from under the barge. Resuspended sediment was detected in the lower half of the water column on the nearest south (starboard) transect, at a distance of 6 m from the barge. TSS concentrations here were less than 50 mg/L. At 12 m from the south side of dredge TSS concentrations above background were detected only in the bottom meter of the water column. Detection of a distinct plume signature against background levels was not made beyond this distance.

Survey NJEA transects occupied down-current from the dredging operation in the direction of plume movement indicated that the plume was largely confined to the lower water column within the navigation channel basin. A surface plume (i.e. at a depth of 2 m) was not evident beyond 100 m from the point of excavation. The detectable plume was not more than 30 m wide and averaged 10 mg/L above background. There was no evidence of the plume leaving the boundaries of the navigation channel. A vertical profile (Figure 8) of TSS concentrations at a distance of 25m down-current shows the concentration gradient structure at the plume's stage of largest lateral development. Note that air entrained in the upper part of the water column is highlighted in red. TSS concentrations in the lower portion of the water column reached 70 mg/L in a small central core of the plume. Maximum TSS concentrations were considerably lower than those estimated during the flooding tide survey. During the ebbing tide survey, currents were not as strong or as unidirectional as were observed during the flooding tide. Also, the dredge had moved to a more central position in the channel. Apparently less sediment needed to be excavated here as indicated by a relatively low production rate of 114.8 cubic meters per hour. Rapid settling of the plume was evident. At 113 m down-current only a faint plume signature remained with concentrations exceeding background by only 10 mg/L, although the diffuse plume still occupied most of the water column (Figure 9). The plume continued to settle lower in the water column over the next 100 m, and at 215 m down-current occupied a swath less than 60 m wide that remained confined to the lower 2 m of the water column (Figure 10). A return to ambient conditions occurred at a distance 270 m down-current from the source.

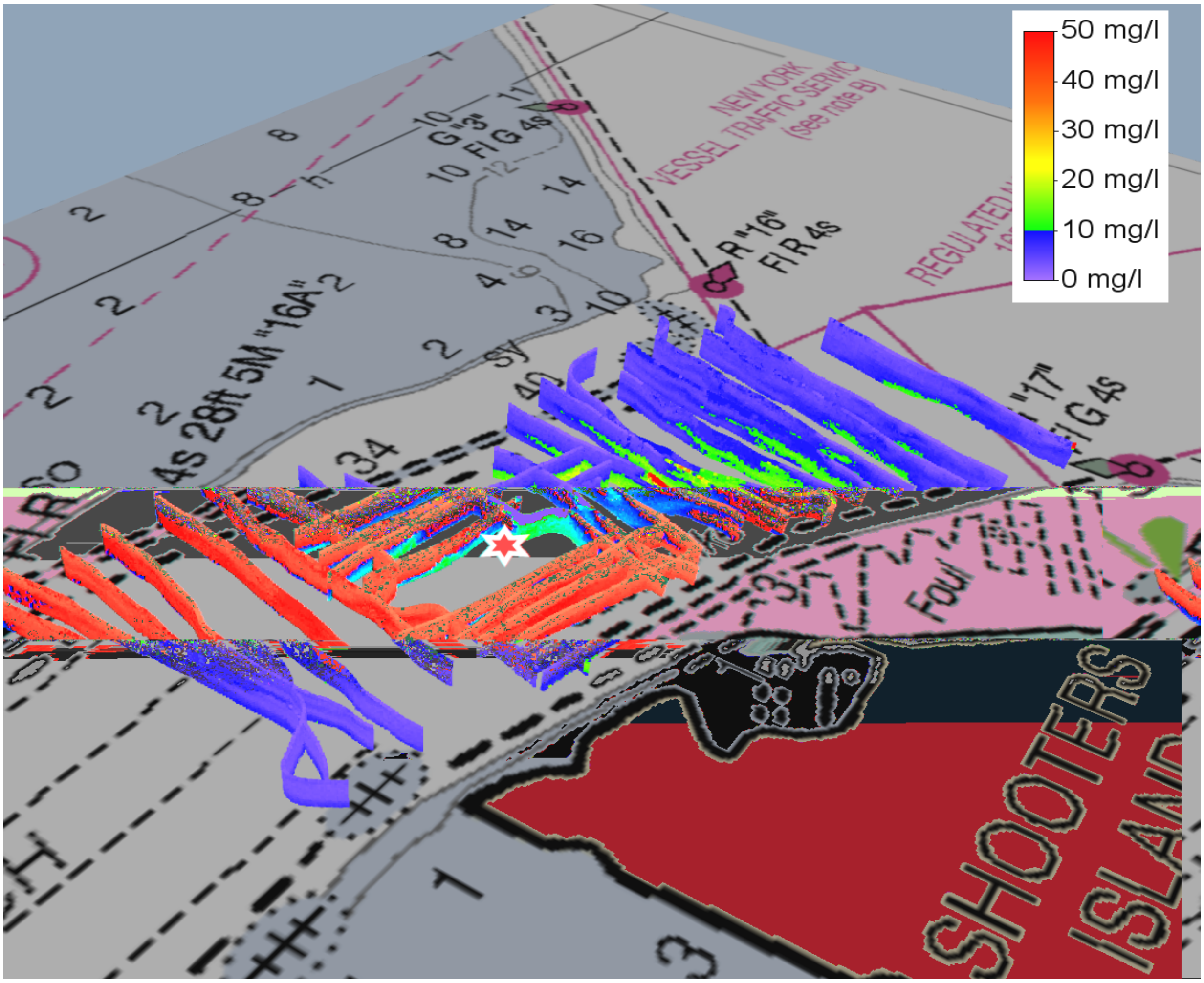

Figure 7. Three dimensional depiction of suspended sediment concentrations for ebbing tide Survey NJEA. Dredge position indicated by star.

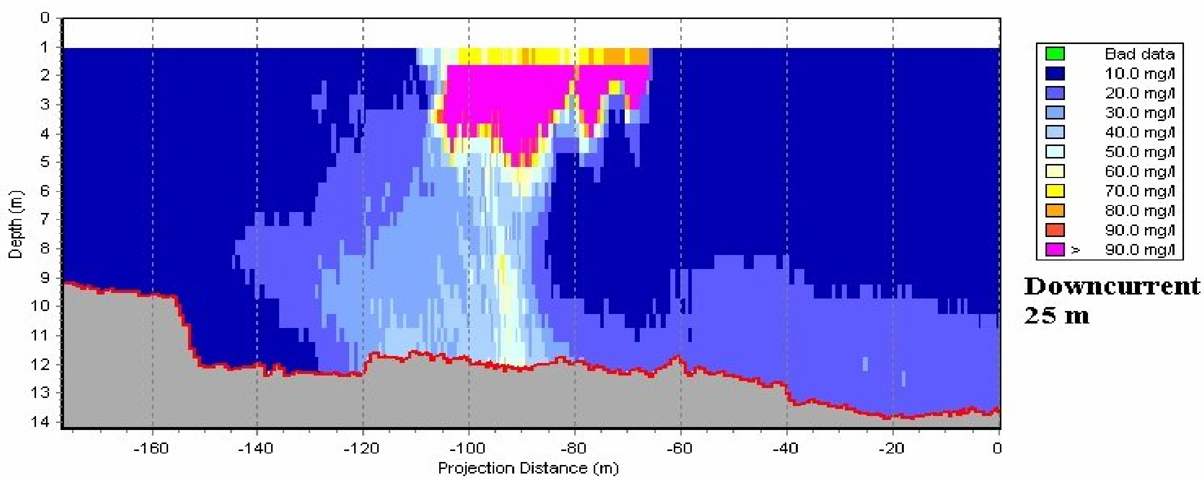

Figure 8. Vertical profile of TSS concentration at a distance of 25 m from the source (Survey NJEA).

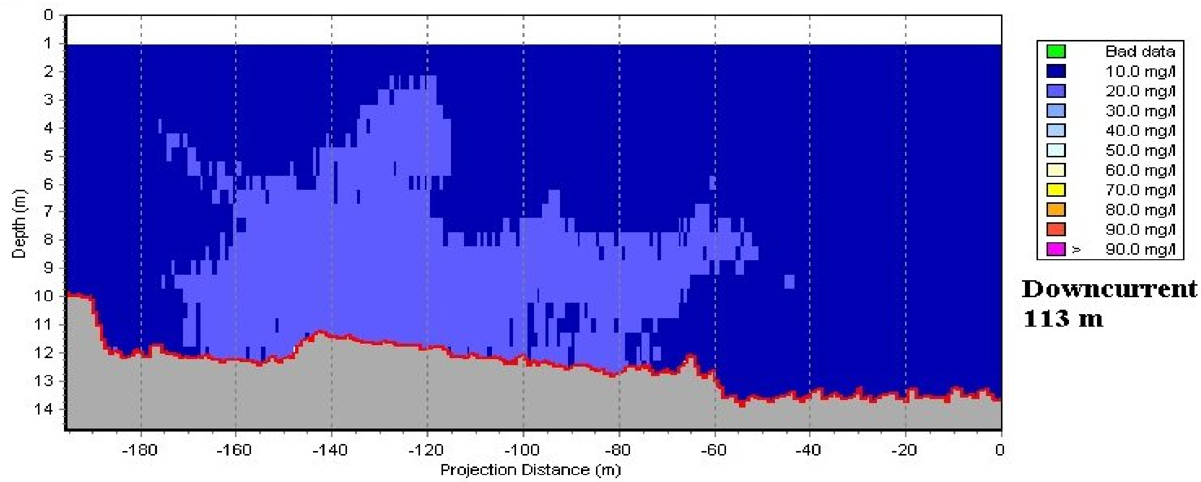

Figure 9. Vertical profile of TSS concentration at a distance of 113 m from the source (Survey NJEA).

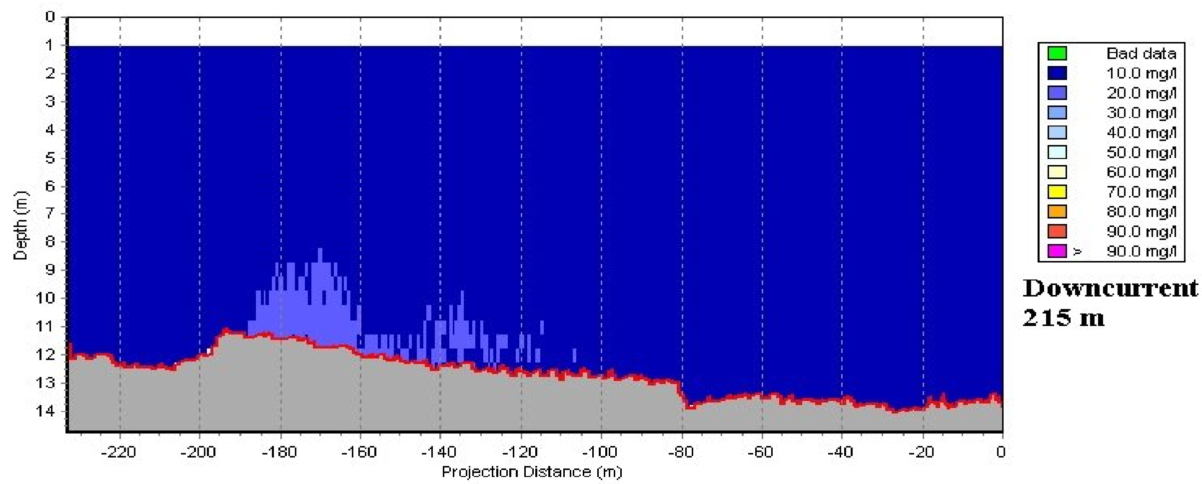

Figure 10. Vertical profile of TSS concentration at a distance of 215 m from the source (Survey NJEA).

The second ebbing tide plume survey (NJEB) was completed (Figure 11) after the dredge had been in full production mode for several hours with the exception of a 15 minute stoppage for bucket maintenance. Halfway through the survey, the dredge stopped removing material and did not resume until after the survey was completed. As seen in the previous ebbing tide survey, some lateral spreading of the plume occurred to the north (port) side of the dredge. A small area of relatively intense acoustic signal is present in the lower water column at the stern of the dredge and is most likely associated with the somewhat mixed flows and overall weak current pattern. The main body of the plume apparently drifted under the dredge and accompanying barge. The majority of the surface plume present was confined to the area immediately abreast of the dredge, although a narrow band approximately 50 m in width did travel down-current as far as 100 m. Beyond 50 m, TSS concentrations exceeded ambient by less than 20 mg/l in surface waters. Movement of the plume was predominantly in a west to east direction and stayed within the boundaries of the navigation channel. The largest down-current "footprint" of the plume was found at a water depth of 8 m. Higher TSS concentrations were found along the north side of the dredge and up-current from the dredge at a depth of 12 m, dispersed by a reversed current flow along the channel bottom.

Maximum TSS concentrations of 130 mg/L were found in the bottom depth stratum (> 11 m) on a transect encircling the dredge and barge at a distance of 5 m. A small area of intense plume signature located on the port side of the dredge was not present on a ensuing transect occupied at a distance of 20 m. This may reflect passing between pulses of resuspended sediment created by consecutive bucket cycles. On this transect only the main body of the down-current plume was detected. The plume in this survey can be characterized as a narrow band of elevated TSS concentration initially extending throughout the water column within a swath less than 50 m wide with

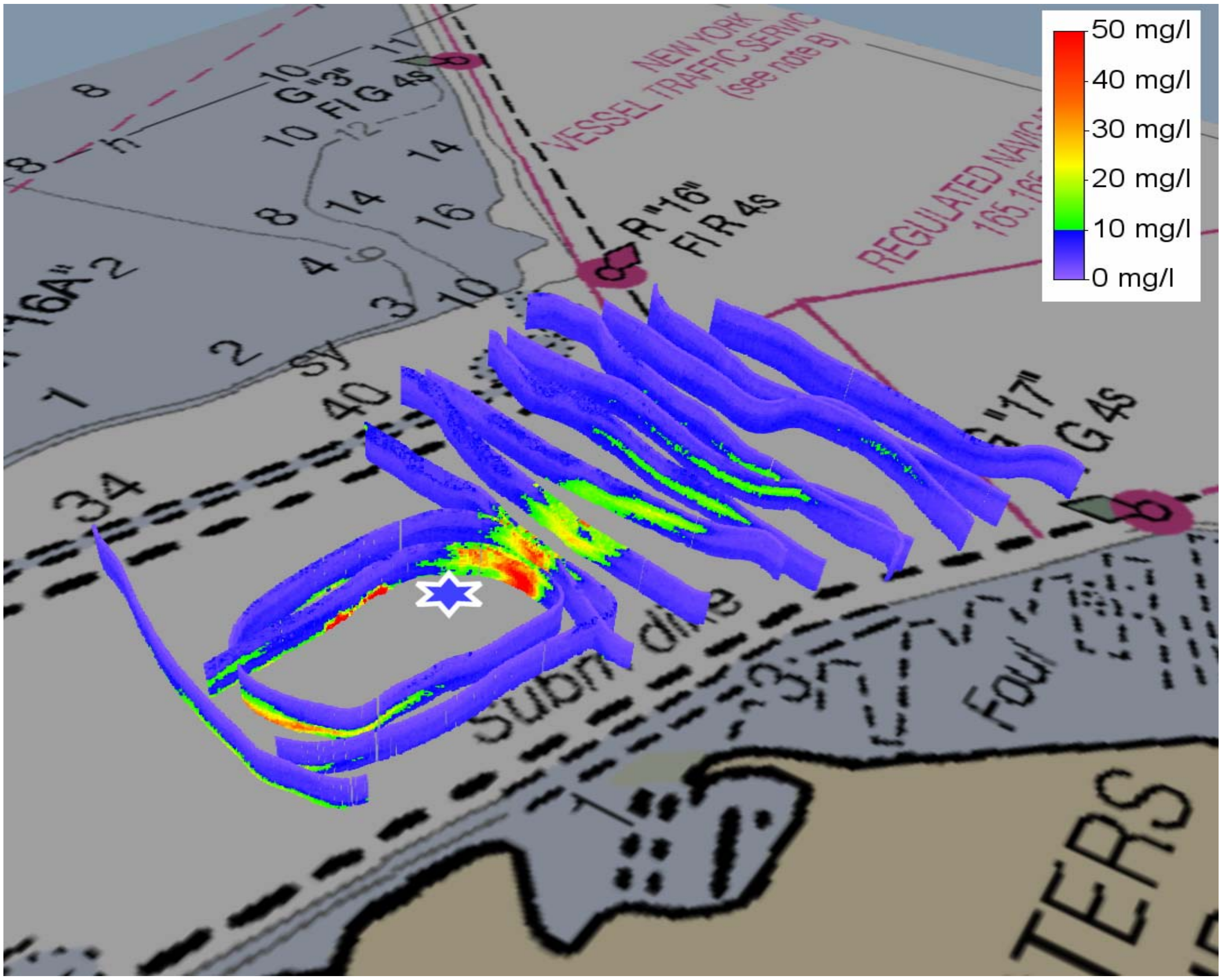

Figure 11. Suspended sediment concentrations for Survey NJEB plotted with respect to their x, y and z coordinates. (Dredge position indicated by star).

maximum TSS concentrations of 60 mg/L. Movement of the plume was generally to the east. Very little lateral spreading of the plume was observed in the down-current direction. At 88 m from the source TSS concentrations had fallen to less than 40 mg/L and were confined to depths greater than 7 m. At 142 m, however, current flow along the bottom of the channel had reversed direction, moving opposite to the flow in the upper part of the water column. At 210 m from the source, only a faint plume signature remained with TSS concentrations exceeding background by less than 10 mg/L. At 270 m, distinct plume signatures could no longer be detected against background conditions.

Flood Tide During-Dredging Plume Characteristics

Prior to the start of flood tide Survey NJFD, the dredge had been in full production mode for over one hour. Dredging production rates on the day of the survey averaged 258 cubic yards per hour, the highest rate during any of the plume tracking surveys.

Figure 12 provides a three dimensional depiction of plume TSS concentrations for Survey NJFD. Along the northern extent of transects occupied on the up-current side of the dredge TSS concentrations exceeding ambient were found from mid-water to the channel bottom. This plume resulted from the passage of a deep draft vessel traveling from west to east through the study area. TSS concentrations in the ship-induced plume as high as 40 mg/L occurred in the lower 3 meters of the water column. Background levels were exceeded by 10 to 20 mg/L across almost the entire width of the navigation channel. Because the exact time of ship passage was not recorded the state of decay of the ship-induced plume cannot be evaluated.

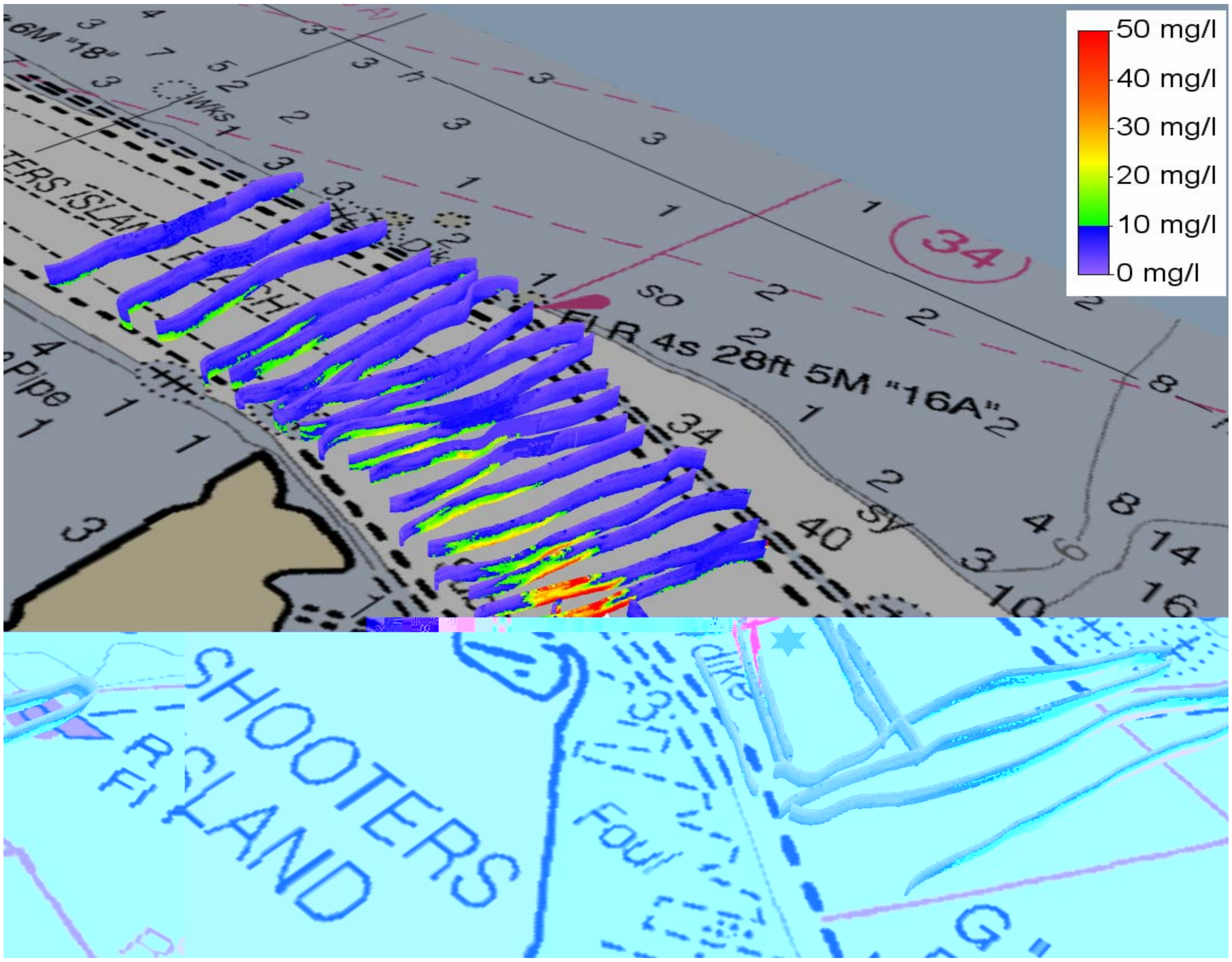

Figure 12. TSS concentrations for Survey NJFD plotted in x, y z coordinates. (Dredge location indicated by star).

On the inner two transects run on the south (starboard) side of the dredge TSS concentrations ranged as high as 350 mg/L, although concentrations estimated this close (2 to 10 m) to the source may include some air contamination. Lower in the water column, where air entrainment is less likely to be present, the maximum observed concentration did not exceed 250 mg/L. At 30 m south of the dredge, plume signatures above 10 mg/L were not detected. Plume signatures against background were absent on the two transects along the north side of the dredge.

Figure 13 depicts a well-defined down-current suspended sediment plume extending from the surface to the bottom 100 meters from the dredging operation. TSS concentrations ranged from 20 mg/L along the outer periphery of the plume to greater than 120 mg/L in the plume's central core. Some air entrainment in the upper portion of the plume is evident as the area shaded in red in Figure 13. Note the change in concentration scale between Figures 13 and 14, which represent transects only 15 m apart. Decay of the plume over this short distance is apparent as maximum TSS concentrations fell from 120 to 90 mg/L. Highest TSS concentrations at 115 m down-current were confined to the lowest meter of the water column. Over the next 50 m TSS concentrations continued to decline to 50 mg/L, or approximately 40 mg/L above background. A distinct plume was detected at 167 m down-current from the source. However, TSS concentrations exceeding background by more than 10 mg/L occurred only in the lower third of the plume signature (Figure 15). The surface portion of the plume had dissipated and was undetectable against background at 195 m from the source. As mapped by this survey, the surface plume can be described as predominantly a “near-field” feature. At 195 m from the source, the plume occupied only the lower half of the water column with maximum TSS concentrations of 30 mg/L or less. These concentrations were detected in a small central core of the plume as far as 317 m down-current from the source (Figure 16). At 344 m, only a faint signature of the degraded plume was detected above background. This faint signature continued to diminish in size, but remained detectable against background as far as 621 m from the source (Figure 17).

Overall plume movement was in a northwesterly direction until it reached the channel dogleg at Channel Marker 16A, then turned further to the west. The plume remained entirely within the navigation channel boundaries, primarily along the southern half of the channel basin. Some lateral spreading was observed as the plume broadened from approximately 65 m wide near the source to a maximum width of 100 m approximately 225 down-current from the dredging operation. No evidence of plume excursion over the adjacent shoals was seen, as clearly shown in Figure 12.

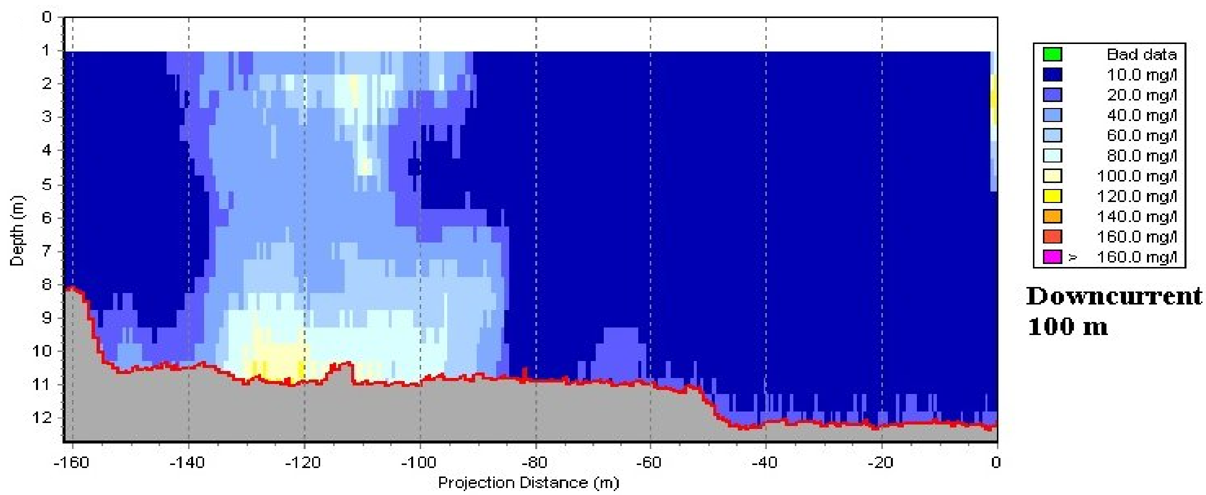

Figure 13. Vertical profile of TSS concentrations at 100 m from the source (Survey NJFD).

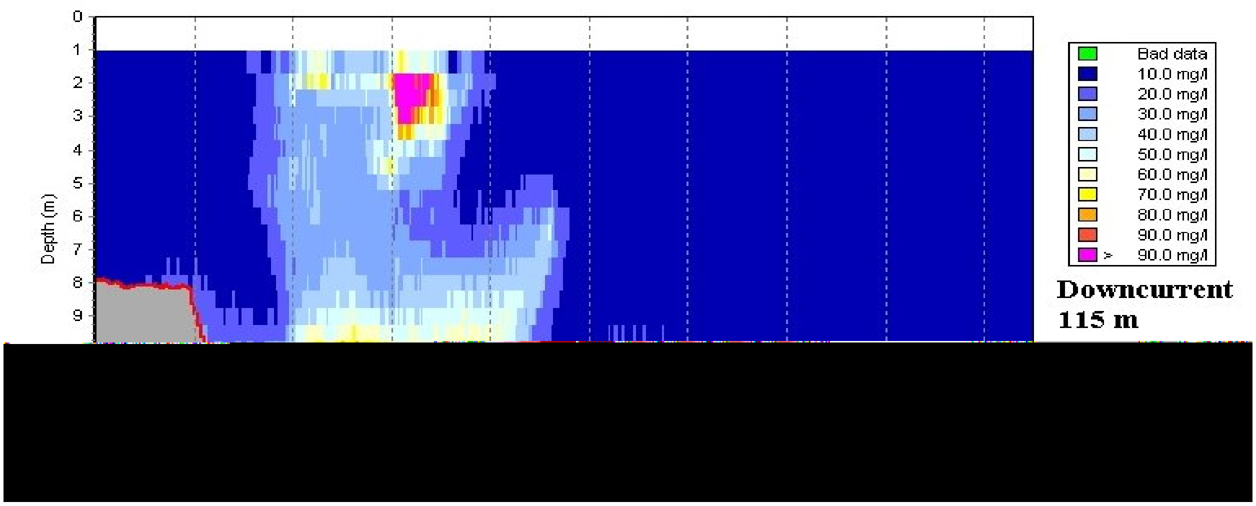

Figure 14. Vertical profile of TSS concentrations at 115 m from the source (Survey NJFD, Note change in TSS concentration scale from Figure 13).

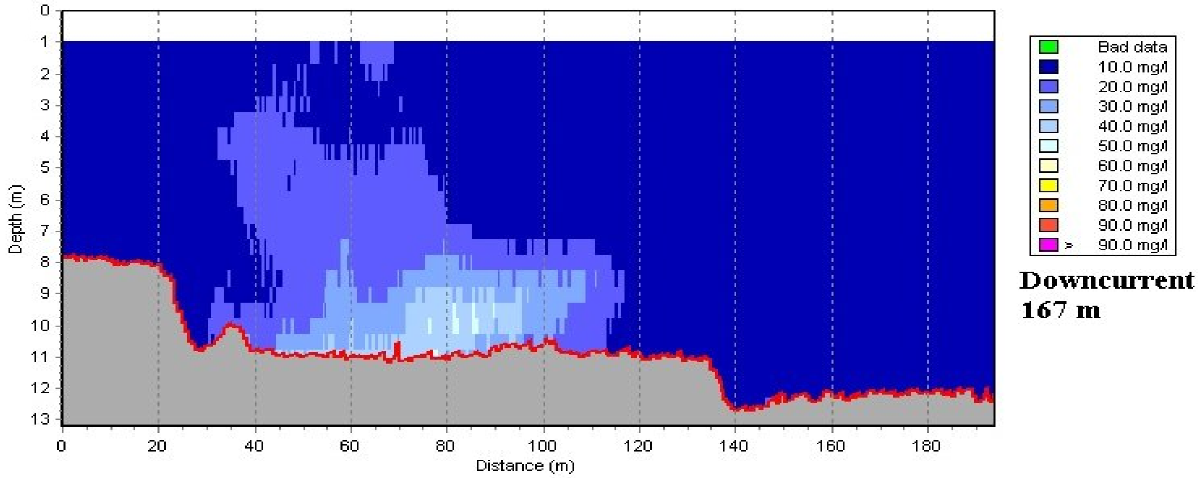

Figure 15. Vertical profile of TSS concentrations at 167 m from the source (Survey NJFD).

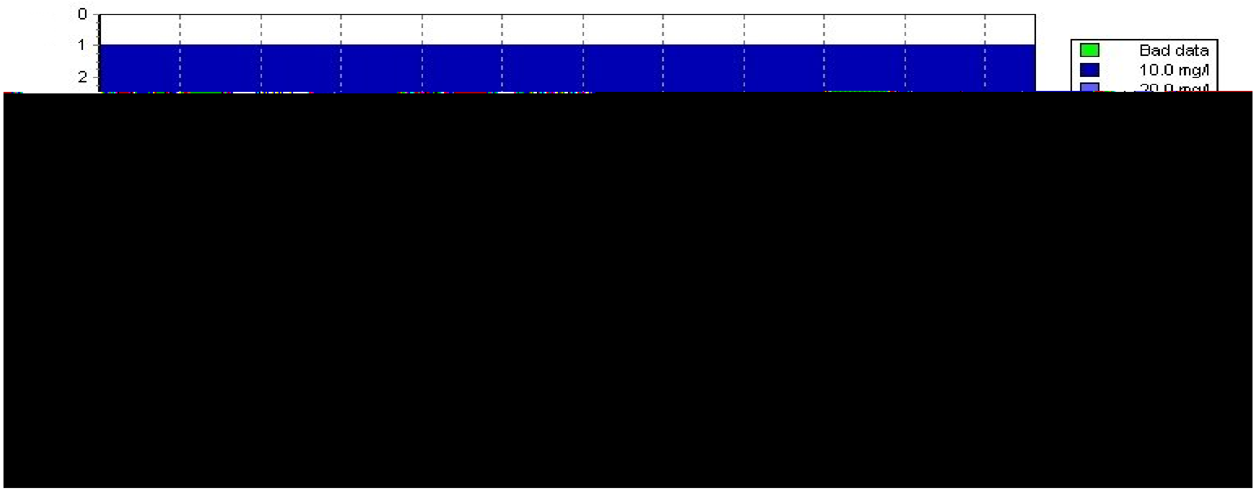

Figure 16. Vertical profile of TSS concentrations at 317 m from the source (Survey NJFD).

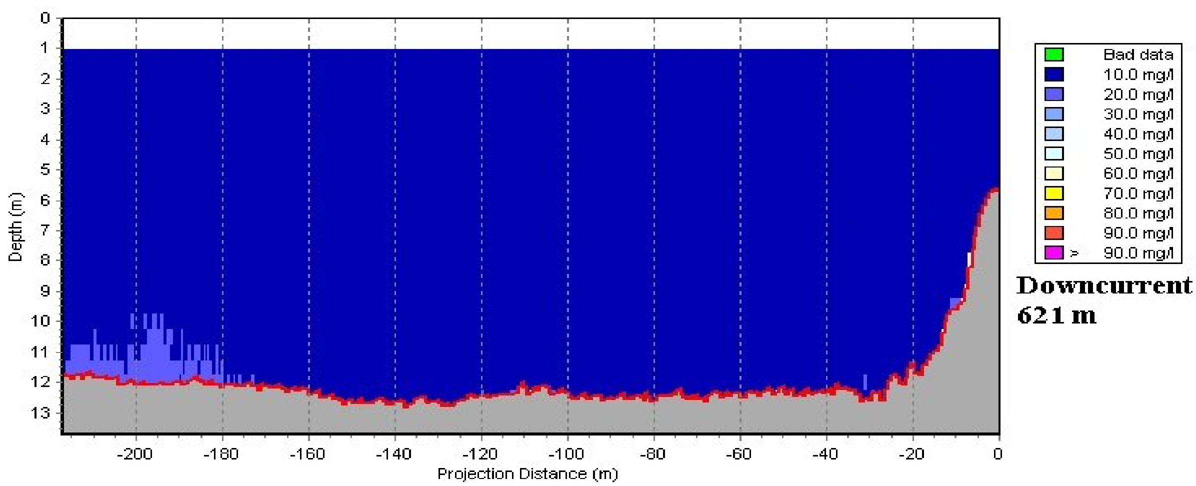

Figure 17. Vertical profile of TSS concentrations at 621 m from the source (Survey NJFD).

During the second suspended sediment plume survey (Survey NJAB) conducted during a flooding tide the dredge was digging near the centerline of the navigation channel. Dredging had been underway for four hours prior to the start of the survey. Production rates on this date were relatively low at 59.5 cubic yards per hour. Reflecting the low sediment removal rate, the plume signature was not as prominent as that observed in the previous flooding tide survey. A 3-D representation of the resultant spatially compact plume is given in Figure 18. Plume movement was to the west and followed the centerline of the channel. Down-current movement of this small plume occurred mainly within the lower portion of the water column.

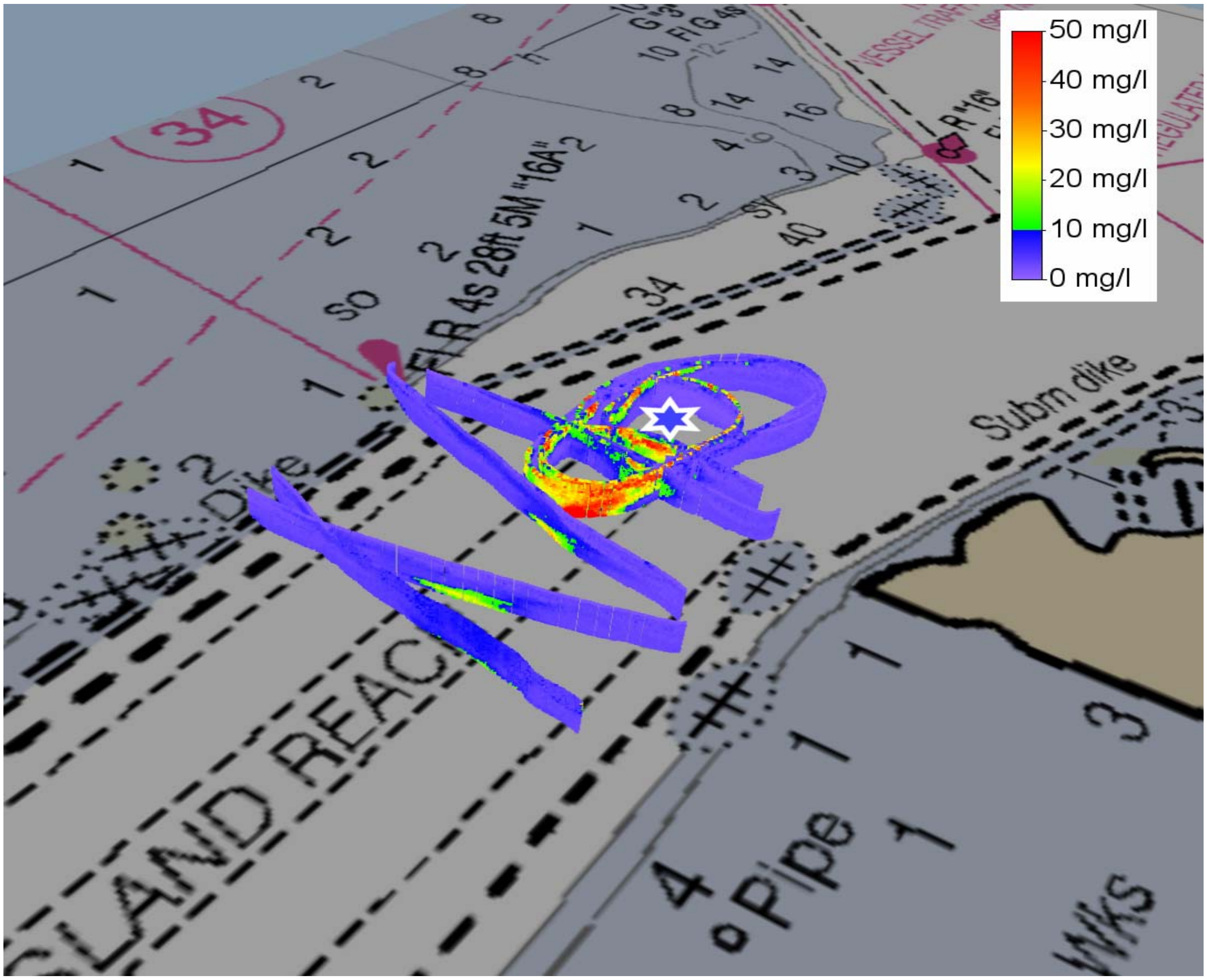

Figure 18. TSS concentrations for Survey NJAB plotted as to their x, y and z coordinates. (Note: dredge position indicated by star.)

As in the previous survey two transects encircled the dredge at distances of 5 and 20 m. TSS concentrations of 70 to 80 mg/L were found in the central portion of the plume in the lower 3 m of the water column on the inner transect. At a depth of 6 m TSS concentrations ranged from 20 mg/L along the periphery to 40 mg/L within its core. TSS concentrations as high as 50 mg/L occurred in the surface plume, but may have been influenced by air entrainment. Concentrations fell from a maximum of 80 mg/L to 50 mg/L over a span of 15 m, although the plume signature still occupied the entire water column. After the completion of second transect, the dredge advanced 55 m to the east to begin a new cut. The circle transects were then repeated at 5 and 10 m distances. Plume signatures were not well defined along either transect, even in such close proximity to the source. Obviously some time was required for a plume to fully develop. The down-current portion of the plume was mapped over 5 transects, the first crossing 3 m from the point of excavation. Some air entrainment was evident in the upper 3 m of the water column. Maximum TSS concentrations, however, were less than 60 mg/L. Plume width was less than 60 m in the lower water column.

At 28 m down-current the plume was a relatively narrow band of elevated TSS, with a small inner core at depths below 10 m with TSS concentrations up to 40 mg/L, a slightly larger outer core in mid-water at 30 mg/L, and an outer periphery extending from near the surface to the bottom at 20 mg/L. Over a span of 50 m (total distance of 78 m from the source), the plume had settled to the lower half of the water column and was not detectable against background down to a depth of approximately 7 m. The overall appearance of the plume changed little over the next 60 m, with continued settling in the water column. At 163 m down-current only a faint trace of the plume signature could be detected against background.

DISCUSSION

Prevailing ambient turbidities and TSS concentrations during the study were relatively low, creating an almost ideal set of conditions for plume detection. Optically measured ambient turbidity varied slightly between sampling days, ranging from 2.6 to 8.7 NTU. The higher values were exclusively found in the uppermost meter of the water column. Results obtained from the gravimetric analysis of ambient water samples indicated that ambient TSS concentrations fell within the 5.2 to 17 mg/L range (mean = 8.4 mg/L). Ambient ADCP data indicated that background TSS concentrations were consistently low, ranging from 3 to 10 mg/L throughout the water column. Thus all characterization methods employed in this study are consistent in support of the finding of generally low ambient turbidities and TSS concentrations.

With respect to turbidity, the data obtained from OBS deployments can collectively be used to describe general plume characteristics at near- and far-field distances, herein defined as approximately 60 m and 150 m respectively. The near-field plumes had average turbidities that exceeded background levels by 5 to 15 NTU in the upper portion of the water column, 25 NTU above background in mid-water column, and 50 NTU above background in the lower portion of the water column. Maximum near-field turbidities occurred in short pulses that exceeded background by as much as 70 NTU at the deepest sensor. The far-field (150 m) deployments collectively produced a characterization of plumes with average turbidities of 13 NTU above background in the upper water column, 39 NTU above background in mid-water, and 47 NTU above background near the bottom. These values reflect measurements during moderate dredge production rates.

Some variation at comparable near- and far-field depths and distances from the source between sampling events was noted, possibly linked to short-term variation in production rates. Visual observations over the course of the field efforts repeatedly noted the start-stop-start again nature of the dredging operation. Rather than a continuous operation, numerous intermittent breaks in the bucket cycles were the norm. Frequent pauses and stoppages were due to a variety of circumstances, including vessel passage, routine periodic maintenance, equipment repairs, and so on. Likewise, visual observations noted that series of bucket cycles alternated between buckets obviously removing full capacity sediment loads and loads that consisted almost entirely of water. Because the operation was intermittent, plumes would not be expected to attain a steady state condition, but rather be constantly dissipating and re-establishing as pulses of sediment released at the bucket were carried downstream.

Maximum TSS concentrations measured acoustically approached 300 mg/L within 10 m of the source near the surface, although air entrainment likely affected these measurements to some degree. Concentrations measured in the lower third of the plume near the source ranged from 150 to 200 mg/L. TSS concentrations 100 m down-current from the source generally did not exceed 120 mg/L. These values are consistent with the results of gravimetric analysis of water samples taken within the plume, which ranged from 100 to 190 mg/L within 60 m from the source.

TSS concentrations decreased from approximately 300 mg/L immediately adjacent to the source to less than 50 mg/L at a distance of approximately 150 m from the source, and to 20 mg/L at 350 m from the source. Faint plume signatures with concentrations less than 10 mg/L above background did persist as far as 620 m from the source.

For all plumes surveyed a general pattern of relatively rapid plume concentration gradient decay and settlement within the water column was apparent. Plumes exhibited minimal lateral diffusion with distance traveled down-current, seldom measuring more than 70 m across at substantial concentrations. Maximum spatial extent of the plumes always occurred in the lower water column. Movements of plumes were generally confined to the basin of the navigation channel, with no evidence of excursion beyond the channel side slopes.

All results were consistent with previous studies of plumes created during mechanical dredging operations. For example, Bohlen et al. (1979) studied plumes created by a mechanical dredge equipped with an open bucket during operations in the Thames River Estuary, Connecticut. TSS concentrations of 200 to 400 mg/L were measured adjacent to the dredge and plumes dissipated to background concentrations within 700 m downstream. These results were also presented by Bohlen (1978), who described the suspended sediment plume induced by a clamshell bucket under estuarine conditions as essentially small scale features with three distinct zones: an initial mixing zone where the dredge mixes materials throughout the water column, a secondary zone extending downstream approximately 100 m in which gravitational settling predominates, and a final mixing zone in which plume sediments continue to settle governed primarily by turbulent diffusion. In a later study Bohlen et al. (1996) used an acoustic echo sounder to track plumes and a fixed station instrument array that recorded bottom current velocities and optical turbidity to assess potential effects of sediment dispersion from an open clamshell bucket to winter flounder habitat. They concluded that high TSS concentrations (maximum 662 mg/L) were generally confined to within 100 m of the source, and that the plumes rapidly settled into bottom oriented features. Dredge-induced pulses of suspended sediment at the fixed instrument array were concluded to be minor perturbations in contrast to wind and freshwater discharge-induced resuspension events, consistent with earlier findings in the Thames River Estuary (Bohlen 1980).

McLellan et al. (1989) described similar plumes dimensions produced by both conventional open clamshell and closed clamshell buckets. They did speculate that an enclosed bucket minimized surface plumes but produced comparatively larger bottom plumes due to an enhanced shock wave created by a closed bucket as it impacts the bottom. The enclosed bucket in the McLellan et al. (1989) study was an early generation model with plates welded to enclose a conventional bucket. The Cable Arm® bucket in the present study incorporates flaps that vent water during bucket descent and reduce the bottom shock wave.

Randall (2001) described the advantages and disadvantages of mechanical and hydraulic dredges for consideration in removal of contaminated sediments. He reported that the major disadvantage of both open and closed buckets was low production rates (< 100 cu yd/hr), but that closed buckets had the advantage of low resuspension rates. Tradeoffs between production and resuspension are complex and necessarily must consider the volume of material to be removed. In navigation projects the volumes tend to be large. In addition, mechanical buckets can be used to remove debris more effectively than hydraulic dredges.

Recent studies by Bilimoria et al. (2006) and Thompson et al. (2006) detail the results of dredge-induced resuspension monitoring at a contaminated sediment site in the Lower Passaic River, New Jersey. In this cleanup pilot study a mechanical dredge using an 8 cu yd Cable Arm environmental bucket removed approximately 5,000 cu yds of sediment with a production rate of approximately 90 to 215 cubic yards per hour and average bucket cycle times of 105 to 165 seconds. Preliminary data indicated that TSS concentrations ranged as high as 115 to 120 mg/L down-current from the dredge.

Reine et al. (2003) used survey designs and sampling approaches similar to those in the present study to characterize plumes created by mechanical dredging in an open-water navigation channel in Upper Chesapeake Bay. Plumes generated from a 26 cu yd open bucket were detected as far as 1,500 m downstream from the source. Tidal current were relatively strong, peaking at over 130 cm/sec. OBS units measured turbidities as high as 220 NTU at a distance of 70 m from the source, and TSS concentrations as high as 300 mg/L at that distance. Plumes expanded laterally to widths of up to 400 m before being lost against background conditions. Reine et al. (2003) also monitored plumes from mechanical dredging operations in Baltimore Inner Harbor, where currents were much slower, generally less than 20 cm/sec. Surface plumes were generally undetectable beyond 100 m from the source and TSS concentrations remained below 40 mg/L beyond 350 m from the source. Maximum turbidities measured by OBS units deployed near the bottom at 47 m from the source were approximately 145 NTU.

Clarke et al. (2005) reported the results of monitoring mechanical dredge plumes at the Port of Oakland, California. Plumes generated by a 12 cu yd closed bucket generally decayed to background TSS concentrations within 400 m from the source. Prevailing tidal currents were weak, largely less than 30 cm/sec. TSS concentrations above 275 mg/l were detected only immediately adjacent to the source. The plumes were observed to settle rapidly and remain within the navigation channel boundaries.

Reine et al. (2006) monitored plumes associated with mechanical dredging of maintenance materials in the Providence River, Rhode Island. At two locations plumes were found to decay to background conditions within

1,100 m of the source, a 26 cubic yard closed bucket. In this project the dredge operator was aggressively digging and maintaining high production rates. TSS concentrations as high as 1,000 mg/L were measured immediately adjacent to the source, but concentration gradients declined steeply over short distances as the plumes settled into the lower portion of the water column.

In a previous study of plumes in the Kill Van Kull (SAIC 2002), plumes associated with two excavator dredges were monitored. Based largely on OBS data, SAIC was able to detect plumes as far as 1,500 m from the dredges, although in this case the plumes from both dredges had apparently merged. Background turbidity in the KVK at that time ranged from 7 to 13 Formazin Turbidity Units (FTU) and background TSS concentrations ranged from 19 to 24 mg/L, slightly above values obtained in the present study. Direct comparisons of plumes monitored in the KVK and those of the present study are limited in that the dredge plants were very different, the sediments being dredged were substantially different (mixed glacial till versus primarily silts), and currents at the KVK site were considerably stronger (54 to 97 cm/sec in the KVK). However, observed peak TSS concentrations and turbidities within the KVK plumes were comparable, as well as the observed tendency for the KVK plumes to settle and evolve into bottom features.

CONCLUSIONS

A mechanical dredge equipped with a Cable Arm® environmental bucket operating in the Arthur Kill Waterway produced suspended sediment plumes that were relatively small and confined to the navigation channel. The comparatively small, diffuse plumes can be attributed to several factors. First, effective use of the environmental bucket served to minimize loss of sediment, particularly in the upper portion of the water column. Second, compliance with stipulation of a slow bucket hoist speed as management practice may have further minimized resuspension, although the degree of reduction cannot be estimated based on data in the present study. Third, the relatively low to moderate production rates in effect during the plume surveys limited the absolute loss of sediment to the water column over the time course of the study. Finally, prevailing water current velocities and circulation patterns at the dredging site were not conducive to far-field dispersion of prominent plumes.

The dimensions and TSS concentration gradients of plumes mapped in the Arthur Kill Waterway were entirely consistent with the results of previous mechanical dredge plume monitoring efforts. In all cases the properties of the sediments being dredged and prevailing current forces largely determined observed plume dispersion patterns.

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