ASSESSMENT OF POTENTIAL IMPACTS OF BUCKET DREDGING PLUMES ON WALLEYE SPAWNING HABITAT IN MAUMEE BAY, OHIO

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ABSTRACT

Annual dredging of a major navigation channel in Lake Erie's Maumee Bay occurs in close proximity to walleye (*Sander vitreus*) spawning and nursery habitat. Concerns raised by regulatory agencies over potential impacts focus largely upon sediment resuspension. Hypothetical impacts include smothering of demersal eggs by re-deposited sediment, altered egg incubation and hatching success due to increased turbidity effects on water temperature regimes, and clogging or abrasion of gill tissues caused by suspended particles. Monitoring of a clamshell bucket dredging operation was conducted to assess the risk factors posed by typical maintenance dredging in Maumee Bay. Efforts included deployment of optical backscatter sensors (OBS) for time series records of turbidity and acoustic Doppler current profiler (ADCP) surveys to determine the spatial extent, concentration gradient structure, and temporal dynamics of resuspended sediment plumes. Estimates of total suspended solids (TSS) concentrations were derived from ADCP relative backscatter data. Water samples were collected for gravimetric analysis and used to calibrate the acoustic backscatter data. Results indicated a rapid settling of suspended sediments within a relatively short distance from the dredging source. TSS concentrations fell from 800 mg/L at the source to less than 300 mg/L over a 25 m span. Maximum observed TSS concentrations decreased to 40 mg/L (15 mg/L above background) at a distance of 115 m from the source. Detectable plume signatures against background became indistinct at distances greater than 125 m, where TSS values did not exceed 5 to 10 mg/L above background. Plume signatures were not detected in surface waters beyond 60 m or in the lower water column beyond 200 m. Waters overlying adjacent shoals, which represented walleye habitat, were examined for elevated TSS attributable to the dredging operation. TSS concentration ranges observed on shoals closest to the dredging activity were not measurably different than on shoals outside the area influenced by plumes. TSS concentrations on the shoals remained generally within 25 mg/L background levels and were consistent with background concentrations for all depth strata within the navigation channel. Turbidities were also monitored in both the navigation channel and adjacent shoals. Turbidities within the plume generally did not exceed 400 nephelometric turbidity units (NTU) at 25 m and 300 NTU at 46 m from the source in the lower water column, but peaked at 500 to 700 NTU in short duration spikes when the dredge advanced to within 15 m of a moored OBS. In contrast, ambient turbidities in the navigation channel did not exceed 25 NTU. Background turbidities measured at 5 stations located on the adjacent shoals ranged from 5 to 15 NTU. At one of three stations located on the shoals immediately adjacent to the dredge, measurements exceeded background conditions twice during ten minute pulses that occurred approximately 3.5 hours apart. At two sensors located 157 and 186 m from the dredge, single occurrences were recorded in which ambient conditions were exceeded by 3 to 10 NTU. In summary, it is very unlikely that bucket dredging operations conducted under similar conditions in Maumee Bay pose a meaningful risk to walleye in terms of either physical disturbance of spawning habitat or exposure of eggs to problematic sedimentation. Prevailing water current velocities were relatively slow, with depth-averaged velocities of 0.17 m/sec in the channel and 0.21 m/sec over the shoals. In the absence of swifter current flows to drive far-field dispersion of plumes, the spatial extent of plumes at any point in time would be limited such that exposures of larvae in the water column to elevated doses of suspended sediments or other altered water quality parameters would be minimal.

Keywords: Suspended sediment, turbidity, fishery, navigation

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INTRODUCTION

In terms of volume, dredging of the deep-draft Toledo Harbor navigation channel, which extends from the Lower Maumee River to the outlet of Maumee Bay into the Western Basin of Lake Erie, represents the largest project conducted on an annual basis in the Great Lakes. Between riverine and bay portions of the navigation channel, approximately 850,000 cubic yards are removed per year. Much of the sedimentation in the channel occurs during winter and early spring freshets. Consequently, in order to maintain navigable depth, dredging is most effectively performed as soon after shoal formation as possible. The optimal time to dredge, however, may conflict with the established environmental window, a seasonal constraint imposed by Ohio regulatory agencies with the intent to protect fishery resources. At present the State of Ohio Department of Natural Resources (ODNR) restricts dredging in the Maumee River and Bay to between July 1st and February 28th, specifically to protect walleye (*Sander vitreus*) spawning and nursery habitat. Potential detrimental effects of turbidity on Great Lakes fishes have been a long-standing issue (Van Oosten 1947). Assessments of impacts require an understanding of both the risk of exposure of target resources to elevated turbidity and suspended sediment concentrations and the specific levels of exposure that trigger detrimental responses. The present study was undertaken to characterize plumes generated by bucket dredging in terms of spatial extent and suspended sediment concentration gradient structure in order that risks to walleye could be evaluated. Spawning is known to occur on shallow shoals adjacent to the Maumee River/Bay Navigation Channel and therefore sampling focused on a channel reach in proximity to these sensitive habitats.

Walleye generally spawn soon after ice break-up (Colby et al. 1979) with peak spawning activity usually occurring in mid-April. Spawning begins as rising water temperatures approach 7 to 9^{o}C, and peaks before temperatures reach 11^{o}C (Scott and Crossman 1973, McMahon et al. 1984). Spawning walleye broadcast eggs over hard substrates (gravel/rock) in shallow areas of tributaries and mid-lake reefs. Eggs typically hatch in about 10 days, but duration of incubation and survival are temperature dependent. In addition, spawning success requires oxygen levels above 35% saturation. Larvae are pelagic and are passively carried by water currents. Surveys frequently report highest densities of larvae in nearshore areas and embayments (Roseman et al. 2005). Walleye become demersal and generally leave their nursery areas when they reach 20 to 40 mm TL (Ney 1978).

Hypothetical impacts of dredging-induced sediment resuspension on fish and shellfish have been reviewed previously (Priest 1981, LaSalle 1991, Kerr 1995, Wilber and Clarke 2001). Several potential impacts specific to walleye have been identified in reviews by Sweeney et al. (1975), Clapp et al. (1997), Rieger and Summerfelt (1997), Johnston (1999), Roseman et al. (2002), and Jones et al. (2003). According to these reviews walleye habitat, reproduction, and survival may be detrimentally affected by both natural and anthropogenic factors, including: 1) smothering of eggs via reduced oxygen exchange, 2) hydrologic modification of channelized tributaries leading to increases in current velocity, which may reduce larval survival, 3) increased water temperatures due to increased turbidity, which may shorten incubation periods for walleye eggs, thereby impacting growth and development to both larval and juveniles stages, 4) entrainment by hydraulic dredge pumps, particularly egg and larval stages, 5) gill abrasion due to exposure to resuspended sediment particles, 6) modification of spawning substrates, particularly loss of rock and gravel, 7) altered olfactory cues used by adults, which might affect homing and spawning site fidelity, and 8) altered prey distributions and ability to forage due to increases in turbidity for larval, juvenile and adult stages. Although most impacts remain hypothetical, some data exist upon which to evaluate specific risk factors. For example, Mion et al. (1998) computed indices of larval survival in the Maumee and Sandusky Rivers and found that survival was consistently low when river velocity was >0.6 $m \cdot s^{-1}$ but could be very high when velocity was <0.3 $m \cdot s^{-1}$. It should also be noted that evidence exists of possible beneficial impacts of dredging with respect to walleye. For example, some increases in turbidity may optimize visual contrast of prey such that feeding success and the onset of first feeding are enhanced (Vandenbyllaardt et al. 1991, Reiger and Summerfelt 1997). Roseman et al. (2005) reported that slightly turbid nearshore waters were more productive walleye nursery areas than clear offshore areas. Also, the low relief sandy mounds paralleling the channel representing historical placement of dredged material are apparently viable walleye spawning habitat (Roseman et al. 2002).

Dredging maintenance sediments in the Maumee River is typically conducted with small hydraulic cutterhead or mechanical bucket dredges. Depending on the location of the channel reach being dredged, the sediment is either placed in upland Confined Disposal Sites or loaded in barges and taken to a designated open-water disposal site in Lake Erie. In this study MCM Marine Incorporated Dredge #55 used a 15 cubic yard capacity open clamshell bucket for barge loading, with subsequent transport to the offshore site (Figure 1).

Figure 1. MCM Marine bucket dredge removing maintenance material from Maumee Bay. Red buoys marking positions of turbidity sensors shown in the foreground.

METHODS

Study Area

The plume characterization study was conducted in Maumee Bay, the westernmost embayment of Lake Erie. Monitoring efforts were concentrated within the navigation channel between Channel Markers 29/30 to the east and Channel Markers 37/38 to the west, as well over the adjacent shoals, which represent potential walleye spawning and nursery habitat (Figure 2).

Current Structure

An RD Instruments 600-kHz Mariner Workhorse Series ADCP was used to collect current velocity, direction, and acoustic backscatter data. RD Instruments WinRiver software was used to display and record these data. The instrumentation package calculates and records vessel and current direction in three directional axes to an accuracy of +/- 0.2 cm/sec. Data were recorded for predetermined horizontal and vertical bin sizes. Bottom depth and surface water temperatures were also recorded. An internal fluxgate compass allowed the instrument to correct ADCP current vectors for vessel speed and orientation. Navigation data received from a differential Global Positioning System were collected synoptically and integrated during post-processing.

Detection of Suspended Sediment Plume Acoustic Signatures

ADCP backscatter data were analyzed using Sediview Software provided by Dredging Research Ltd. The Sediview Method (Land and Bray 2000) derives estimates of total suspended solids (TSS) concentration in each ADCP data bin by converting relative backscatter intensity to concentration. This process requires collection of sufficient water samples for gravimetric analysis to represent the entire TSS concentration gradient at all water depths. This "groundtruth" data set is then used to calibrate the acoustic data. The individual water samples are collected at known locations within the ensonified portion of the water column, so that each sample can be directly compared with acoustic estimates of concentration for the same water parcel. An example of the acoustic methodologies for plume characterization can be found in Reine et al. (2002).

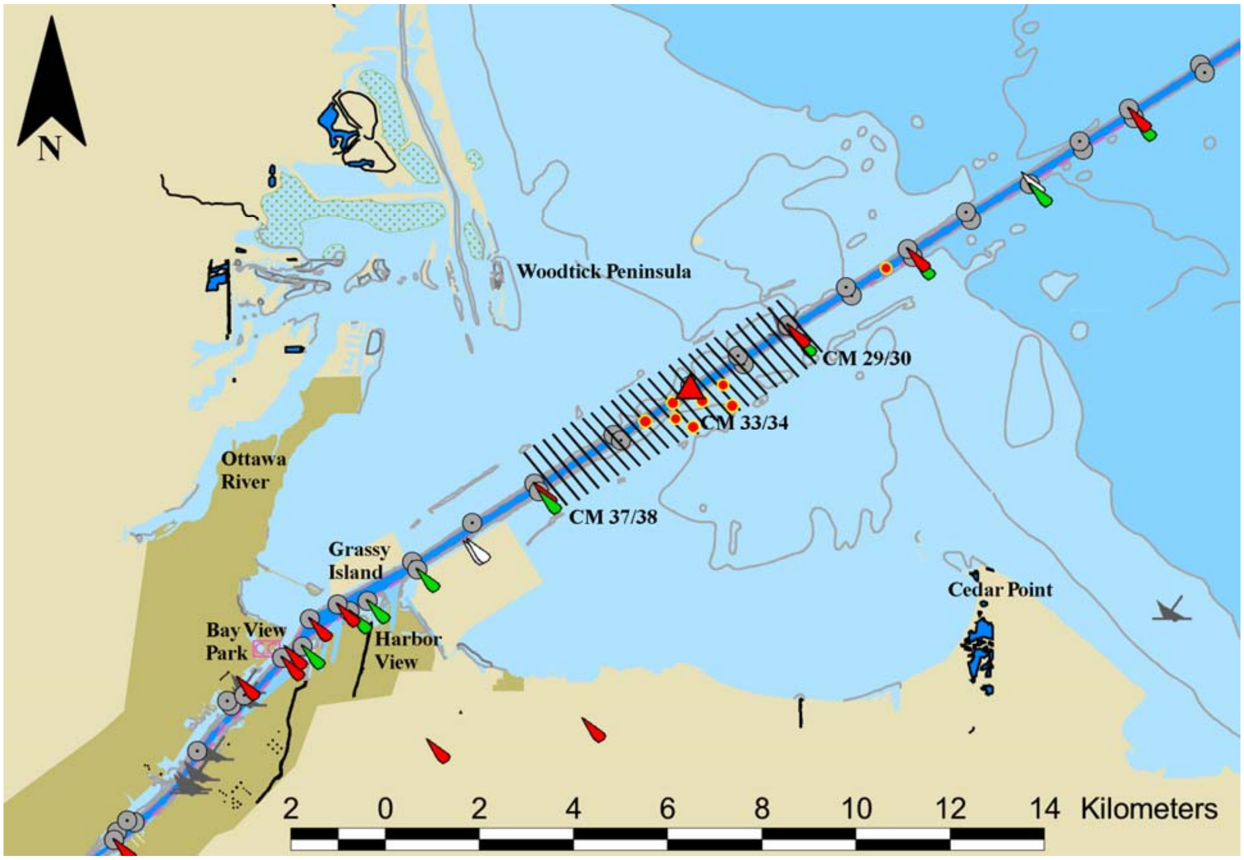

Figure 2. Study site. (Red triangle = dredge location, Red dots = moored OBS units, Parallel black lines = ADCP transects. See text.)

Turbidity

D&A Instrument Company Model OBS-3A units, capable of measuring optical turbidities in the 0-1,000 nephelometric turbidity unit (NTU) range, were used in this study. On 2 August 2005 eleven OBS units were deployed to collect both ambient and internal plume data. All OBS units were tethered to a taut line buoy and anchor. Three monitoring stations were established in the channel and 5 stations were established over the southern shoal. The ambient station (Station 1), located on the southern side of the channel well outside of the direction of plume movement, consisted of sensors deployed at depths of 2.2 and 7 m. No data were collected from the upper OBS unit of Station 1 due to sensor failure. Stations 2 and 3 were located in the navigation channel in the direction of plume movement to capture time series records of turbidity within the plume. Station 2 consisted of upper (2.2 m) and lower (7 m) sensors at a location 46 m from the bucket dredge. Station 3, consisted of two sensors deployed at depths of 2.3 and 7.5 m at a distance of 100 m from the dredge. Stations 4 to 8 were deployed across the southern shoal to measure turbidity over the walleye spawning grounds. Stations 4, 5 and 6 were located along a line parallel to the long axis of the channel at distances of 75, 105, and 125 m from the dredge. These were designated as "near-field" stations. Stations 7 and 8 were deployed in a second parallel line at distances of 157 and 186 m from the dredge, herein designated as "far-field" stations. Depth of OBS units deployed across the southern shoal was 0.5 m.

Water Samples and System Calibration

In order to convert backscatter data (decibel units) to suspended sediment concentration (mg/L), the ADCP data must first be calibrated against known concentrations. To accomplish this step, water samples were collected at specific locations within the ADCP beam at several stations exhibiting a range in concentration. The water samples were analyzed gravimetrically using standard methods. Water sample TSS concentrations were then matched to an exact acoustic ping number in a corresponding ADCP data file. Therefore, for each ADCP calibration file there is a corresponding water sample of a known TSS concentration. Differences between known and estimated sediment concentrations are then examined and corrected in the Sediview data analysis program.

Eighty-four water samples were collected using a 2.2 liter Van Dorn sampler. Each sample was collected in a horizontal orientation with an OBS-3A unit, configured for real time deck readout, strapped to the water sampler. The water sampler was manually triggered when observed backscatter signal from the ADCP and turbidity measurements from the OBS units indicated a suitable position within the plume. Water samples were processed gravimetrically for TSS (mg/L) and optically for turbidity (NTU) using standard laboratory procedures. A single *in situ* sediment grab was collected for grain size determination to assist in the calibration. This sample was processed according to procedures established by Plumb (1981).

Ambient Surveys

Ambient data were collected on 1 August 2005 during a period of dredge inactivity. Nineteen parallel acoustic Doppler current profiler (ADCP) transects were established at 30 m intervals between Channel Markers 29/30 and 33/34 (Figure 2). Transect length ranged from 285 to 453 m to cover the entire width of the channel and extending into each opposing shoal. Transects were oriented in a southeast-northwest direction. The survey vessel ran in opposite directions on alternating transects.

Plume Characterization Surveys

Two plume characterization surveys were completed on 2 August 2005. To cover the full extent of the plume, 22 transects were occupied spanning an area from 600 m east to 250 m west of Channel Markers 33/34. Dredge #55 was digging on the southern side of the channel approximately 150 east of Channel Marker 33. As in the ambient survey transects covered the full lateral extent of the navigation channel and extended into the adjacent shoals. Transects were continued for up to 515 m until the acoustic signature of the plume was completely lost against background conditions. Transects 1-10 were located astern of the dredge in the prevailing downstream direction of current flow. Two U-shaped transects (11 and 12) were occupied on the port and starboard sides of the dredge respectively to detect any lateral dispersion of the plume. The upstream portion of the surveyed area was covered by Transects 13 through 22. Inter-transect distance was approximately 30 m.

A second plume survey was completed later on the same day using the same protocol. Fewer transects were need to adequately map the full extent of the plume. Transects 1-5 were occupied astern (downstream) of the dredge, whereas Transects 11-14 extended upstream past Channel Markers 33/34. An additional survey line consisted of a tight circle around the dredge plant in order to capture maximum TSS concentrations. Two parallel transects were also added on the port and starboard sides of the dredge plant to replace the U-shaped transects previously used.

RESULTS

Current Structure

ADCP-derived directional vectors for depth-averaged flows lacked a strong pattern of uniform movement, attributable to the overall slow velocities measured throughout the study area. Depth-averaged current velocities in the channel were less than 0.2 m/sec (range (0.16 to 0.19 m/sec) during the morning survey. Depth-averaged velocity across the shoals (mean = 0.21 m/sec) was higher than that observed in the channel (mean = 0.11 m/sec) proper. Somewhat slower flows were observed in the late afternoon survey conducted on the same day, as depth-averaged current velocities ranged from 0.11 to 0.18 m/sec.

Acoustic Data Calibration

The acoustic backscatter to TSS concentration calibration data set consisted of a total of 84 samples. Of these, 28 samples were taken from stations located over the shoals, whereas 56 were taken from locations randomly chosen within the navigation channel. TSS concentrations ranged from 3 to 93 mg/L (mean = 30.7 mg/L). Turbidity (NTU) ranged from 8 to 124.9 NTU (mean = 29.7 NTU). In Figure 3 the populations of gravimetric and acoustic concentrations measurements are compared. A high degree of correspondence between gravimetric and acoustic measures of TSS was found for the Maumee Bay samples. Water samples with very high TSS concentrations were not obtainable due to the relatively small size of the plume generated by the 15 cubic yd bucket. Weak water currents did not disperse the plume down-current from the point of excavation quickly enough to allow the sampling vessel to find high concentrations. Because air is entrained into the water column at the point of bucket insertion, samples obtained within 20 m of the source could not be used for calibration. The correlation between TSS (mg/L) and NTU values collected concurrently with an OBS unit strapped to the water sampler was not particularly strong (R^2 = 0.626) but may have been affected by an algal bloom that appeared to be underway.

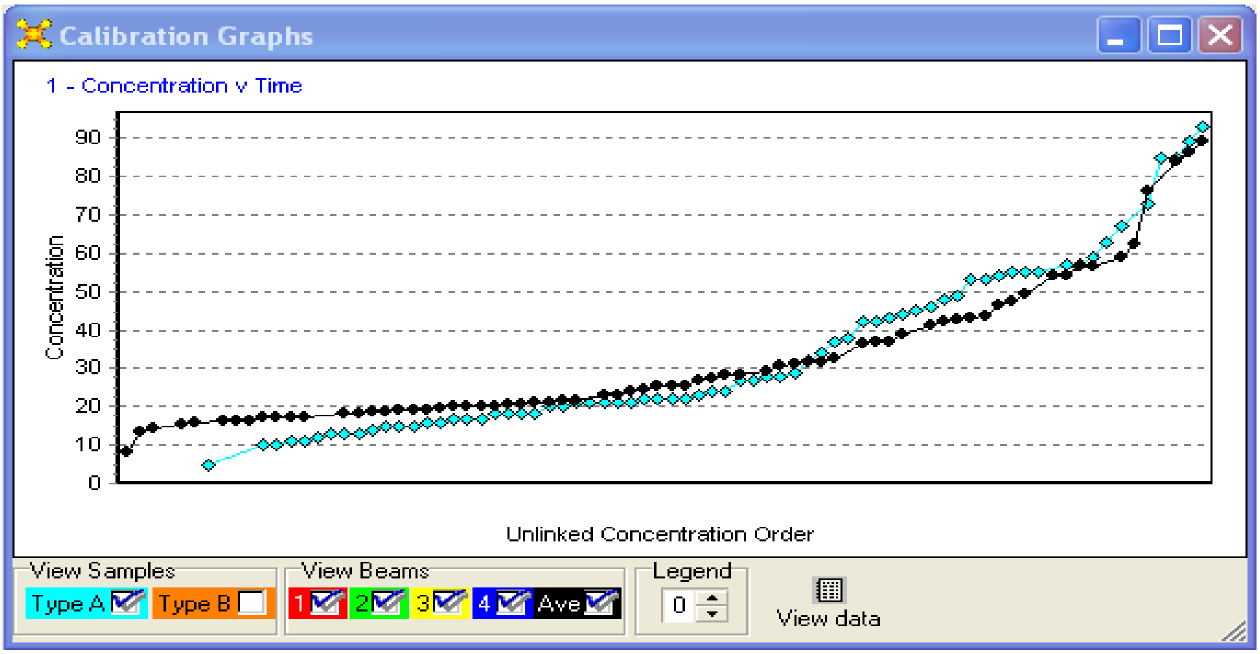

Figure 3. Comparison of gravimetric and acoustic estimates of TSS concentration for all samples in rank order. Gravimetric measurements are represented in blue, whereas acoustic estimates are in black.

Sediment Grain Size

Grain size distribution of a single sediment grab sample taken from the dredge site indicated that dredged material consisted almost entirely of silts (48.8% very coarse silt, 25.8% coarse silt, 10.0% medium silt, 8.7% fine silt, and 6.5% very fine silt). Clay comprised only 0.3% of the sample. This sample analysis was consistent with findings of a sediment trend analysis conducted by the Toledo-Lucas County Port Authority and the U.S. Army Corps of Engineers Buffalo District (McLaren and Hill, 2003), which indicated that silts dominate sediments at the mouth of the Maumee River and throughout the length of the Toledo Harbor navigation channel in Maumee Bay.

Turbidity

Turbidity measurements were taken at ambient, near and far-field stations within the navigation channel during a period of active dredging on 2 August 2005. Concurrently, turbidity data were collected at 5 southern shoal stations in the prominent direction of plume movement. Turbidities were measured in 1-minute intervals, with the exception of two OBS units that logged data at 15-second intervals, as presented in Figures 4 through 6. Ambient readings ranged from 12.6 to 27.3 NTU (mean = 19.1 NTU) in the lower water column (7.0 m). No ambient data were collected in the upper water column (2.2 m) of the channel due to sensor failure. Data obtained from one sensor positioned over the southern shoal outside the influence of the plume recorded upper water column turbidities ranging from 4.6 to 13.8 NTU (mean = 9.2 NTU). These values were comparable to the ambient range found at the lower sensor deployed within the navigation channel, and likely reflect ambient conditions in the upper portion of the channel as well. Turbidity measurements for all OBS deployments are summarized in Table 1.

Near-field Plume Turbidity

OBS units were deployed on an anchored taut-line buoy for 4 hours in the plume at depths of 2.2 and 7 m. During this 4 hour period, as the dredge moved across its cut, distances between the buoy and the dredge ranged from 15 to 46 m. At this station (Figure 4) turbidities in the upper water column were lower (mean = 30 NTU) than in the lower water column (mean = 123.9 NTU). Lowest turbidities (< 10 NTU) were encountered at the upper sensor prior to the plume reaching the monitoring station. The highest turbidity value recorded at the near-field monitoring station occurred at the lower sensor (724.1 NTU). Readings above 500 NTU occurred only twice during the monitoring event. Short-duration pulses of turbid water generally had peak values approaching 300 NTU. A comparison of time of arrival of turbid water at the upper and lower sensors indicated that sediment movement occurred initially along the channel bottom. Turbidity reached 134 NTU in the initial pulse of sediment-laden water that reached the bottom sensor 39 minutes after deployment, while measurements at the upper sensor remained less than 20 NTU. Detection above background turbidity did not occur at the upper sensor until 2-hours after deployment. Higher NTU values typically occurred in "pulses" with durations of 15 to 30 minutes before falling back to ambient conditions.

Table 1. Summary of turbidities recorded at various depths and distances from the dredge.

Station #	Buoy Location	Sensor Depth (m)	Distance To Dredge (m)	Range (NTU)	Mean (NTU)
1	Channel	2.2	250	Failed	Failed
1	Channel	7.0	250	12.6-27.3	19.1
2	Channel	2.2	46	8.3-173.6	30.0
2	Channel	7.0	46	25.7-724.1	123.9
3	Channel	2.3	95	16.5-87.4	41.3
3	Channel	7.5	95	30.1-218.8	83.7
4	Shoal	0.5	75	6.6-35.5	13.2
5	Shoal	0.5	115	4.5-15.0	11.2
6	Shoal	0.5	125	4.6-13.8	9.2
7	Shoal	0.5	157	5.7-26.6	10.9
8	Shoal	0.5	186	4.5-19.6	10.6

Far-field Plume Turbidity

OBS units at depths of 2.3 and 7.5 m were deployed 95 m from the dredging operation (Figure 5). Turbidity values ranged from 16.5 to 87.4 NTU (mean = 41.3 NTU) at the upper sensor. Peak values at the upper sensor were substantially lower than those recorded at the near-field station, although the overall mean increased by slightly more than 10 NTU (Table 1). At the lower sensor, turbidity values ranged from 30.1 to 218.8 NTU (mean = 83.7 NTU) and average turbidities were 40 NTU lower than at the near-field station. Peak NTU measurements at the lower sensor were 500 NTU lower than at the near-field station. Turbidities above 200 NTU occurred in two pulses over the 5 hour deployment at the far-field station. Highest turbidities at the lower sensor fell within a relatively narrow range, from 90 to 110 NTU. Fewer "spikes" were observed for both sensors at the far-field station.

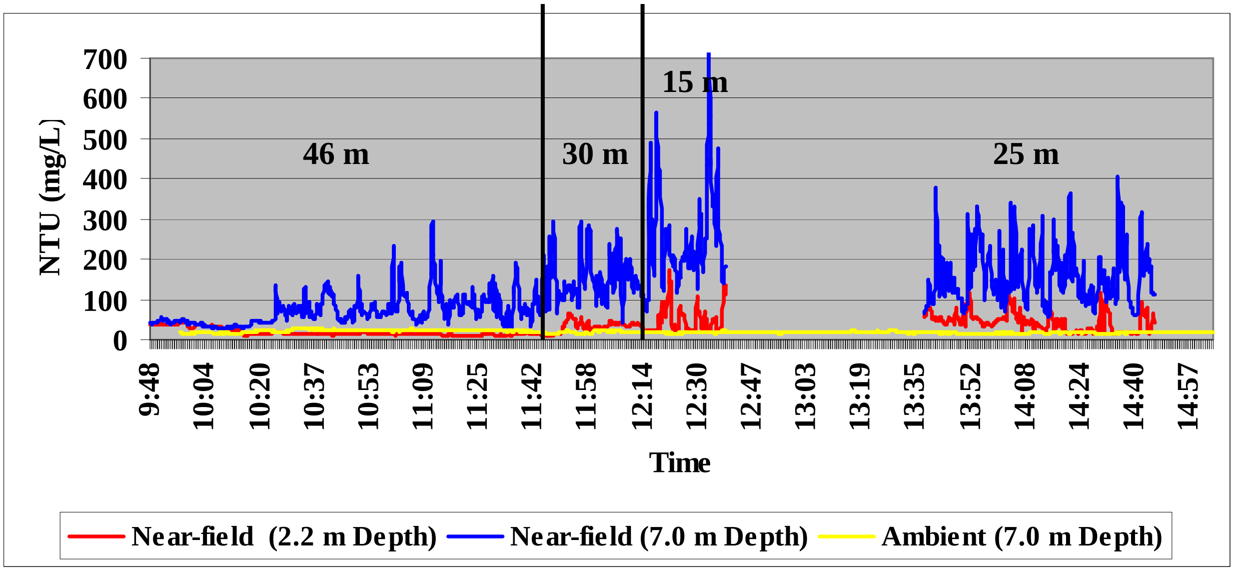

Figure 4. Near-field turbidities at various depths and distances from the bucket.

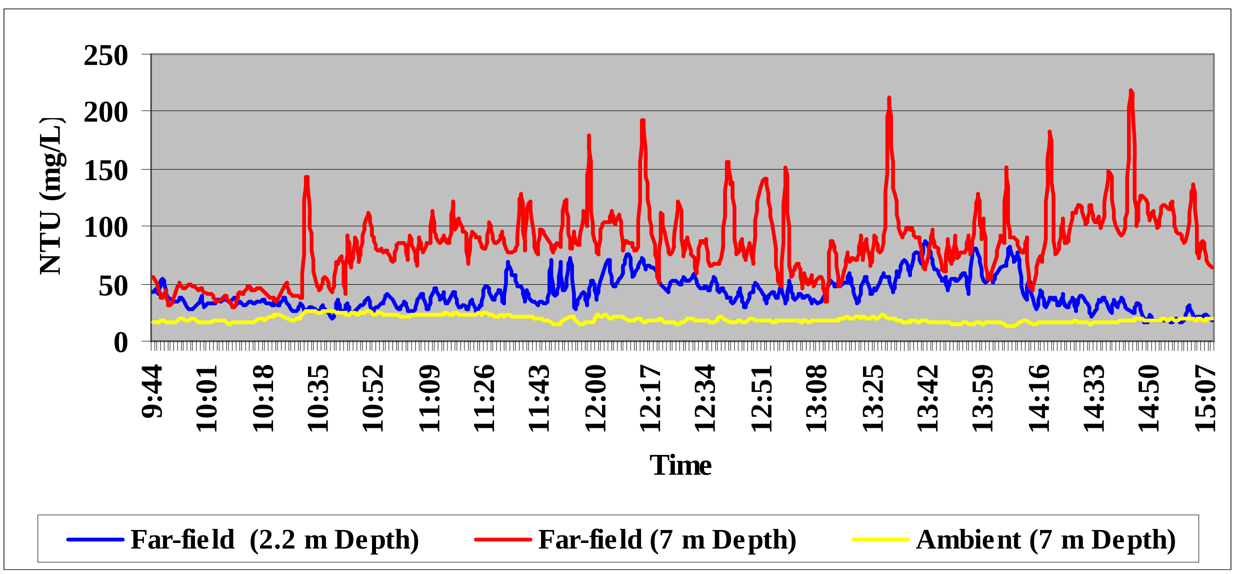

Figure 5. Far-field turbidities at 2.3 and 7.5 m water depths at a distance of 95 m from the bucket. (Note: Ambient sensor deployed at 2.2 m failed.)

Turbidities on the Shoals

Time series of turbidities measured at a depth of 0.5 m at five stations (S1-S5) located on shoals just south of the dredging operation are presented in Figure 6. Stations were arrayed to detect potential movement of the plume out of the navigation channel. During 5.5 hours of monitoring, ambient conditions (5 to 15 NTU) were rarely exceeded. Station S1, located 75 m southwest of the dredging operation, recorded only two pulses, each lasting less than 20 minutes in duration, in which background turbidities were exceeded by 20 NTU (peak value = 35.5 NTU). Turbidities at Stations S2 and S3, located 105 and 125 m southeast of the dredging operation, averaged 11.2 and 9.2 NTU respectively and peak turbidities did not exceed 15 NTU. At Station S4 one 25 minute pulse occurred during which background turbidities were exceeded by up to 10 NTU. Other than during this pulse turbidities at this station, located southwest of the dredging operation, were generally less than 11 NTU. At Station S5, located southeast of the dredge, a single pulse occurred during which turbidities exceeded ambient by approximately 5 NTU. Turbidities ranged from 4.6 to 19.6 NTU (mean = 10.9 NTU) at Station S5.

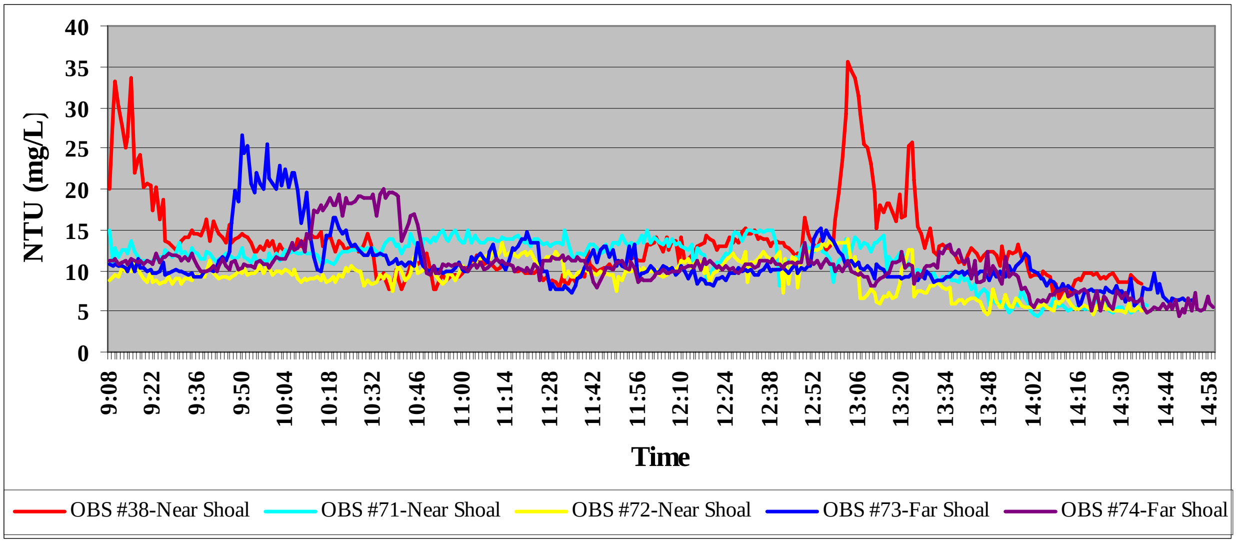

Figure 6. Turbidities recorded at 5 stations over shoals adjacent to the navigation channel.

Ambient Suspended Sediment Conditions

Acoustic estimates of suspended sediment concentrations were lowest in the upper part of the water column (< 3m), averaging less than 20 mg/L. TSS concentrations of 20 to 30 mg/L were generally limited to depths greater than 3 m. Thus 25 mg/L represents an average background TSS concentration prevalent during this study. Periodically small pockets of the water column were surveyed with TSS values ranging from 25 to 30 mg/L. For the purposes of this study and TSS concentrations exceeding 30 mg/L were considered to be generated by the dredging operation.

Bucket Dredge-Induced Plumes

A suspended sediment plume (Survey TCSB) was tracked on 2 August 2005 from 600 m east to 240 m west of Channel Markers 33/34. A plan view layout of transects is shown in Figure 7. The dredge was digging on the south side of the channel, removing material along the toe of the channel side slope. The dredge had been in full production for 2 hours prior to starting the survey. The general direction of plume movement was southwest along the channel side slope. A second area of higher sediment concentration was found northwest of the starboard side of the dredge in the center of the navigation channel.

To fully examine plume structure in significantly greater detail, a series of equally spaced vertical cross-sectional profiles were occupied in both the up- and down channel directions, using the bucket dredge as a focal point. Selected examples of vertical profiles of TSS concentration across transects are given in Figures 8 through 12. Note that the southern shoal is depicted on the left side of each vertical profile. Ten transects were occupied astern (east) of the dredge's position at distances ranging from 2 to 261 m. TSS concentrations over the northern and southern shoals did not differ from that observed during ambient data collection, generally ranging from 10 to 20 mg/L. Within the channel, suspended sediment concentrations astern of the dredge did not exceed background (25 mg/L) throughout most of the water column except for the lowest 2 meters, where TSS concentrations exceeded ambient by 35 mg/L along the southern side slope. Concentrations decreased with increasing distance from the source, but routinely exceeded background by 15 mg/L to 200 m distance from the dredging operation.

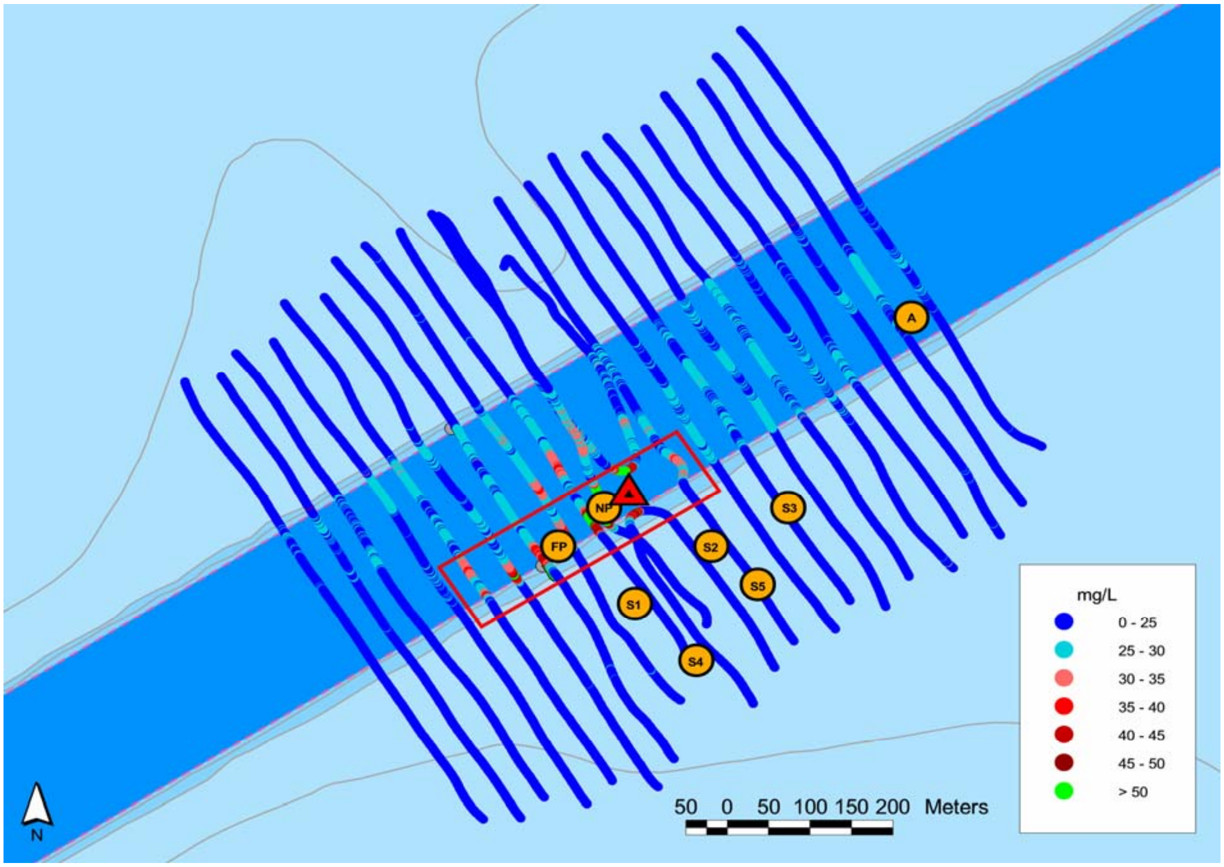

Figure 7. Depth-averaged suspended sediment concentrations during bucket dredging operations in the Maumee Bay navigation channel. Dredge location indicated by red triangle. Orange circles are OBS stations.

Of ten transects occupied up-current side of the dredge, the first passed within 3 m of the point the bucket entered the water (Figure 8). At this distance, the "body" of the plume was approximately 50 m wide with maximum TSS concentrations as high as 800 mg/L. Although TSS concentrations estimated acoustically this close to the source may be artificially inflated due to air entrainment in the plume, air bubbles have been shown to dissipate quickly. At prevailing current speeds air should influence concentration estimates only in the area immediately adjacent to and slightly down-current from the bucket.

Rapid plume decay was observed as maximum TSS concentrations decreased to less than 300 mg/L, or approximately 275 mg/L above background, over a span of 24 m. Very high TSS concentrations were found only in the lower half-meter of the water column (depth > 8 m) along the channel side slope in proximity to the area where material was being excavated (Figures 9 and 10). TSS concentrations diminished rapidly with decreasing water depth, falling to 150 mg/L (125 mg/L above ambient) at a depth of 7 m. In surface to mid-water depths (1-5 m), TSS concentrations exceeded background by 35 mg/L. At 57 m up-channel the surface plume was no longer detectable above background. Highest concentrations (100 mg/L) continued to be found along the southern channel side slope, 1-meter off the channel bottom. At 114 m up-channel, TSS concentrations ranged from 40 mg/L (15 mg/L above background) along the periphery of the plume to 60 mg/L (25 mg/L above background) within a small volume of water in the lower meter of the water column (Figure 11). The plume dissipated over the next 60 m until only trace detections above background were made. At 200 m the plume was no longer detectable above background. No evidence of plume excursion over the adjacent shoals was observed (Figure 11).

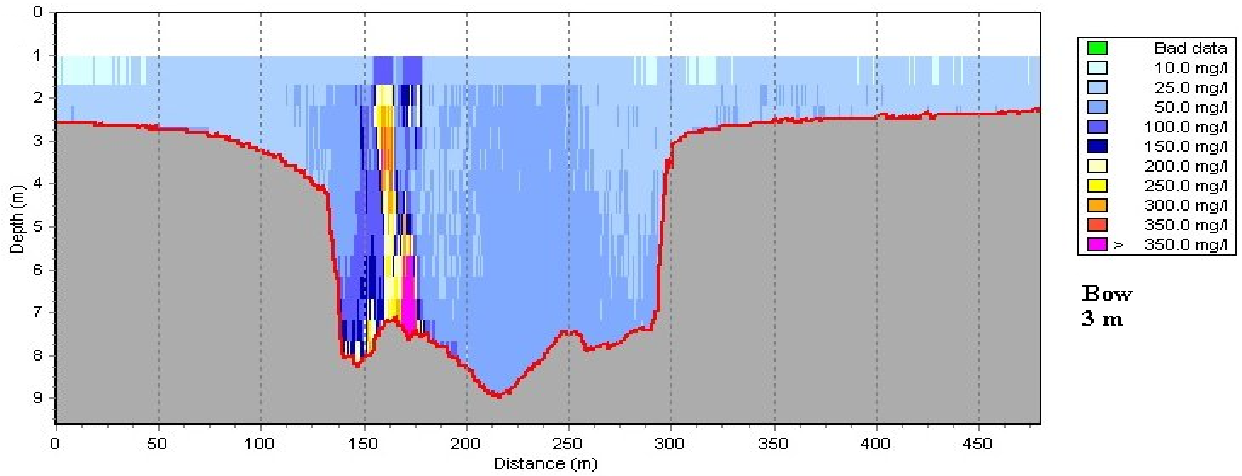

Figure 8. Vertical profile of TSS concentrations at 3 m from the source (Survey TCSB).

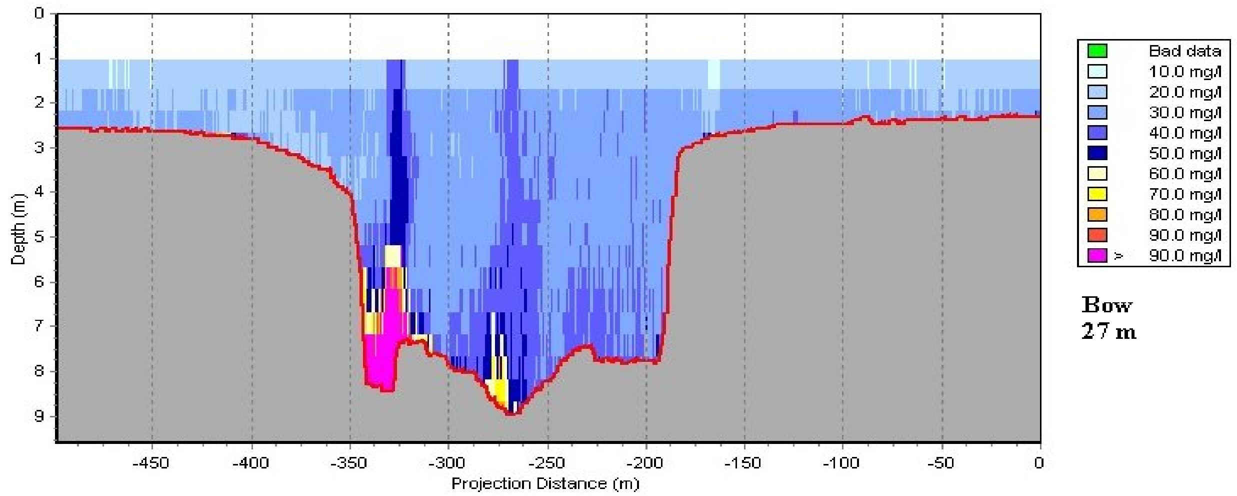

Figure 9. Vertical profile of TSS concentrations at 27 m from the source (Survey TCSB).

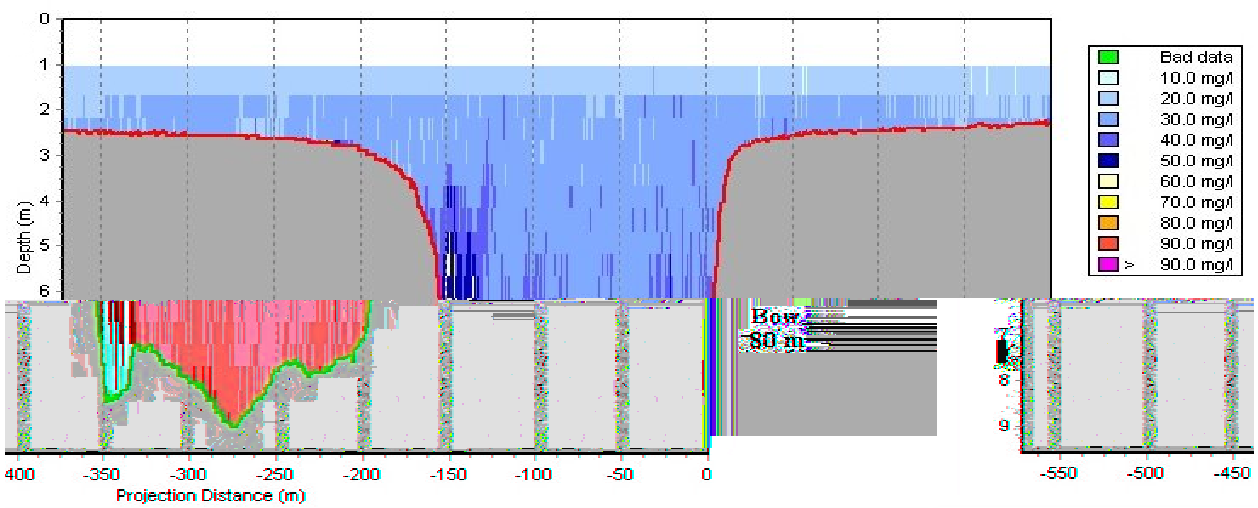

Figure 10. Vertical profile of TSS concentrations at 80 m from the source (Survey TCSB).

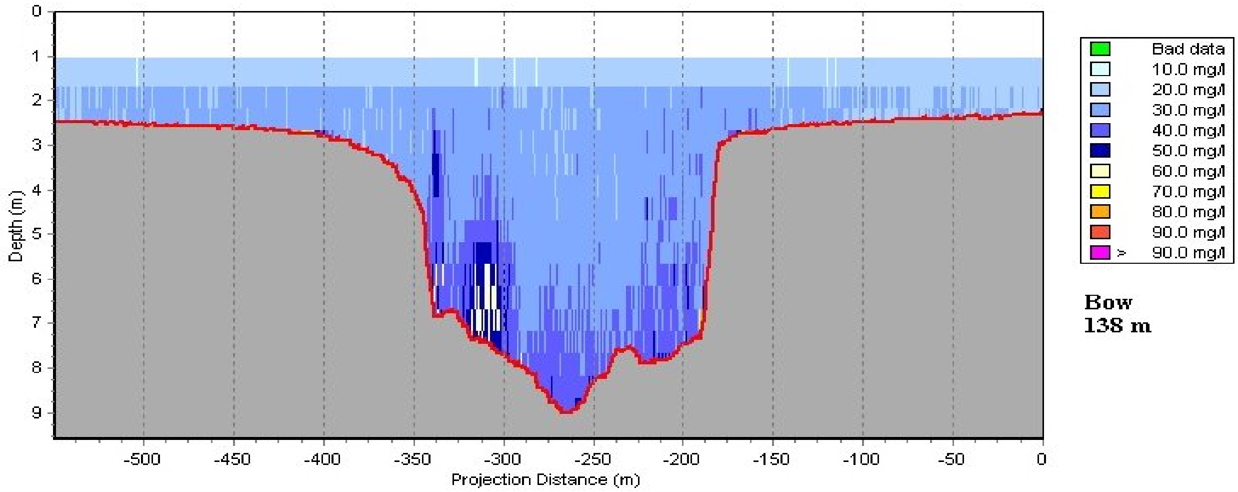

Figure 11. Vertical profile of TSS concentrations at 138 m from the source (Survey TCSB).

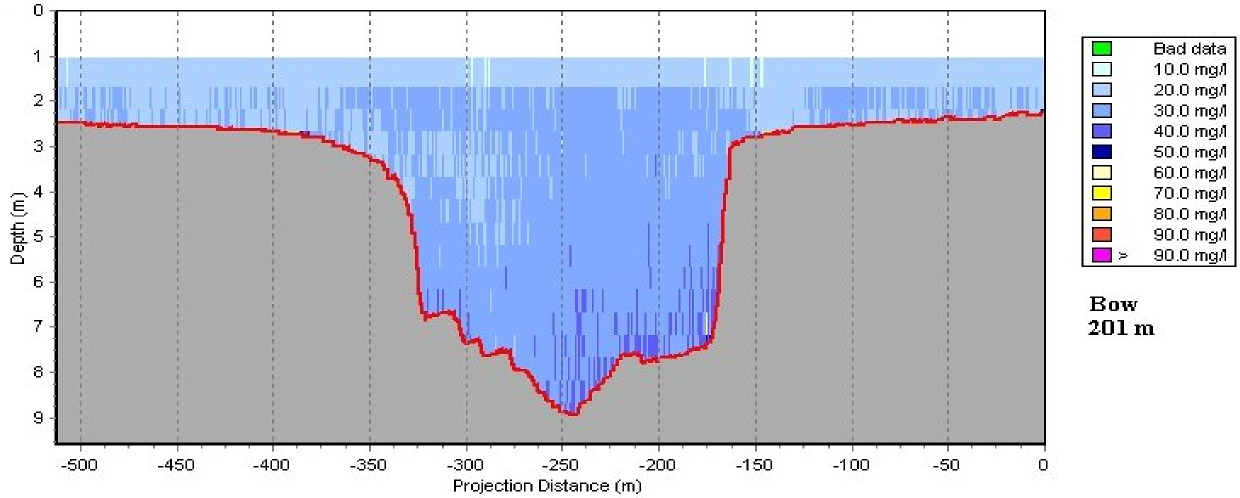

Figure 12. Vertical profile of TSS concentrations at 201 m from the source (Survey TCSB).

A second plume characterization survey was completed later on the same day in the vicinity of Channel Markers 33 and 34. A plan view of transects can be found in Figure 13. Prior to the survey, the dredge had been in full production for 1 hour after having shut down briefly to change barges. Of five transects occupied astern of the dredge two transects, located at distances of 29 and 48 m from the source, show distinct plume signatures, again located along the southern side slope of the channel. The footprint of the plume was confined to the lower half of the water column (> 5 m) with a maximum width of 35 m. TSS concentrations exceeded background by 15 mg/L along the periphery of the plume. The inner core of the plume, largely confined to the bottom of the water column, exceeded background by 35 mg/L. Depth-averaged TSS concentrations were close to ambient throughout the central and northern half of the channel basin. No plume signature was detected beyond 79 m astern (east) of the dredging operation. No evidence of plume excursion onto the adjacent shoals was seen, as TSS concentrations averaged less than 20 mg/L.

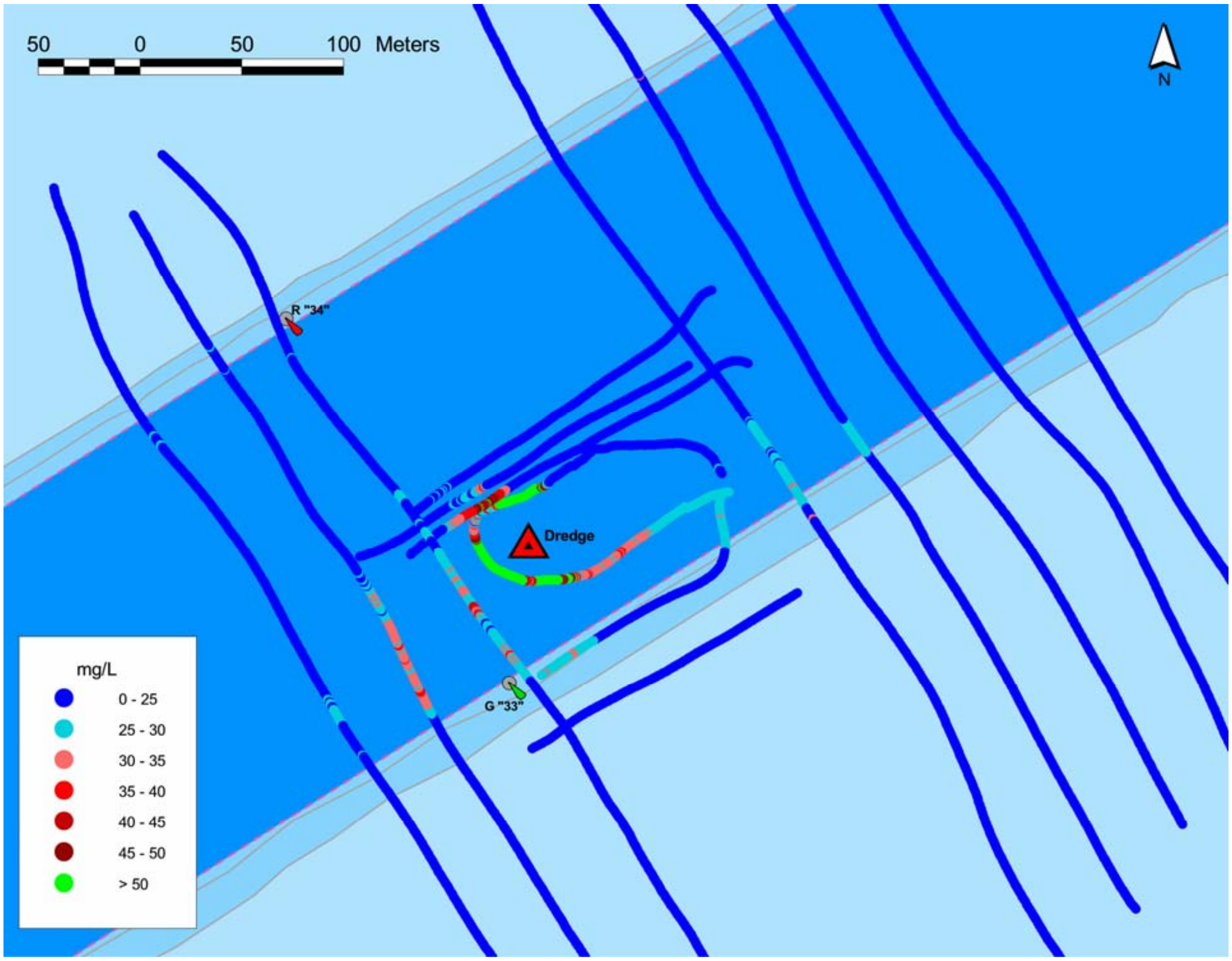

Figure 13. Depth-averaged suspended sediment concentrations during dredging operations in the Maumee Bay navigation channel. Red triangle indicates position of dredge.

Five transects astride of the dredge's position were occupied and parallel to the long axis of the navigation channel. TSS concentrations of 40 mg/L (15 mg/L above ambient) were found at the western terminus of the innermost transect north of the dredge (distance from dredge 31 m). An outer transect occupied 46 m south of the dredge was sailed west to east over the shoal immediately adjacent to the channel. Only trace plume detections, approximately 5 mg/L above background, were observed at the transect's western terminus, due south of the source. At 19 m south of the dredge a well-defined plume with TSS concentrations as high as 180 mg/L, or approximately 155 mg/L above ambient, was present. Highest concentrations were found only in the lower portion of the water column, just above the channel bottom. TSS concentrations fell to less than 50 mg/L (25 mg/L above ambient) slightly higher off the bottom. The plume at this location was slightly more than 30 m wide, and confined to depths greater than 2.5 m. At 30 m from the dredge, the plume occurred only within a meter of the channel bottom. Concentrations to 100 mg/L were found in a small central core, approximately 5 m in width. Sediment concentrations exceeding ambient by 15 mg/L or more were confined to a narrow swath of the channel less than 25 m wide. At 35 m, TSS concentrations exceeded background by 5 to 15 mg/l only along the extreme channel bottom.

Three transects were occupied west of the dredge at 48m, 78 m, and 105 m from the source. Here the plume was confined to the lower half of the water column. A maximum TSS concentration of 130 mg/L was detected in the immediate vicinity of the bucket. Just outside of this area, TSS concentrations of 60 to 80 mg/L were more typical. These concentrations were found generally within the bottom meter of the water column in a swath no wider than 50 m. At 105 m from the source detections above background were limited to the bottom meter of the water column and exceeded ambient by less than 10 mg/L. No evidence of plume excursion outside of the channel was seen. The surface component of the plume only extended approximately 25 m down-current from the point of bucket entry into the water.

DISCUSSION

During dredging and dredged material disposal operations, some sediment is invariably lost to the water column. Sediment is stirred off the bottom by the pressure wave and physical impact of the descending bucket with the substrate. Some additional sediment is washed off the outer surfaces of the bucket as it transits the water column. Some sediment is washed out of the bucket as the bucket breaks through the water-air interface, and some sediment may be lost as spillage as the bucket is slewed to and from the barge. The mass of sediment loss is dependent on numerous factors, including the type of equipment, *in situ* sediment characteristics, prevailing hydrodynamic conditions, site-specific bathymetric features, and skill of the dredge operator. Bohlen et al. (1979) estimated that approximately 1.5 to 3.0 % of the excavated sediment is reintroduced to the water column by bucket dredges. Resuspension losses reported in a review by Anchor Environmental (2003) averaged 2.1% for mechanical dredges, in contrast to 0.77% for hydraulic dredges. Barge overflow practices are another source of loss to the water column, but are not relevant to the present study. Losses during bucket dredging are thought to be greater when open rather than closed buckets are used. In the present case an open bucket was used. Therefore, if a conservative 3% loss rate is applied to the entire 850,000 cubic yard project, then as much as 25,500 cubic yards of sediment could be returned to the water column. Although a substantial mass, this loss must be considered in context with the spatial scales and duration of dredging. During mechanical dredging, much of the “lost” sediment mass returns rapidly to the bottom as aggregates or cohesive clumps rather than disaggregated silt particles. Some of this material is re-dredged as the dredge swings through a digging cut.

Depth-averaged TSS concentrations for surface, mid-and bottom depth strata as estimated by acoustic methods corresponded well with TSS concentrations obtained by gravimetric analysis of water samples taken at varying depths and distance from the dredging operation. Acoustic surveys of plumes, optical measurements and adequate “groundtruthing” efforts in the form of TSS samples measured gravimetrically, provided detained three-dimensional depictions of individual plume behaviors and concentration gradient structure.

Optical turbidity data clearly revealed the pulsing nature of bucket dredging plumes. At fixed points within the plume, spikes in near-field turbidity values were apparent, reaching 400 mg/L at 25 m distance and 300 mg/L at 46 m from the source in the lower water column. Highest turbidity spikes, (3 occurrences at 500 NTU, 1 occurrence at slightly more than 700 NTU) were reached as the dredge advanced to within 15 m of a moored OBS string. During 95% of the monitoring, turbidity spikes were more commonly in the range of 300 NTU. These turbidities (300-400 NTU) given the observed relationship with TSS concentration are roughly equivalent to 400 to 550 mg/L. The detected pattern of moderate turbidities above ambient with intermittent spikes of one to fifteen minute duration is indicative of a heterogeneous rather than a homogeneous plume. These results are consistent with existing knowledge of sediment resuspension by bucket dredges, in which sediment deposition into the water column is influenced by many factors. The factors include bucket speed, angle of insertion into the water column and sediment surface, bucket size and configuration, presence of debris that impedes complete closure of the bucket, and dredge operator skill. The differential influences of these individual factors, combined with site specific hydrodynamics, produces a non-uniform plume.

Of particular concern to resource agencies is whether adjacent shoals, commonly used as walleye spawning habitat would show significant increases in turbidity or TSS resulting from nearby dredging operations. During approximately 6 hours of monitoring, ambient conditions ranging from 5 to 15 NTU (7-20 mg/l) were rarely exceeded. The OBS sensor deployed nearest the dredge reached 35 NTU (17 NTU above background) on two occurrences, approximately 3.5 hours apart, with each episode lasting less than 10 minutes. The two other near-field units did not detect turbidity readings exceeding ambient. The two far-field units each had one occurrence in which ambient conditions were exceeded by 3 to 10 NTU lasting from 15 to 25 minutes. It is likely that the two episodes of increased turbidity recorded by the single near-field OBS unit is dredging-related. But due to the long time periods between the two encounters, it is uncertain that it is related to the excavation process (i.e. the actual digging), but may be related to a support activity such as sediment dispersed in the direction of this OBS sensor by a tug removing a full scow and/or positioning a empty scow near the dredge plant. It is unclear whether the single encounter of increased turbidity at each far-field sensor is dredging-related, especially since vertical profiles did not detect plumes in surface waters at this distance even within the channel.

Both spatial extent and concentration gradient structure were examined for plumes generated by bucket dredging operations. Maximum observed TSS concentrations from acoustic estimates indicated that dredge induced sediments potentially reached 800 mg/L, three meters up-channel of the dredging operation. Since this transect passed within the immediate vicinity of the bucket insertion into the water column, it is likely that air entrainment has skewed the acoustic estimates to some degree. However this peak concentration occurred only in the bottom 1-m of the water column and likely represents a reasonably accurate value at this range from the source. This concentration level does not fall outside of ranges reported for this dredge type by LaSalle (1991). He reported TSS concentrations of 700 mg/L for surface waters and <1,100 mg/L in the lower water column during bucket dredging operations.

Vertical profiles indicated a rapid settling of suspended sediments within a relatively short distance from the source. TSS concentrations fell from 800 mg/L on Transect 1, occupied at 3 m from the dredging operation, to less than 300 mg/L over a 24 m span (27 m total distance from the source). Maximum observed concentration estimates were reduced by 87% to 40 mg/L (15 mg/L above background) over the next 90 m (115 m total distance from source). Detections above background were marginal at distances greater than 125 m, where values ranged from 5 to 10 mg/L above background. Plume signatures were not detected in surface waters beyond 60 m or in the lower water column beyond 200 m. The observed rapid settling may be accounted for, in addition to the prevailing weak currents flows, by incomplete disaggregation of the silts by the mechanical dredge process. Cohesion among silt particles increases the effective bulk density of the aggregated particles in suspension, thereby accelerating settlement.

Movement of sediment was not restricted to the up-channel direction, as TSS concentrations exceeding ambient were made to 200 m down-channel of the dredging operation. Vertical profiles occupied down-channel of the dredge maybe somewhat misleading in that sediment movement in that direction would have to first pass underneath the dredge and scow before emerging astern of the dredge in an area capable of being surveyed. By the time sediments had travel the length of the dredge plant, suspended sediment had settled to the lower 2-m of the water column. These plumes were quite small by comparison to plumes generated by larger bucket dredging operations in tidally influenced rivers and estuaries. For example, plumes were detected to 1,500 m in the open-waters of Chesapeake Bay where water velocities were relatively strong, ranging as high as 1.3 m/sec during a flood tide (Reine et al., 2003).

Vertical profiles of adjacent shoals were examined for increases in TSS concentration above background estimates. Differences between the southern shoal, nearest the dredging activity and the northern shoal were not apparent. TSS estimates to 25 mg/L was detected across both the southern and northern shoals, consistent with background estimates at all depth strata within the channel proper. Concentrations greater than 20 mg/L were confined to the lowest 1-m directly off the bottom. TSS estimates in the upper 1-m of the water column typically ranged from 10 to 20 mg/l. No evidence was seen from vertical profiles of the plume infiltrating the shoals.

CONCLUSION

ADCP surveys effectively characterized suspended sediment plumes produced by bucket dredging during maintenance of the Maumee Bay navigation channel. Plumes generated by the 15 cubic yard bucket dredge in this study can best be described as a relatively narrow band of elevated concentrations of resuspended sediments that decayed rapidly over short distances from the source. The spatial extent of the plume measured no more than 200 m either up- or down-channel from the source with a maximum width of 100 m. Suspended sediment plumes initially extended vertically throughout the water column (surface to bottom). Lateral dispersion of sediment within the channel was limited, as the core of the plume generally “hugged” the southern channel side-slope. Although maximum concentrations exceeded ambient conditions by as much as 775 mg/L in the immediate vicinity of the point of excavation, rapid decaying of the plume reduced these levels by approximately 63% to 300 mg/L over a 25 m span. Over the next 90 m, this level was reduced by an additional 87% to 40 mg/L, or 15 mg/L above ambient. Detectable plumes decayed to ambient conditions within 200 m of the source. No evidence was seen from vertical profiles of the plume infiltrating the shoals. Due to the lack of directional current flow, the plume was not restricted in movement to any particular direction. Plume movement seemed more influenced by the pressure wave generated by the bucket entering and exiting the water column. This surface plume typically was detected to only 60 m from the source. Beyond this point the plume was below the "lip" of the shoal and completely confined to the ship channel. Based on the results of this study, it is unlikely that bucket-dredging operations as conducted in the Maumee Bay navigation channel pose a meaningful risk to walleye spawning habitat. Given the relatively small spatial dimensions of the suspended sediment plumes in the bay portion of the navigation channel, risk factors to walleye eggs present over the shoals in Maumee Bay should be very minimal. Exposures of hatched larvae to elevated suspended sediment concentrations would likewise be limited as the probability of encounters of passively drifting larvae with a plume at any point in time would be small. The absolute number of larvae that could potentially be exposed to TSS concentrations above their tolerance limits would therefore be small.

Assessments such as conducted herein are always subject to limitations inherent in the quantity of field data and the fact that prevailing conditions (e.g., river discharge, winds, equipment variations) may or may not be considered typical. With regard to dredging the Maumee Bay navigation channel, the equipment in place was indeed representative of the large majority of previous dredging events. Occasionally hydraulic cutterhead dredges or hopper dredges have been used in the same channel reaches. However, sediment loss rates at the dredging site associated with mechanical dredges are generally known to be higher than those of hydraulic dredges (Anchor Environmental 2003). In that regard the present study represents a worst case scenario in terms of the absolute loss of sediment to the water column. Also, sediment loss by mechanical dredges occurs throughout the water column, whereas losses by hydraulic cutterheads or dragheads occur primarily at the sediment water interface. Plumes generated by cutterhead or dragheads would therefore tend to be confined to the lower portion of the water column and even less likely to disperse beyond the channel's side slopes. Had this dredging event occurred during a period of high river discharge stronger currents could have dispersed the plumes further, but ambient turbidities and TSS concentrations would likely have been sufficiently high to mask prominent plume signatures. In summary, given the current state of knowledge of the dredging process in Maumee Bay, it is difficult to conceive of a scenario in which sufficient sediment mass could be displaced to any significant surface area of bottom that might trigger detrimental effects on walleye or their habitat.

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