ACOUSTIC DETERMINATION OF SEDIMENT LOSS TERMS FOR MECHANICAL DREDGING OPERATIONS AT PROVIDENCE, RI, USA

John Land[1], Douglas Clarke[2], Kevin Reine[2], and Charles Dickerson[3]

ABSTRACT

Elevated suspended sediment concentrations or sedimentation rates during dredging operations have been a persistent cause of concern among regulatory agencies charged with protection of the environment. Assessments of potential detrimental effects on exposed organisms are hindered by a lack of predictive tools that can accommodate the diverse ways in which mechanical and hydraulic dredges process and release sediment. Exposures also depend heavily on site-specific factors including sediment properties, hydrodynamics, and bathymetry. Recent advances in dredging simulation capabilities based on far-field particle tracking models driven by sophisticated hydrodynamic models offer promising means to calculate exposures but all models require accurate input parameters. In common among the current generation of far-field particle tracking models are input parameters that capture the properties of the sediment, how it is injected into the water column, and the rate of release into the water column. The latter is referred to as the loss term which is derived from dredging process models that require calibration and validation, steps which in turn require field measurements for comparison of observed and simulated data sets. Field measurements of the magnitudes of sediment loss to the water column and subsequent re-deposition have been attempted for decades and have proven to be technically challenging. Reported losses for mechanical dredges have ranged from less than 1% of the mass of sediment dredged to over 5%. Discrepancies have been difficult to attribute to variation of soil type, variation of dredge plant (e.g., open versus closed bucket), or operational measures (e.g., bucket hoist speed). In this study an acoustic Doppler current profiler was used to estimate sediment loss during closed bucket mechanical dredging of maintenance sediments in the Providence River, Rhode Island. Acoustic backscatter was converted to total suspended solids concentration and the net flux of sediment across transects perpendicular to the movement of the plume was determined at varying distances (or elapsed times equivalent to plume "age" at a given distance) from the source. Repetitive transects were occupied at specified down-current distances/times to capture variation in net flux due to the spatially heterogeneous distribution of sediment comprising a fully developed plume. Loss terms for dredging during flooding tides at two locations were derived by extrapolation of flux back to the source at time zero. Using this approach we estimated losses of 5.4% and 9.6%. These losses are at the high end of those previously reported in the literature. We attribute this to a combination of factors, including extremely soft soil, aggressive dredging by a contractor attempting to achieve maximum production and possibly by differences in measurement methodologies. These findings are discussed with respect to implications for future applications of dredge simulation models.

Keywords: Suspended sediment, plume, bucket dredge, particle tracking model

INTRODUCTION

Sediment resuspension by dredges and subsequent deposition of those sediments form the basis for longstanding concerns voiced by regulatory agencies charged with protection of the environment. Assessments of potential detrimental effects resulting from exposure of organisms to elevated suspended sediment concentrations or sedimentation rates are hindered by a lack of predictive tools that can accommodate the diverse ways in which mechanical and hydraulic dredges process sediment. Exposures also depend heavily on site-specific factors including *in situ* sediment properties, hydrodynamics, and bathymetry. Recent advances in dredging simulation capabilities based on far-field particle tracking models driven by sophisticated hydrodynamic models offer promising means to calculate exposures. However, all models require accurate input parameters. In common among the current generation of far-field particle tracking models are input parameters that capture the properties of the *in situ* sediments, how the sediment is injected into the water column, and the rate of release of sediment mass into the water column. The latter is referred to as the loss term. Dredging process models require calibration and validation, steps which in turn require empirical data as a basis for comparison of observed and simulated data sets.

[1] Dredging Research Ltd., 3 Godalming Business Centre, Woolsack Way, Godalming, Surrey GU7 1XW, UK
[2] Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180, US
[3] Bowhead Information Technology Services, 1905B Mission 66, Vicksburg, MS 39180, US

Field measurements of the magnitudes and rates of sediment loss to the water column and subsequent re-deposition have been attempted for decades and have proven to be technically challenging to obtain. Sampling in the immediate vicinity of a dredge is logistically difficult and various approaches have been attempted. Direct sampling of water parcels for gravimetric analysis at precisely known locations in relation to a moving source of sediment release is generally impractical.

Researchers have developed several analytical means to estimate resuspension rates by various dredge types. Based on measurements of either turbidity or total suspended sediment (TSS) concentration taken as close as possible to the source, each approach calculates a source strength parameter. Nakai (1978) proposed the Turbidity Generation Unit (TGU), measured in kg/m^3, which relates sediment mass in the water column to the sediment mass removed from the substrate by the dredge. Note that "turbidity" as used by Nakai (1978) refers to mass and not the optical properties of a volume of water containing sediment. Pennekamp et al. (1990, 1996) later proposed the Suspension Parameter, or S-parameter (in kg/m^3), which relates an estimate of dry weight of bed material in the water column to dry weight of sediment in a specified volume of dredged sediment. Collins (1995) described the sediment resuspension process as a mass of sediment originating from the dredging source, and therefore as a mass flux. Collins (1995) then described a source strength (termed R) model that incorporated information on geometry of the source and source boundary surfaces, fluid velocity structure, and resuspended sediment concentration at the source boundaries. Recently Hayes (2000), and Hayes and Wu (2001) described and refined a new approach to estimating TSS source strengths by means of a resuspension factor (R), which represents the sediment mass loss rate as a percentage of the sediment removed by a dredge. Where reported, methodologies for collecting empirical data for calculating TGU, S, or R have involved combinations of optical turbidity sensors and direct water sampling for gravimetric analyses.

In 2003 H.R. Wallingford and Dredging Research Limited published Measurement Protocols for measuring sediment releases from various dredge types (HRW-DRL 2003). The guidance was developed during the on-going TASS study which is intended to develop field-calibrated computer models of sediment release by the main types of dredge (Burt et al., 2000). For mechanical dredges, the primary measurement method relies on acoustic data collected with acoustic Doppler profilers (ADCPs), and measures the loss in terms of sediment mass flux.

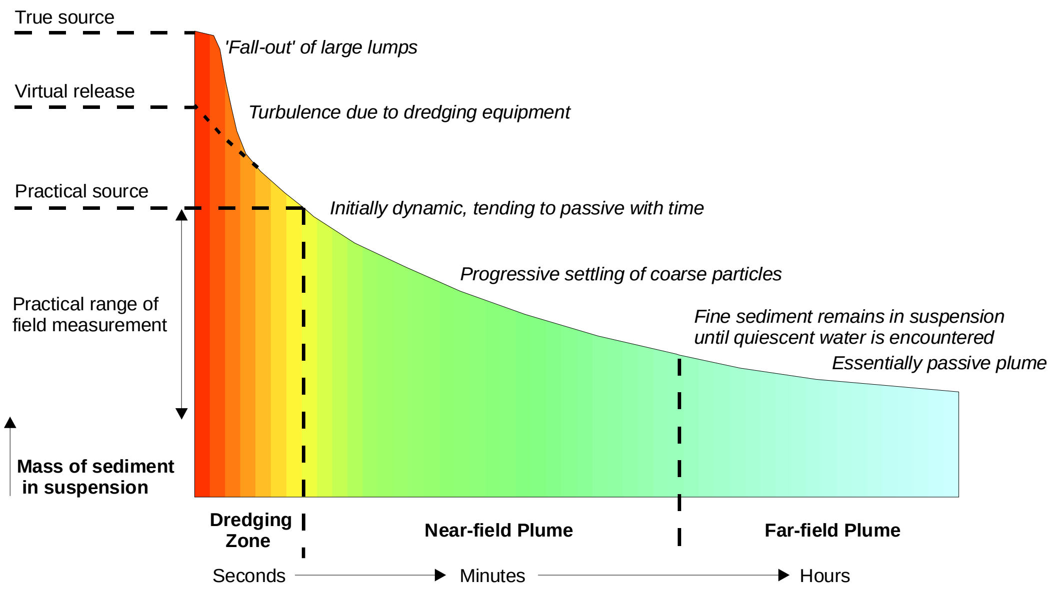

Figure 1. Stages and processes of plume development.

The process operating during plume development are schematically illustrated in Figure 1 (HRW-DRL, 2003). The dredging zone is the area close to the dredge within which it not safe or practical to undertake measurements. Within this zone, there is intense turbulence due to the operation of the dredging equipment. In the case of bucket dredges, lumps of material will fall rapidly to the bed without contributing significantly to the plume that moves away from the dredge into the near- and far-fields that are of interest to researchers. Figure 1 leads to a practical definition of sediment release rate. This is the 'virtual' release rate defined as the apparent release rate back-calculated from multiple reliable measurements obtained in plumes of varying age in the near-field and far-field and is the release rate input to numerical plume models.

This paper describes an application of acoustic methods for measuring the virtual release rate. In this case, an opportunity to collect flux data arose during mechanical dredging of maintenance sediments in the Providence River, Rhode Island, USA. Documentation of methods used to generate the loss terms are a necessary precursor to the use of derived loss terms in far-field particle tracking models. Thus our objective is also to stimulate discussion of realistic bounds for model input parameters, and ultimately increase the utility and credibility of modeling tools.

It should be noted that the primary purpose of the surveys described here was to obtain data on the environmental impacts of the dredging operations, not to measure the source term. The TASS Measurement Protocol demands very detailed measurements of, for example, dredger operation and soil properties, which were not possible in this case. Therefore, although the estimates of sediment release rates presented here are thought to be rather accurate, they must not be assumed to be typical of mechanical dredging operations.

METHODS

Study Areas

Field data collection occurred in the tidal portion of the Providence River navigation channel at two sites adjacent to Sabin Point and Bullock Point. These areas are located midway between the City of Providence and the river's confluence with Narragansett Bay. The study sites are depicted in Figure 2.

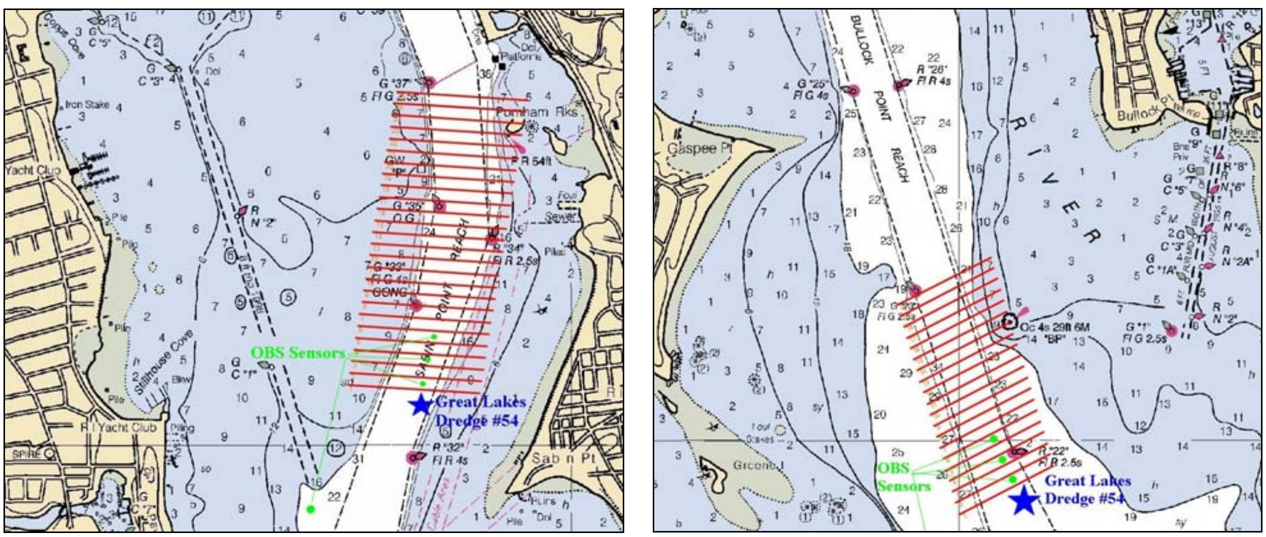

Figure 2. Study sites showing dredge locations (blue stars) at Sabin Point (left) and Bullock Point (right). The red lines are the approximate locations of the ADCP transects.

ADCP Surveys

Plumes were characterized by tandem deployments of moored turbidity sensors and mobile acoustic Doppler profiler (ADCP) surveys. In brief, in addition to measuring current velocities and vectors the ADCP records relative acoustic backscatter from sediment particles and other reflectors in suspension. The backscatter data are then converted to estimates of total suspended solids (TSS) concentration (Land and Bray 2000). Plume characterization data were collected at Sabin Point during a flood tide on 20 April 2004 by surveying 26 east-west transects (Figure 2). The transects extended beyond the full width of the navigation channel, continuing laterally into background conditions based on real-time display of the ADCP return signal. A second plume characterization survey was completed at Bullock Point during the flood tide later on the same day. Twenty east-west transects were needed to fully cover the spatial extent of the plume.

The Dredging Operation

Great Lakes Dredge and Dock Company bucket dredge #54 used a modified closed bucket at both study sites. Originally a 19.9 m^3 open bucket, a canopy and vents had been added, increasing the bucket volume to 22.9 m^3 (Figure 3). At both sites the dredge worked along the toe of the channel's eastern side. Analysis of core samples showed that the *in situ* maintenance sediments were approximately 90% clay and silt and 10% sand.

Figure 3. Closed 22.9 m^3 bucket in use during plume characterization surveys.

Video records of bucket cycles were obtained at both sites, although not simultaneously with the plume observations. These were used to determine the average times for each component of the bucket cycle (i.e., descent from water surface to bottom, closure, ascent from bottom to surface, slewing from surface to barge, return from barge to water surface). Average cycle times at Sabin Point and Bullock Point were 70.3 and 48.6 seconds respectively. Assuming that the bucket handled 22.9 m^3 of sediment per cycle, and that cycle times were consistent during the ADCP surveys, production rates were approximately 1,175 m^3 and 1,700 m^3 per hour at Sabin Point and Bullock Point respectively.

Current Data

An RD Instruments 600-kHz Mariner Workhorse Series ADCP was used to collect current velocity, current direction, and acoustic backscatter data. RD Instruments WinRiver software running on a laptop computer 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. 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 simultaneously and integrated during post-processing.

Conversion of Acoustic Backscatter to TSS Concentration

Acoustic backscatter data were analyzed using Sediview Software provided by DRL Software Ltd. The Sediview Method (Land and Bray 2000) derives estimates of suspended solids concentration in each ADCP data bin by converting relative backscatter intensity to TSS concentration. This process requires collection of a calibration data set consisting of discrete water samples analyzed gravimetrically. The sample population represents the concentration gradient at the study site and is used to "groundtruth" the acoustic data. The calibration samples are collected at known depths and times so that individual gravimetric samples can be directly compared with acoustic estimates of TSS concentration for an ensonified "bin" of water as close to the water sample as possible.

Turbidity

D&A Instrument Company optical backscatter sensors (Model OBS-3A), capable of measuring turbidities in the 0-1,000 NTU range, were deployed using taut-wire buoys to obtain time series data describing variation of turbidity at known water depths and distances from the source. Ambient data were collected prior to commencement of dredging activities on 19 April. During dredging four stations (one ambient, three in plume) were occupied at each site with sensors at predetermined water depths. The sensor array closest to the source at Sabin Point consisted of 3 sensors at depths of 2.5, 5.6 and 8.2 m at a distance of approximately 100 m from the bucket. Stations were also established at distances of 155 m and 255 m from the bucket. The deployment at Bullock Point involved in-plume stations at distances of 135 m, 200 m, and 350 m down-current from the bucket.

Air Entrainment Experiment

One of the known difficulties of acoustic measurements of backscatter for conversion to TSS concentration is air contamination of the signal. Although it is desirable to derive estimates of TSS as close to the source as possible, air entrained into the water column as the bucket transits the air-water interface can create an artifact in the acoustic data which could generate high backscatter values and biased TSS estimates. To determine the down-current distance at which acoustic measurements would not be contaminated, an experiment was performed in which the dredge completed rapid bucket descent-ascent cycles without impacting the sediment bed and without releasing sediment to the water column. In this manner the bucket entrained a maximal amount of air into the water column. While the bucket was repeatedly cycled in this manner, ADCP transects were occupied at increasing distances from the bucket until the bubbles were observed to have dissipated. Distances to the source at the point of closest passage along each transect were verified by laser range finder measurements. Bubbles were faintly discernable near the surface 44 m from the source (an equivalent plume "age" of 293 seconds) and absent 46 m from the source (an equivalent plume "age" of 306 seconds). Therefore, acoustic estimates of TSS concentration based on the Providence River backscatter data should be relatively free from air contamination when made in plumes more than 300 seconds old. It is interesting to note that 300 seconds was the bubble dissipation time observed in similar experiments undertaken in the UK for the TASS program by Burt et al (these proceedings).

RESULTS

Calibration of Acoustic Estimates of TSS Concentration

A total of 142 water samples, collected simultaneously with ADCP measurements at known depths, were analyzed gravimetrically. Samples were obtained both within the plumes and in background conditions. Figure 4 compares the post-calibration Sediview concentration estimates with the water sample TSS concentrations.

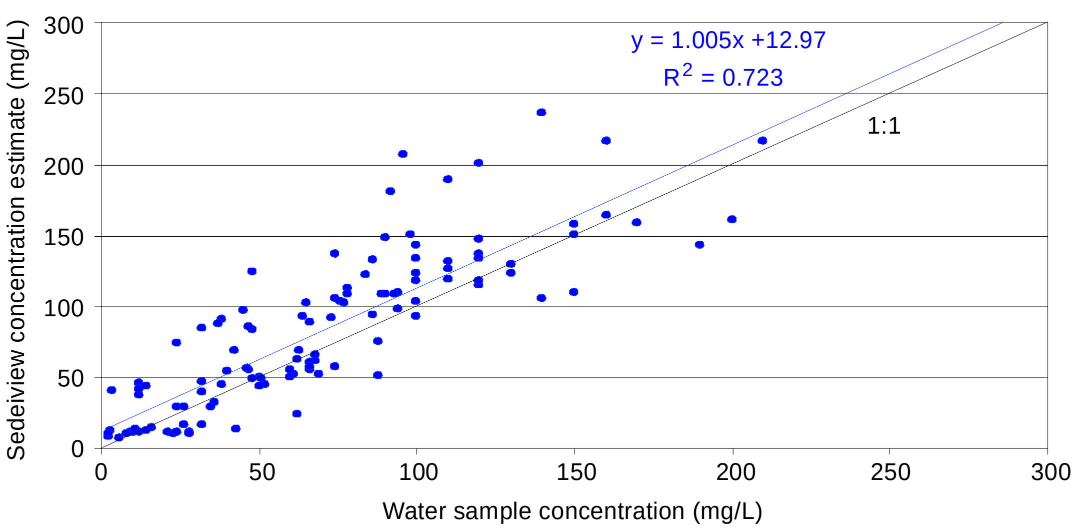

Figure 4. Comparison between Sediview concentration estimates and water sample concentrations.

A proportion of the calibration water samples were obtained close to the dredge where the plume was less than 300 seconds old. The ADCP data corresponding to 10 samples were obviously grossly contaminated by air bubbles and were rejected. There is inevitably limited air bubble corruption of some of the remaining data that have been included in Figure 4 which probably explains why the regression through the data indicates a slight overestimate over the measurement range. This should not influence the sediment flux estimates used to estimate the release rates from the dredges as the measurement data used for the estimates was restricted to those transects sailed through plumes more than 300 seconds old.

Slight air contamination also explains some of the scatter in Figure 4. The remaining scatter is largely due to the impossibility of achieving co-location of ADCP and water sample data. If the water sampler is suspended vertically between the four ADCP beams at 10 metres water depth, for example, the closest ADCP measuring volume is about 3.5 m from the sampler. This presents obvious practical difficulties when working in dredge plumes where concentration gradients, both vertical and horizontal, can be considerable. In order to derive a reliable calibration in these circumstances, it is necessary to obtain numerous water samples and to carefully analyze the data until the calibration yields concentration estimates that are in general agreement with the water sample data and which exhibit no error trend related to concentration, measurement range or time (in this case, plume age).

Current Structure

ADCP measured depth-averaged current vectors indicated general flows to the north and northwest in the study areas during the flooding tide, with peak current velocities approaching 0.20 m/sec and 0.15 m/sec at Sabin Point and Bullock Point respectively. No evidence of stratified flow was observed at either site.

Turbidity

Figure 5 depicts the relationship between TSS concentration and NTU values obtained simultaneously from an OBS-3A unit attached to the water sampler. TSS concentrations determined gravimetrically ranged from 2 to 480 mg/l. The highest concentrations (> 300 mg/l) occurred only within 100 m of the dredge plant.

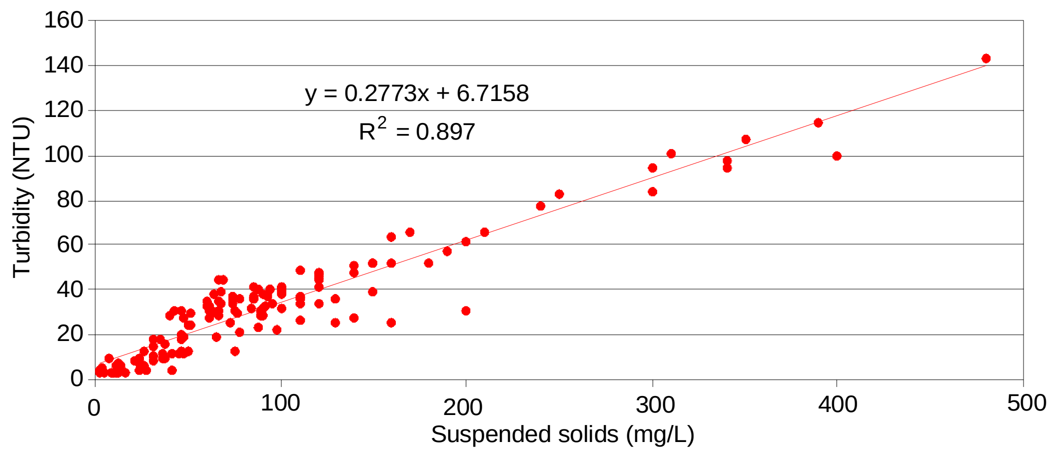

Figure 5. Relationship between turbidity (NTU) and TSS concentration of water samples.

Ambient turbidity readings ranged from 1.8 to 3.1 NTU at depths less than 3-meters, from 13.9 to 16.6 NTU at 6 m, and from 16.1 to 18.0 NTU at 8.5 m. A 3 hour OBS deployment at a distance of 100 m down-current from the bucket at depths of 2.5, 5.6 and 8.2 m at Sabin Point yielded the record shown in Figure 6. Initial readings of relatively uniform turbidities of approximately 10 NTU are indicative of ambient conditions. Arrival of the plume at this station is evident as turbidities rose first at the mid-depth sensor, soon followed by the deep sensor. Turbidities at the shallow sensor did not rise until more than 50 minutes after onset at the deeper sensors. The record clearly shows a pattern of sharp pulses, with turbidity values reaching 90 to 110 NTU for 3 to 10 minute intervals at the deep sensor, 40 to 95 NTU for somewhat shorter intervals at the mid-depth sensor, and 15 to 40 NTU at the shallow sensor. Because readings were recorded at one minute intervals, they represent single points in the average bucket cycle. Therefore, a direct correspondence between pulses at the three depths cannot be discerned. However, the high degree of variation in turbidity throughout the water column clearly demonstrates the non-uniform release of sediments at the source. The illustrated record is typical of all turbidity data collected at both sites. Peak turbidities at the more distant down-current station decreased substantially at comparable depths.

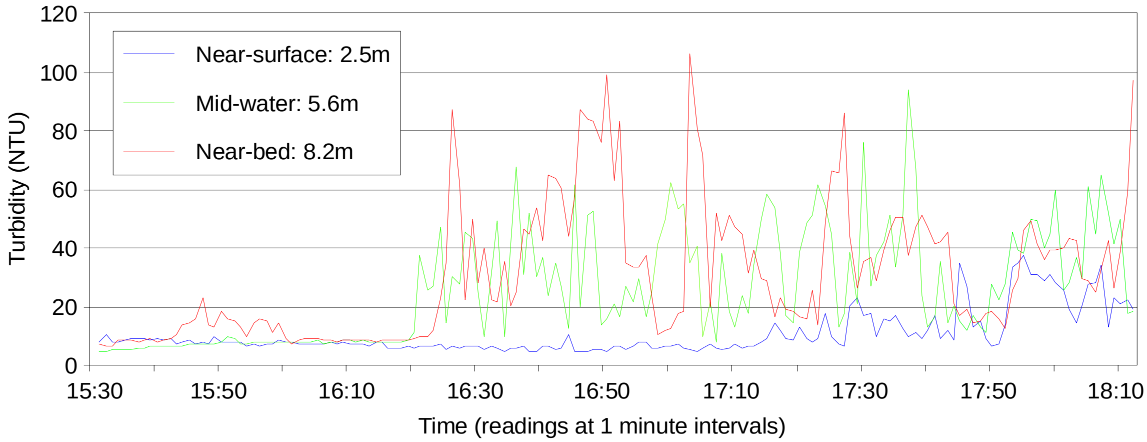

Figure 6. Inner near-field plume (100 m) turbidities at depths of 2.5 m (top) and 8.3 m (bottom) down-current from the dredging operation at Sabin Point.

Acoustic Characterization of Ambient Conditions

Ambient suspended sediment concentrations were characterized while the dredge was inactive and by surveying outside the areas influenced by the plumes. Ambient concentrations ranged from 6.5 to 20.5 mg/l (mean = 12.8 mg/l) at both study sites (Figure 7). Highest ambient concentrations were routinely found in the lower portion of the water column, typically within 2-m of the channel bottom. All acoustically estimated TSS concentrations > 20 mg/l are herein considered to be above background conditions and influenced by the dredging plume.

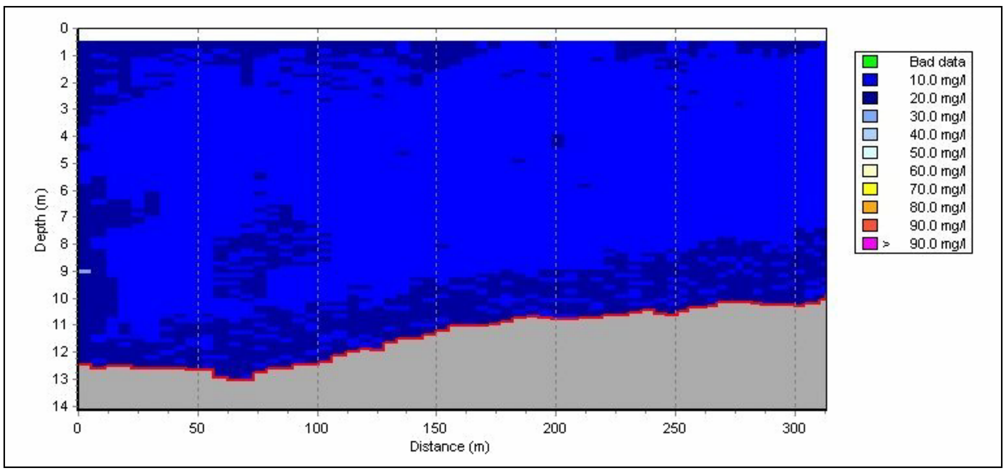

Figure 7. Typical vertical profile of ambient TSS conditions in the Sabin Point reach of the Providence River.

Acoustic Characterization of Sediment Plumes

Sabin Point Reach Plume Characteristics

When the survey commenced, the dredge had been working for sufficient time to generate a fully-developed plume with maximum concentration gradients and spatial dispersion. To capture the variation in release of sediment at near-field distances down-current from the source, repetitive transects were run with the ADCP. The number of transects completed for each down-current distance at Sabin Point are given in Table 1.

Table 1. Transect allocations at specific distance from the source at Sabin Point.

Sabin Point Transect #	Number of Replicates	Distance to Bucket (m)	Current Speed (m/sec)	Plume Age (min)
1	4	29	0.2	2.39
2	4	79	0.21	6.42
3	4	129	0.2	10.75
4	3	179	0.2	14.92
5	3	229	0.2	19.08
6	2	279	0.2	23.25
7	2	329	0.2	27.42
8	2	379	0.2	31.58
9	2	429	0.19	35.75
10	1	479	0.19	42.02
11	1	529	0.19	46.40
12	1	579	0.19	50.78
13	1	629	0.18	58.23
14	1	679	0.18	62.87
15	1	729	0.18	67.50
16	1	779	0.18	72.12
17	1	829	0.17	86.17
18	1	879	0.17	86.18
19	1	929	0.17	91.08
20	1	979	0.16	101.98
21	1	1029	0.16	107.18
22	1	1114	0.15	116.05
23	1	1199	0.15	133.22
24	1	1350	0.15	150.00
25	1	1501	0.14	178.68
26	1	1652	0.14	196.67

The ages of the plumes at each transect have been estimated by integrating the measured current data. A series of ADCP transect vertical profiles for the Sabin Point survey is given in Figures 8 through 31. Note the changes in concentration ranges in the legends for the figures at increasing distances/ages from the source. To illustrate the degree of variation in plume structure at near-field distances most of the replicate profiles are provided. The closest transect to the source was 29 m down-current, where apparent TSS concentrations as high as 1,000 mg/l were detected (Figures 8 - 11) but these are certainly contaminated by air bubbles. Figures 12 through 14 depict a well-defined plume extending from surface to bottom 79 m from the source. TSS concentrations ranged from 40 mg/l along the outer periphery of the plume to greater than 300 mg/l within the plume's core. The near-field plume signature at 129 m (age 10.75 minutes, Figures 15 and 16) can be described as a relatively narrow band of elevated TSS initially extending throughout the water column, with a maximum lateral extent of approximately 50 m.

On succeeding transects the core of the plume remained in the eastern half of the navigation channel, although some lateral dispersion towards the center of the channel occurred. TSS concentrations above 100 mg/l remained detectable at approximately 179 m (age 14.92 minutes) from the source, but the total area influenced by these concentrations was relatively small (Figure 17 and 18). At 229 m from the source, surface decay of the plume is evident. Progressive plume decay is seen at increasing distances from the source (Figures 19 – 26). At 429 m the plume structure is very similar in both replicates (Figures 27 and 28). At 879 m only a faint plume signature remained (Figure 30) with estimated concentrations exceeding background conditions by < 10 mg/l. This faint signature continued to diminish, but remained detectable against background as far as 979 m (age 102 minutes) from the source. Beyond 1,100 m, distinct plume signatures were not detected against background conditions (e.g., Transect 25, Figure 31).

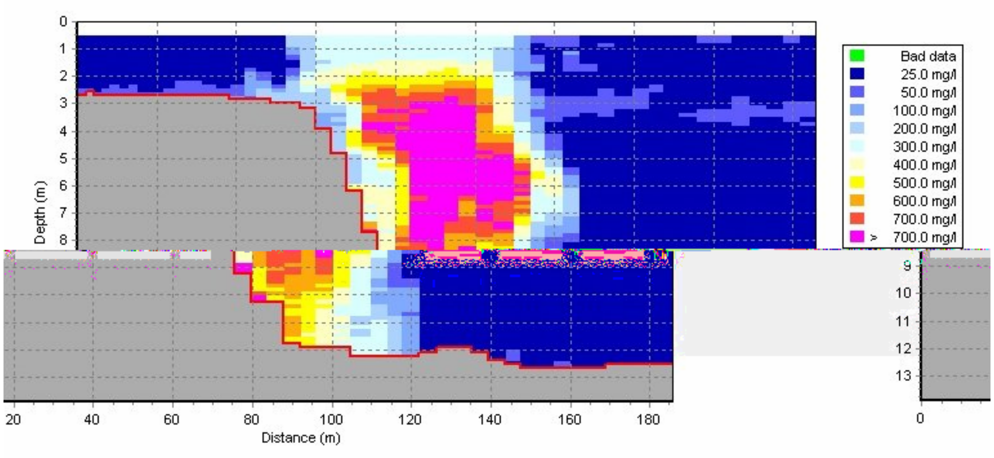

Figure 8. Transect 1, Replicate 1, Distance = 29 m, Plume age = 2.39 min.

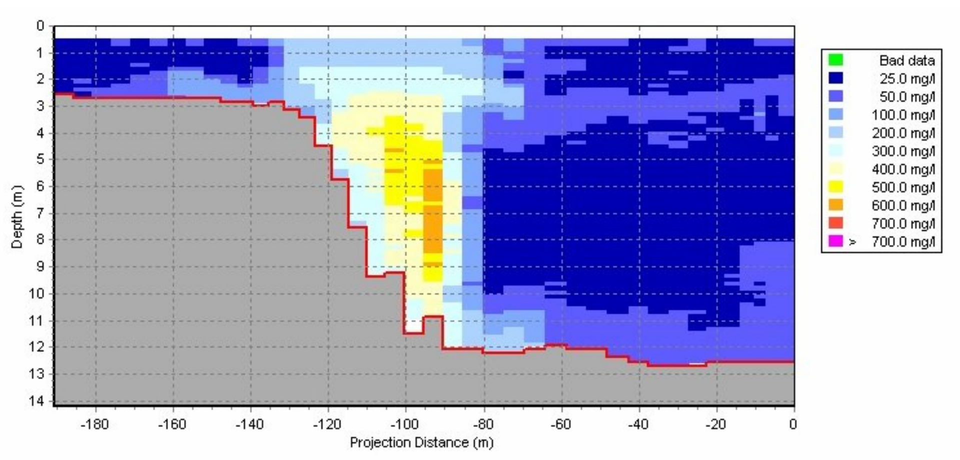

Figure 9. Transect 1, Replicate 2, Distance = 29 m, Plume age = 2.39 min.

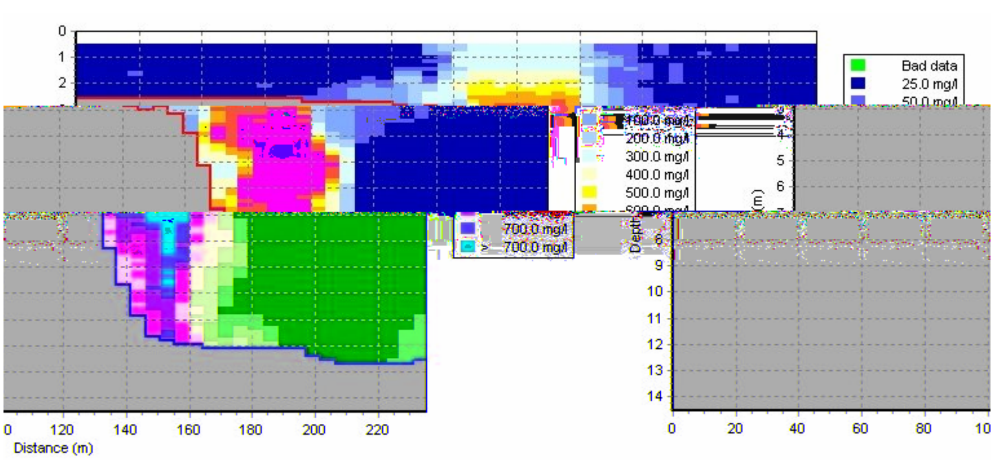

Figure 10. Transect 1, Replicate 3, Distance = 29 m, Plume age = 2.39 min.

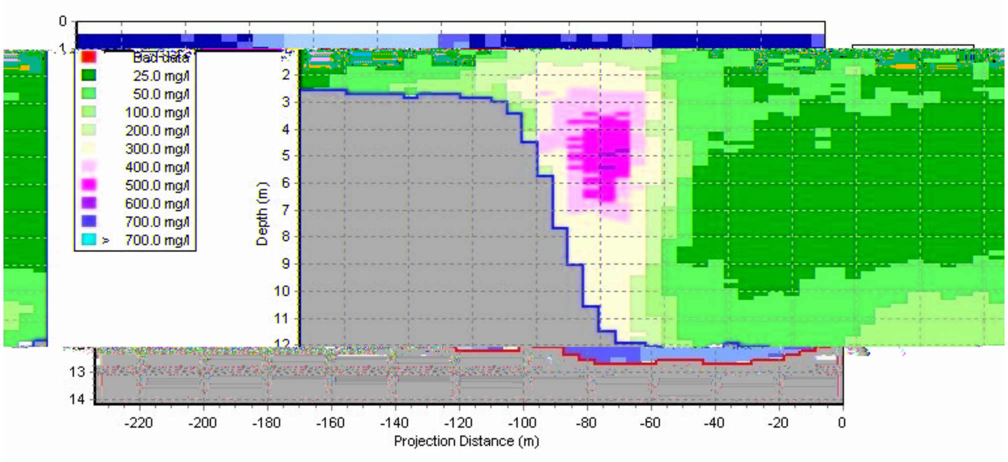

Figure 11. Transect 1, Replicate 4, Distance = 29 m, Plume age = 2.39 min.

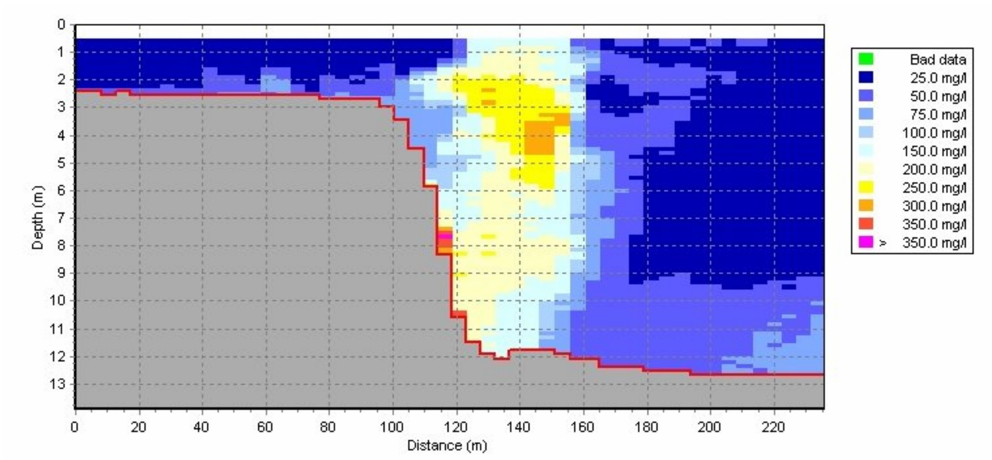

Figure 12. Transect 2, Replicate 1, Distance = 79 m, Plume age = 6.42 min.

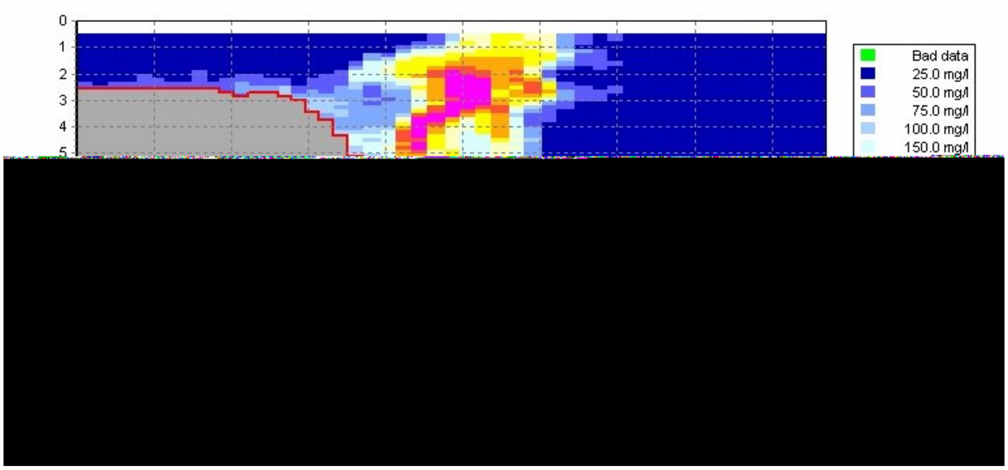

Figure 13. Transect 2, Replicate 3, Distance = 79 m, Plume age = 6.42 min.

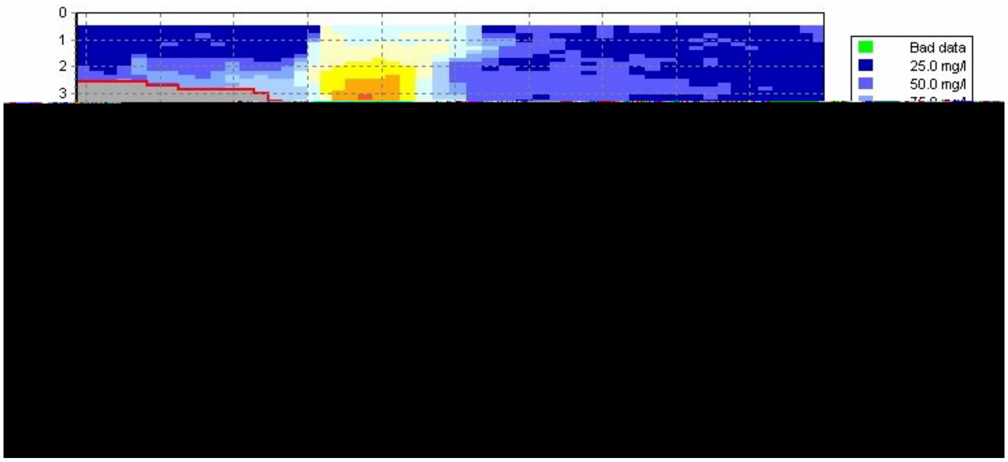

Figure 14. Transect 2, Replicate 4, Distance = 79 m, Plume age = 6.42 min.

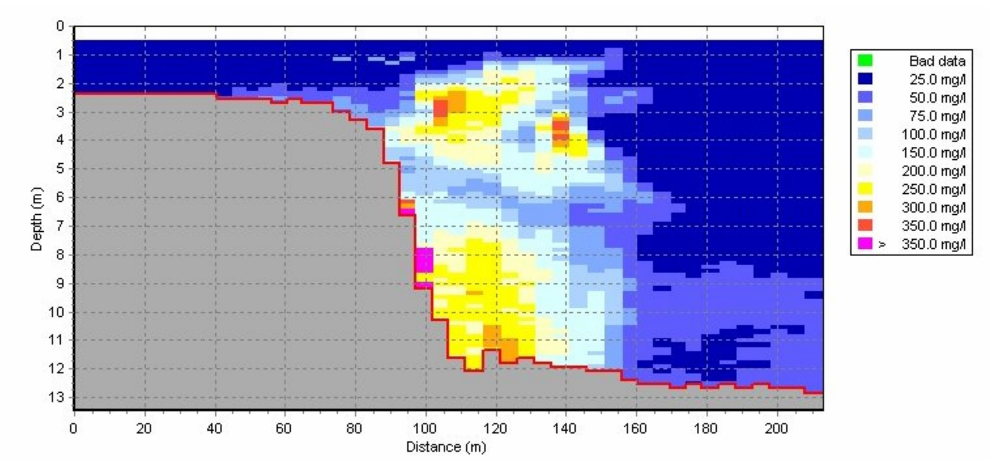

Figure 15. Transect 3, Replicate 1, Distance = 129 m, Plume age = 10.75 min.

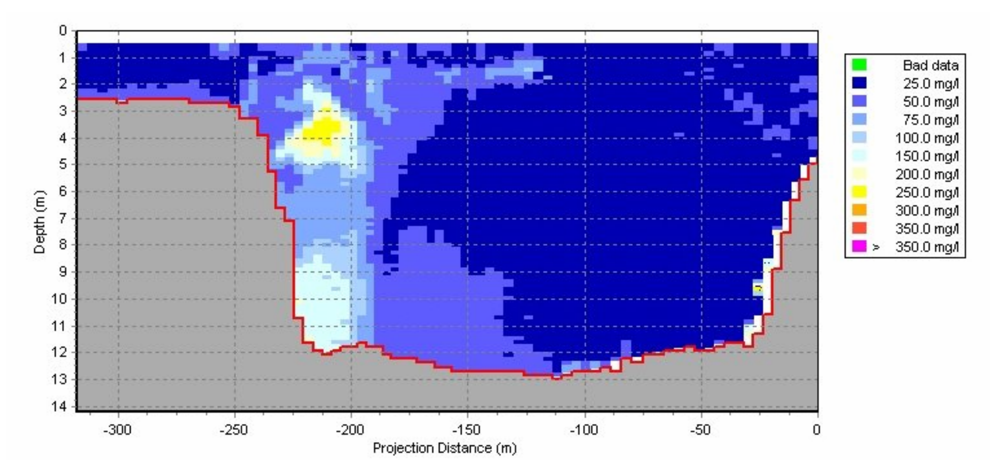

Figure 16. Transect 3, Replicate 4, Distance = 129 m, Plume age = 10.75 min.

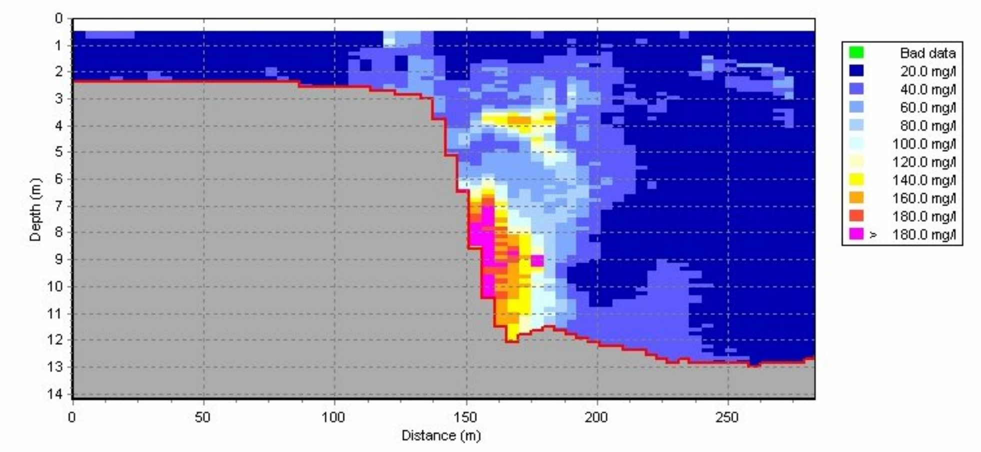

Figure 17. Transect 4, Replicate 1, Distance = 179 m, Plume age = 14.92 min.

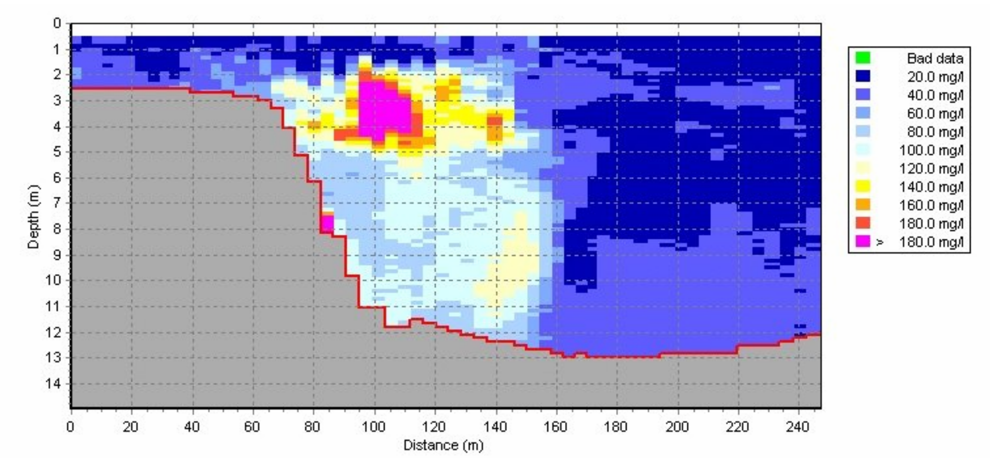

Figure 18. Transect 4, Replicate 3, Distance = 179 m, Plume age = 14.92 min.

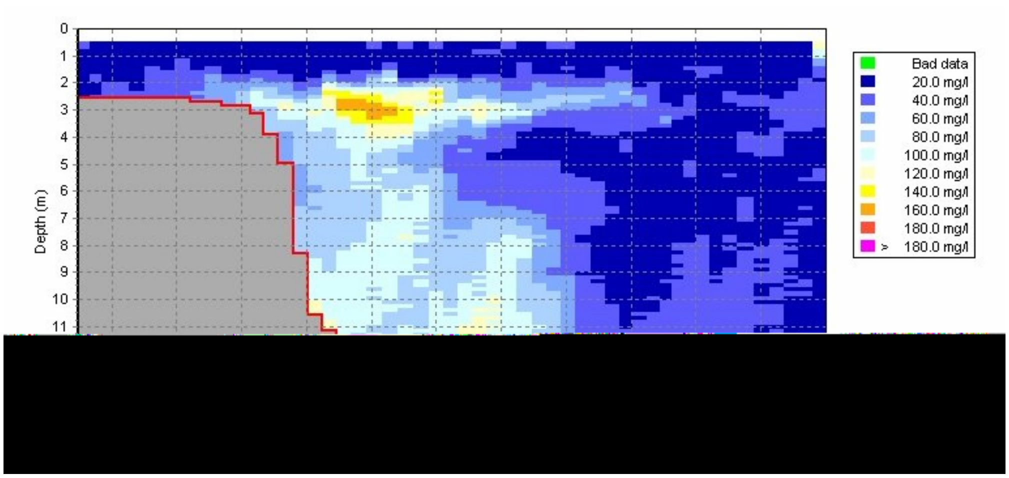

Figure 19. Transect 5, Replicate 1, Distance = 229 m, Plume age = 19.08 min.

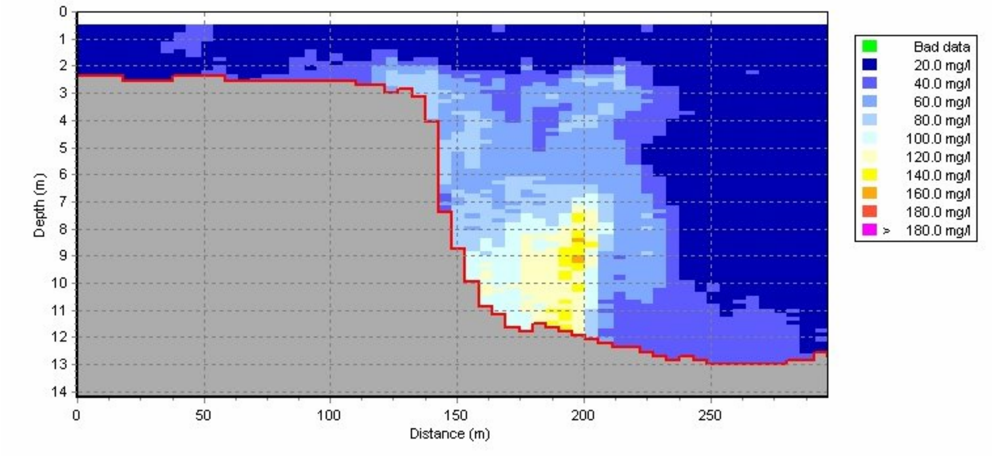

Figure 20. Transect 5, Replicate 3, Distance = 229 m, Plume age = 19.08 min.

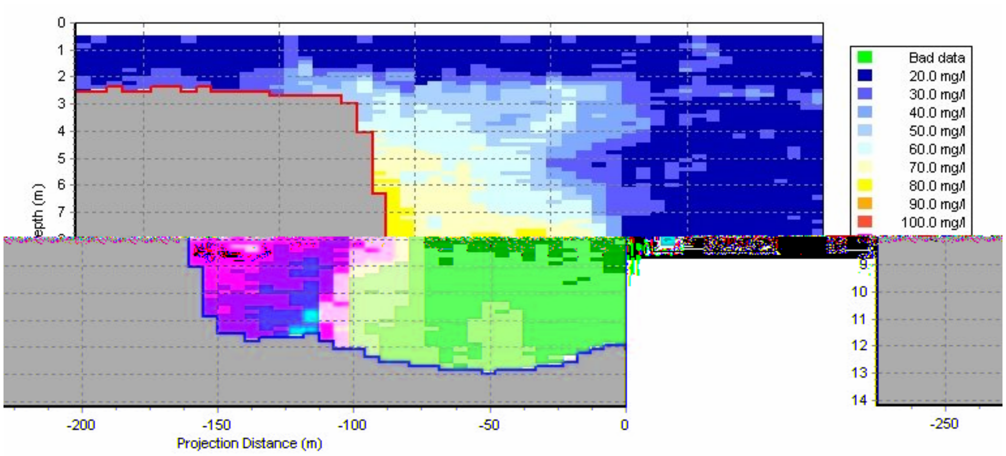

Figure 21. Transect 6, Replicate 1, Distance = 229 m, Plume age = 23.25 min.

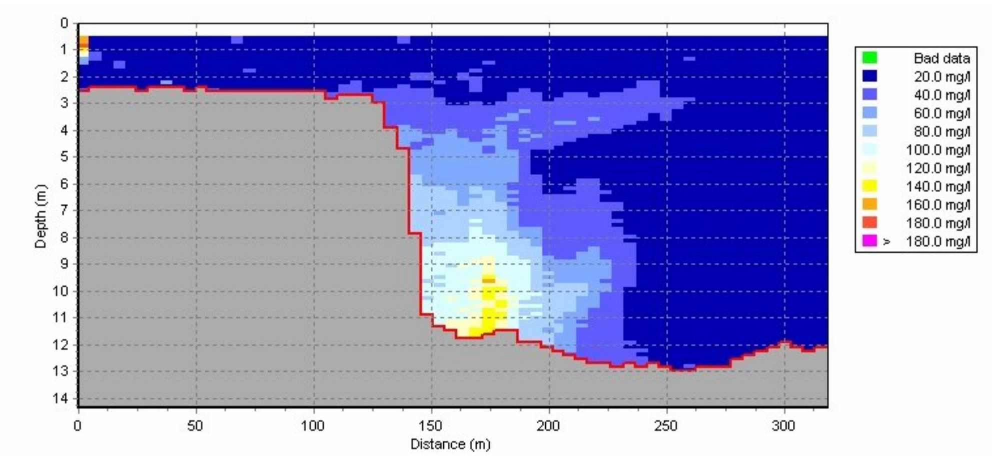

Figure 22. Transect 6, Replicate 2, Distance = 279 m, Plume age = 23.25 min.

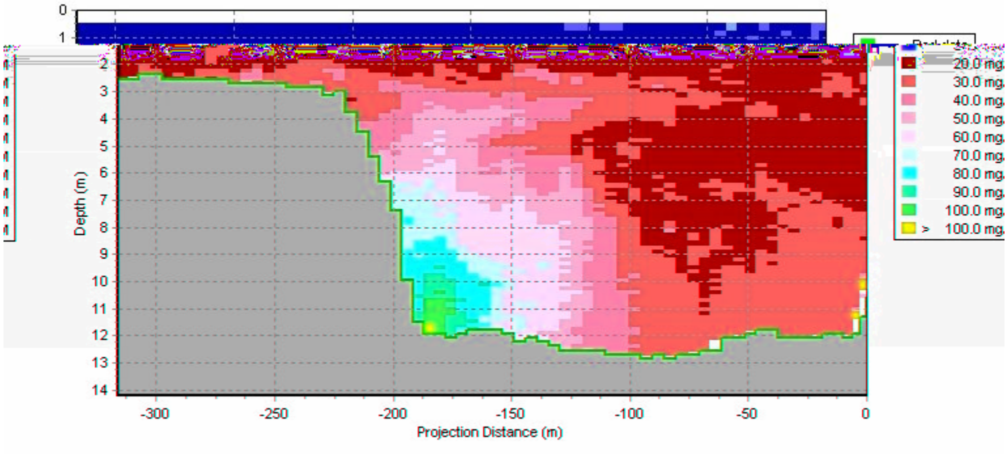

Figure 23. Transect 7, Replicate 1, Distance = 329 m, Plume age = 27.42 min.

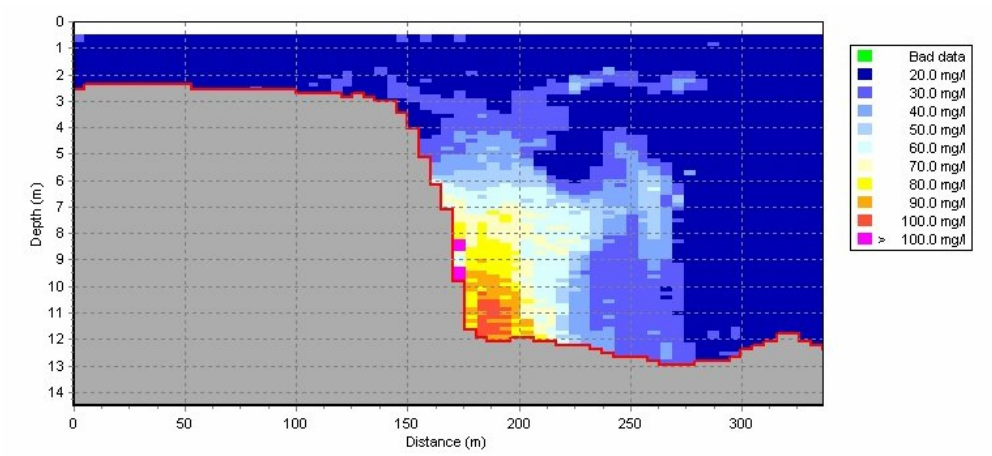

Figure 24. Transect 7, Replicate 2, Distance = 329 m, Plume age = 27.42 min.

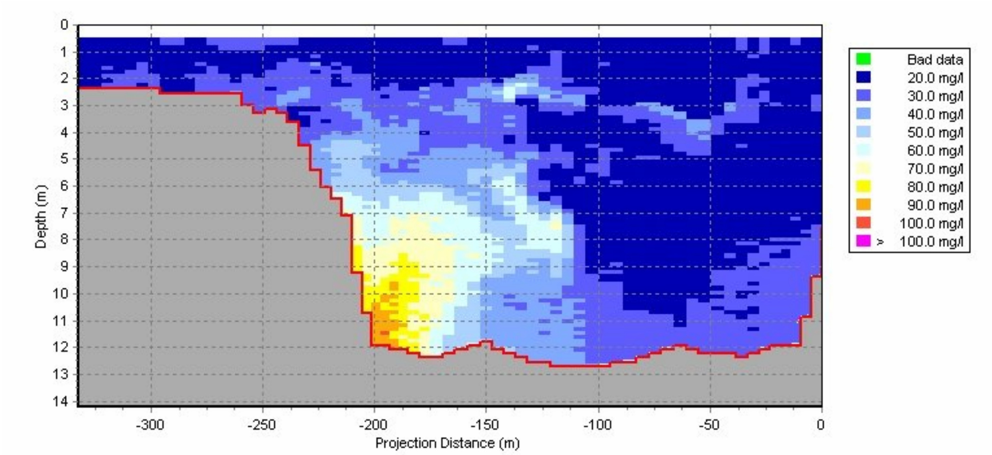

Figure 25. Transect 8, Replicate 1, Distance = 379 m, Plume age = 31.58 min.

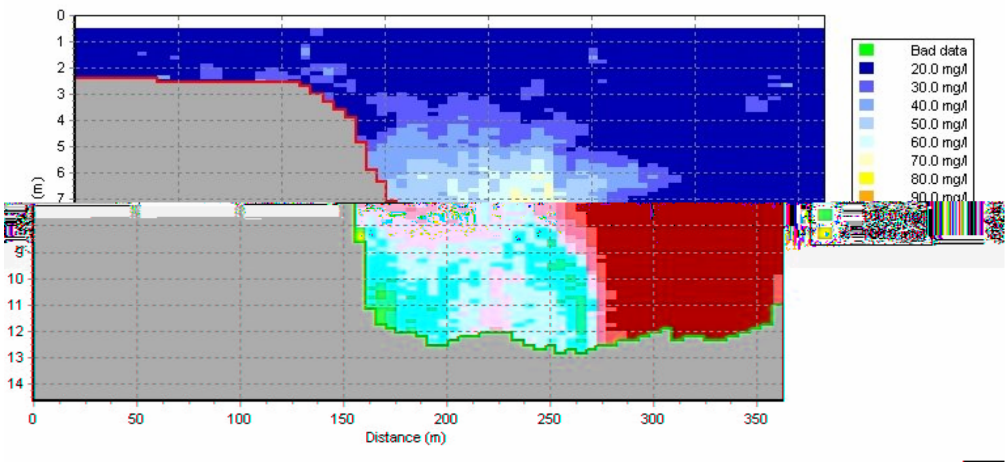

Figure 26. Transect 8, Replicate 2, Distance = 379 m, Plume age = 31.58 min.

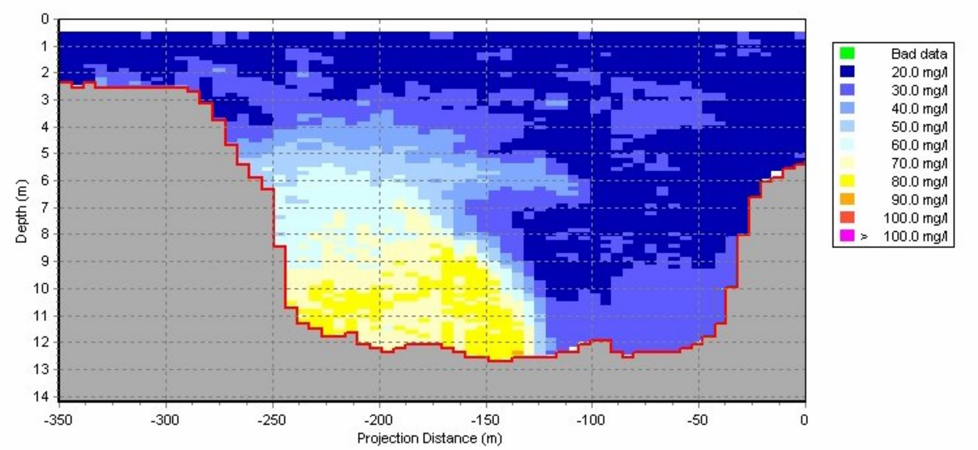

Figure 27. Transect 9, Replicate 1, Distance = 429 m, Plume age = 35.75 min.

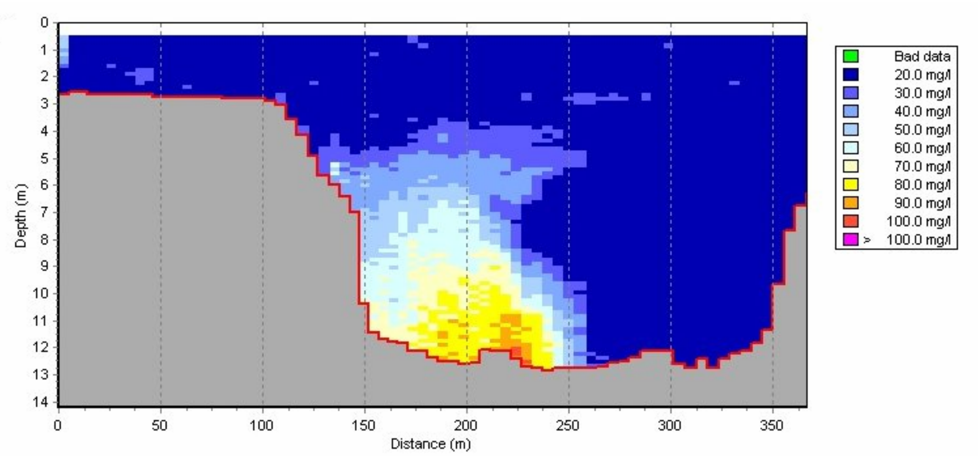

Figure 28. Transect 9, Replicate 2, Distance = 429 m, Plume age = 37.75 min.

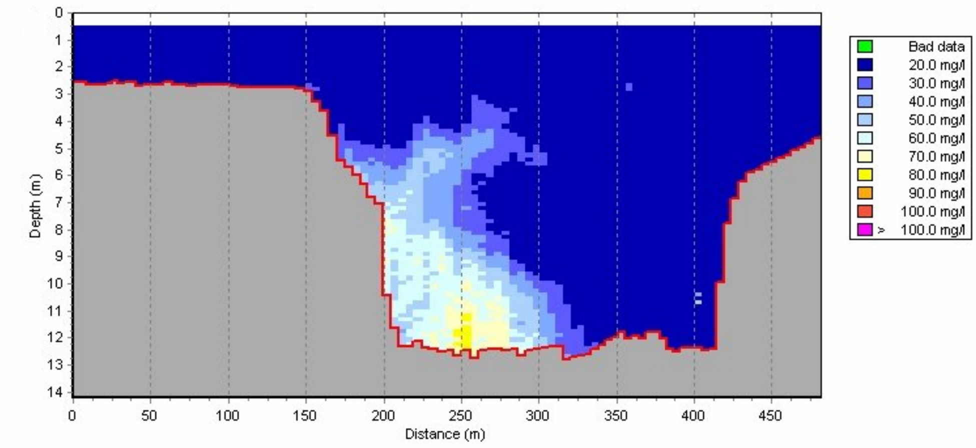

Figure 29. Transect 11, Distance = 529 m, Plume age = 46.40 min.

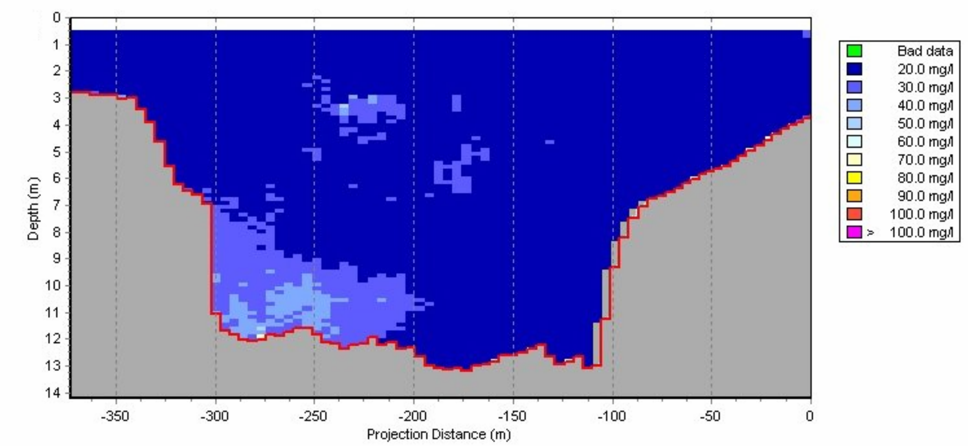

Figure 30. Transect 18, Distance = 879 m, Plume age = 86.18 min.

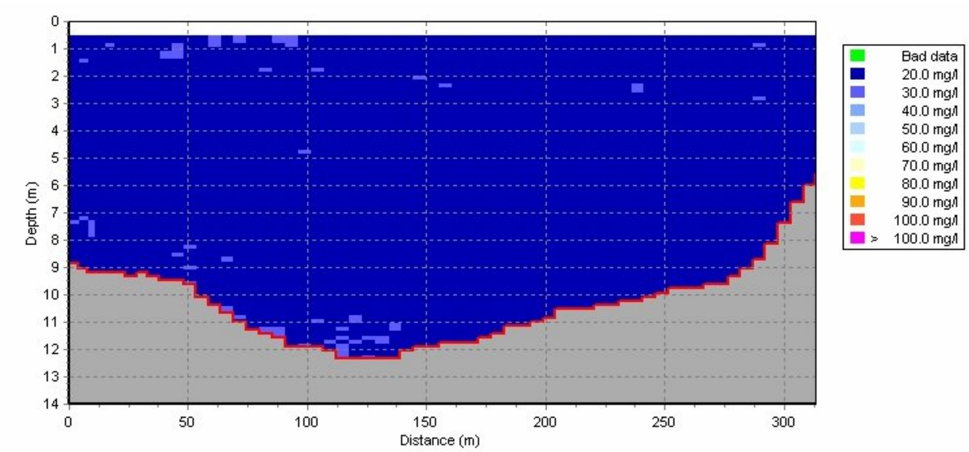

Figure 31. Transect 25, Distance = 1501 m, Plume age = 178.68 min.

Bullock Point Reach Plume Characteristics

The number of transects completed for each down-current distance at Bullock Point are given in Table 2.

Table 2. Transect allocations at specific distance from the source at Bullock Point.

Bullock Point Transect #	Number of Replicates	Distance to Bucket (m)	Current Speed (m/sec)	Plume Age (min)
1	4	59	0.07	14.05
2	4	109	0.09	20.19
3	3	159	0.1	26.50
4	3	209	0.11	31.67
5	2	259	0.11	39.24
6	2	309	0.11	46.82
7	2	359	0.1	59.83
8	1	409	0.1	68.17
9	1	459	0.1	76.50
10	1	509	0.09	94.26
11	1	559	0.09	103.52
12	1	609	0.09	112.78
13	1	659	0.09	122.04
14	1	709	0.09	131.30
15	1	759	0.09	140.56
16	1	809	0.09	149.81
17	1	859	0.09	159.07

As at Sabin Point, the dredge was working in the eastern half of the channel, although slightly further from the toe of the side slope. At a distance of 59 m down-current from the source suspended sediment concentrations of 150 to 200 mg/l were found throughout the water column (surface to bottom). Maximum water sample concentrations did not exceed 350 mg/l. The lateral width of the plume averaged between 50 and 70 m and was almost exclusively confined to below the upper rim of the channel side slopes. At 179 m, the plume descended to water depths > 6 m. Although some re-suspended sediment dispersed laterally along the channel bottom, the highest concentrations (100-150 mg/l) remained confined to a small central core, with a lateral width of less than 40 m. Rapid settling occurred over the next 100 m and maximum concentrations fell to < 80 mg/l. At 359 m and 459 m from the source, maximum TSS concentrations were less than 50 mg/l and 30 mg/l respectively. Only a faint plume signature was detected at 459 m, and at 659 m from the source plume signatures were undetectable against background conditions.

SEDIMENT FLUX AND VIRTUAL RELEASE RATES

The ADCP provides accurate data on the velocity of water movement in numerous small “bins” of known vertical and horizontal dimensions which together form the cross sectional area of a transect. Because the concentration of sediment within each bin can be calculated, a net flux of sediment though a transect can be derived by factoring the concentration and current velocity in each measurement bin and summing the products of all the bins in each transect. The ADCP is unable to measure the current or sediment concentration in the near-surface and near-bed areas due, respectively, to an inability to measure very close to transducers that are already immersed below the water surface and because of data corruption caused by side lobe echoes from the bed. In this case, the near-surface zone extended to a depth of about 0.55 m and the near-bed zone extended to a height of (typically) between 0.5 and 0.85 m above the bed, depending on the water depth.

The currents in these zones were estimated by extrapolating, upwards and downwards, a power function through the current measurements. Sediment concentrations were derived by factoring the measured concentrations in the shallowest and deepest valid bins. The factors were derived by examination of the measurement data.

The sediment flux due to the dredging operations was established by subtracting the background flux from the measured total flux. The background flux was estimated by calculating the average background sediment profile through the water column on each side of the plume using the ADCP data. The concentration profiles were then applied to the current data across the full width of the measurement transect to derive an estimated background flux.

Figure 32 shows the calculated sediment fluxes attributed to the dredging operation plotted against the estimated ages of the plumes. At both sites, there is a well-defined trend of flux reducing with age. Some scatter evident in both sets of data, most noticeably in the younger plumes (< about 40 minutes old). This is attributed to the variation of sediment flux that can be expected to result from a discontinuous dredging process and the variation is similar to that observed by the turbidity meters (e.g. Figure 6). The regression analyses indicate virtual release rates of 15.6 kg/sec at Sabin Point and 12.7 kg/sec at Bullock Point.

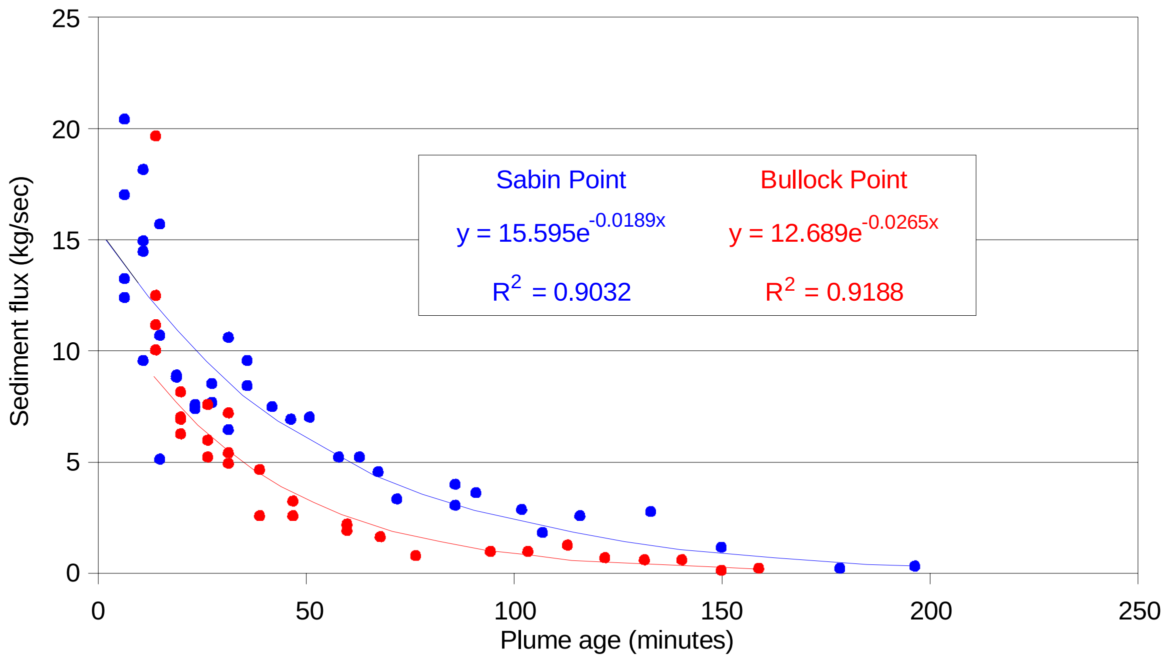

Figure 32. Plot of sediment flux through transects.

As previously explained, this survey was not undertaken specifically to measure the release rates and, in consequence, the work was not undertaken in full accordance with the TASS Measurement Protocol. A particular drawback is that there is very little information concerning the properties of the soil that was dredged. It is known that that it typically comprised about 90% clay and silt and 10% sand. A limited number of determinations of water content suggest that, if full saturation of the soil samples is assumed, the dry density of the soil was of the order of 500 kg/m^3. This, in combination with cycle times of 70.3 seconds and 48.6 seconds at Sabin Point and Bullock Point respectively, and the assumption of full buckets, yields the following:

Sabin Point:	Release = 47.8 kg/m^3 or 9.6% of the dry mass dredged
Bullock Point:	Release = 26.9 kg/m^3 or 5.4% of the dry mass dredged

There is a significant difference between the two loss estimates. Although the estimated virtual release rates (kg/sec) are similar, the releases in terms of percentage of dry mass dredged differ markedly because the cycle time at Sabin Point was about 22 seconds longer than that at Bullock Point, leading to a much lower rate of production. Most of the difference between the cycle times is explained by the fact that at Sabin Point, the dredge was loading the back of the barge while at Bullock Point it was loading the front. At Sabin, the bucket therefore spent much more time over the barge than at Bullock.

There were other differences between the components of the overall cycle times which could explain the relatively high release rate at Sabin compared to Bullock, despite the lower rate of production:

- a faster bucket descent speed (and, probably, bed impact speed);
- a longer excavating period on the bed;
- a longer period of time slewing the loaded bucket over the water to the barge.

All of these would tend to give rise to relatively high losses of material. In addition, and perhaps most significantly, the video records showed that, at Sabin Point, the bucket frequently failed to close completely due to debris and that there was a visually substantial release of soil and sediment-laden water from the bucket as it was slewed towards the barge. In contrast, at Bullock Point, the bucket was usually fully closed and leakage appeared relatively slight. It is also the case that the current velocity at Sabin Point (about 0.2 m/sec) was much higher than that at Bullock Point (about 0.07 m/sec). The higher current speed may have resulted in greater erosion losses from the highly disturbed, freshly-dredged bed.

However, due to survey constraints, the recordings of the dredge cycle times were not coincident with the flux measurements. It is quite possible that the difference between the cycle times during the monitoring periods was not so great. In addition, it is perhaps the case that the soils were, in fact, slightly different. The main purpose of the survey was to establish the fate of the sediment plumes, not to measure the loss term. So, although it is considered that the measured virtual release rates (kg/sec) are reliable, the lack of detailed simultaneous observations of dredge operation and the lack of detailed soils data make it difficult to place the release rates in context. This strongly underscores the importance of working in accordance with the TASS Measurement Protocol if the full value of such measurements is to be realized.

COMPARISON WITH OTHER FIELD MEASUREMENT DATA

Bohlen et al. (1979) estimated that approximately 1.5 to 3.0% of the sediment volume is re-introduced to the water column with a bucket dredge. In a recent review by Anchor Environmental (2003), average resuspension rates were somewhat higher for mechanical dredges (2.1%) than for hydraulic cutterhead dredges (0.77%), although the ranges calculated for the two categories of dredges overlapped. The highest reported loss term for a bucket dredge, 10.11%, is based on Nakai's (1978) data, converted from TGU to R. The dredge was working in silty clay sediments. Likewise, the highest loss rate for a bucket dredge based on conversion of Pennekamp et al.'s (1996) S-parameter data is 6.14%. However, the measurement methodologies used were likely to have somewhat underestimated the true release rates.

Elsewhere in these proceedings, Burt *et al*. describe the first trial of the TASS Measurement Protocol in the UK during which a virtual release rate of about 1.15 kg/sec (equivalent to about 6%) was measured by acoustic methods for a $3m^3$ open bucket working in predominantly fine soft sediments without gross bucket leakage. The release rate was observed to peak at about three to four times this figure for dredge cycles where substantial leakage occurred. The measurements showed that bucket leakage was sometimes a dominant factor in overall release rates and that substantial amounts of sediment could be lost as the bucket was slewed towards the hopper, forming a wide high-level sediment plume.

The release rates of 5.4% and 9.6% measured in the Providence River therefore appear to be broadly in line with other recent measurements. If the video records are representative of the dredge operation during the period when the measurements were undertaken, the relatively high 9.6% measured at Sabin Point would be consistent with a greater degree of bucket leakage.

CONCLUSIONS

During dredging some sediment is inevitably lost to the water column. Loss during bucket dredging is caused by bucket insertion into and withdrawal from the bottom, washing of material from the bucket as it moves through the water column, spillage of sediment-laden water out of the bucket as it breaks the water-air interface, and leakage as the bucket slews to and from the barge.

The measured loss rates, 9.6% at Sabin Point and 5.4% at Bullock Point, fall in the higher portion of the previously reported range but are similar to those measured recently using similar techniques in the UK. It is also the case that the dredge was being operated aggressively (as was the case in the UK observations). The question that arises from review of the present as well as prior studies of bucket dredge loss terms is how much of the observed variation is due to soil conditions and the diverse modes in which mechanical dredging is conducted and how much is due to measurement errors or bias. Discrepancies have been difficult to attribute to particular modes of dredging (e.g., mechanical versus hydraulic), variation in dredge plant (e.g., open versus closed bucket), or operational measures (e.g., bucket hoist or cutter rotation speed limitations), many of which are intended to minimize sediment loss. Clearly, more measurement data are required and, if the data are to contribute towards calibration of predictive models of release, they must be fully supported by detailed measurements of dredge operation and soil properties.

We reiterate our earlier observation that the release rates measured here should not be assumed to be typical and should not be applied in a predictive manner to other bucket dredging operations. They are specific to the Providence River site, the soil, the hydrodynamic conditions and the manner of dredge operation, some components of which could not be fully characterized during the work described here.

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