SUSPENDED SEDIMENT PLUMES ASSOCIATED WITH KNOCKDOWN OPERATIONS AT THE PORT OF REDWOOD CITY, CALIFORNIA

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ABSTRACT

Re-suspension of sediments during the conduct of dredging projects has been a source of persistent concern among regulatory agencies charged with the protection of environmental resources. Potential effects on fish, shellfish and submerged aquatic vegetation are frequently cited as justifications for decisions to place restrictions on dredging projects or to require precautionary operational measures. Prudent dredging project management decisions should be based on a full understanding of the dredging process as well as the biology and ecology of organisms of concern. One specific dredging process which has not been examined in detail is known as “knockdown” or “bed leveling”. In the San Francisco Bay area, the spatial and temporal characteristics of sediment plumes associated with the knockdown operations were identified as a knowledge gap by the Long Term Management Strategy stakeholder forum.

This study characterized suspended sediment plumes resulting from knockdown operations in the Redwood Creek navigation channel, which provides access to the Port of Redwood City. Knockdown operations were performed by a tug pushing a barge equipped with a 9.2 m (30 ft) long I-beam suspended from opposite corners of the stern of the barge. Two winches were used to control depth of the I-beam such that mounds, or high spots, up to 0.6 m (2 ft) above grade were relocated into deeper parts of the channel basin along a 0.8 km (0.5 mi) reach of the waterway. An acoustic Doppler current profiler was used to survey water current structure and suspended sediment concentration gradients during ambient conditions and periods of active knockdown operations on both flooding and ebbing tides. A total of 150 water samples analyzed gravimetrically provided a calibration data set for conversion of acoustic backscatter to suspended sediment concentration.

Knockdown operations in Redwood Creek produced suspended sediment plumes that were highly variable in a temporal context, but very consistent with respect to spatial dimensions. Removal of high bottom elevations along the toe of the channel side slope generally produced the highest detected TSS concentration gradients within the plumes (maximum 600 mg/L). Somewhat more intense plumes were linked to hitting high spots with the bar while the tug applied power, as indicated by intensified prop-wash signals. In general, plumes were narrow, ephemeral features that decayed to below 100 mg/L within 7 to 9 minutes, and remained in the lower half of the water column. Consequently, during knockdown operations bottom-dwelling organisms could be exposed to significantly higher suspended sediment concentrations compared to ambient conditions, whereas organisms occupying the upper portion of the water column would be unlikely to encounter substantially elevated suspended sediment concentrations compared to ambient. Assessing the degrees or risk posed by knockdown operations would require knowledge of the behavior, distribution and tolerance of organisms occupying the waterway.

INTRODUCTION

Re-suspension of sediments during dredging has been a persistent concern of regulatory agencies charged with protection of environmental resources. Potential effects on fish, shellfish, and submerged aquatic vegetation are often cited as justifications for restrictions (e.g., environmental windows, spatial buffer zones) or precautionary measures (e.g., silt curtains, modified equipment) placed on dredging (Wilber and Clarke 2001). However, restrictions and precautionary measures can significantly inflate the cost of a dredging project, and the actual effectiveness or need for specific measures is often unknown. Prudent management decisions should be based on a full understanding of the dredging process as well as the biology and ecology of organisms of concern. The challenge of maintaining navigation infrastructure while providing adequate protection of environmental resources can be complex. Quite often the “pieces of the puzzle” are difficult to assemble in a manner that satisfies all stakeholders involved in project coordination. In almost every case, however, reasonable decisions can be made if a

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knowledge base exists upon which to assess degrees of risk posed by the dredging process at a given location and time.

The basic dredging process for routine maintenance of waterways where the *in situ* sediments are not contaminated has not changed dramatically over the last century. Given the generic nature of the dredging process, efforts to characterize sediment re-suspension characteristics of various dredges have focused on conventional mechanical (e.g., bucket) and hydraulic (e.g., cutterhead, hopper) dredges. One common aspect of the maintenance dredging process that has not been examined in detail involves a process called "knockdown", or "bed leveling." Knockdown involves redistribution of sediments, most often to deeper basins within the channel rather than physical removal from the waterway. Knockdown is also frequently conducted during the "clean-up" phase of a dredging project to remove isolated peaks and ridges after sweeps by conventional dredges. Knockdown gear generally consists of a heavy metal bar towed across the bottom to push sediments into adjacent areas of lower elevation. The towed bar may consist simply of welded I-beams or surplus spuds, occasionally configured with a leading edge that acts as a plough.

The present study evolved from discussions within the San Francisco Bay Long-Term Management Strategy (LTMS) stakeholder forum and was supported by the San Francisco District of the U.S. Army Corps of Engineers (USACE). In October of 2004 an opportunity arose to study sediment re-suspension during a knockdown operation at Redwood City, California.

Project Location

The Port of Redwood City is located approximately 35 km (18 mi) south of San Francisco (Figure 1), accommodating commercial deep draft vessel and barge traffic via an entrance channel through Redwood Creek. The 92 m (300 ft) wide navigation channel is approximately 6 km in length, and is maintained at a depth of 8.5 m (28 ft). Turning basins adjacent to the Port facilities are approximately 325 m (1,066 ft) wide. The channel is bordered along most of its length by tidal flats and drains two sloughs: Corkscrew Slough from the northwest and Westpoint Slough from the southeast. Knockdown operations occurred in a 0.8 km long reach immediately north of the turning basins, and consisted of grading scattered "high spots" representing approximately 2,300 m^3 (3,000 cubic yards) of sediment.

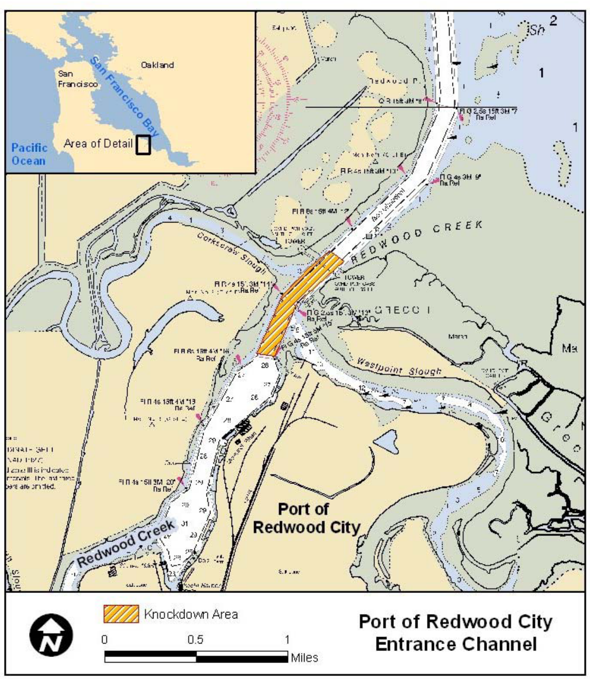

Figure 1. Study location in relation to San Francisco Bay (inset), and detail of navigation channel leading into the Port of Redwood City, where the navigation channel expands into turning basins and berthing areas.

METHODS

Field activities were conducted between 24 and 28 October 2004, with knockdown commencing on 26 October. Dutra Dredging Company performed the knockdown operations using the tug T/V *Sharon Brusco* (Figure 2) in tandem with a barge mounted with a stern winch-lowered bar. Dimensions of the bar (Figure 3) were approximately 3 ft high x 2 ft wide x 30 ft long. Grading occurred primarily along the toes of the channel side-slopes. Time series records of the barge's position were obtained with a global positioning system (GPS, accurate to 5 m (16 ft)) and synchronized with position data for the survey vessel. Plume monitoring was conducted from the R/V *Shearwater*, equipped with a differential GPS providing navigation and position data to an accuracy of ±1.0 m (3.2 ft). These data were downloaded at the end of each day and used to determine the relative position of the survey vessel within the suspended sediment plume at selected times.

Figure 2. Dutra Dredging Company *Sharon Brusko* pushing the knockdown barge.

Figure 3. One end of the knockdown bar suspended from the barge at the water surface.

Acoustic Doppler Current Profiler

An RD Instruments 600 kHz Workhorse Mariner Acoustic Doppler Current Profiler (ADCP) was used to collect current velocity, direction, and acoustic backscatter data. Data were recorded for predetermined horizontal and vertical bins (vertical bin size = 0.5 m (1.6 ft)). Bottom depth and surface water temperatures were also recorded. Navigation data received from the DGPS were collected synoptically and integrated during post-processing. ADCP acoustic backscatter data were analyzed using Sediview Software provided by Dredging Research Software, Ltd. The Sediview Method (Land and Bray 2000) derived estimates of TSS concentration in each ADCP data bin by converting relative backscatter intensity to TSS concentration. This process required collection of a calibration data set consisting of discrete water samples collected at known locations within the insonified portion of the water column and analyzed gravimetrically. The sample population represented the concentration gradient prevailing at the study site, and was used to "groundtruth" the acoustic data.

ADCP surveys were conducted during both flood and ebb tidal stages using several techniques in order to capture the spatial and temporal dynamics of the knockdown plume. Because the knockdown process involved active towing of a bar across the bottom, the source of sediment re-suspension was continuously moving along the path of the barge. Another challenge in characterizing the bar-induced plumes was distinguishing sediment re-suspension from the prop-wash created by the tug pushing the barge. Prop-wash injects air into the upper portion of the water column. Because gas bubbles are acoustic reflectors, they produce strong backscatter signals, which are a form of noise in the data. Bubbles rise in the water column over a period of minutes, and the prop-wash signature dissipates. All interpretations of acoustic data in this study take into consideration the presence of tug-derived prop-wash, which was not a major impediment to plume detection.

Plume detection was optimized using several survey designs. One survey design consisted of "zigzag" transects run astern of the barge while maintaining a consistent distance (50 to 100 m) from the barge. Zigzag transects were designed to measure the width of the plume at known distances behind the knockdown barge. Another transect design involved following directly behind the barge at a consistent distance maintaining position in the central portion of the plume, and repeating transects at distances varying from approximately 50 to 130 m from the barge. These transects were designed to measure variation in plume intensity at a known distance (or age of the plume) as the knockdown bar impacted high spots along the bottom. Lastly, transects were run perpendicular to the main axis of the channel to measure the decay of the plume intensity at increasing distances (or age of the plume) as the knockdown barge approached, passed, and continued away from the transect location. All distances from the survey vessel to the barge were measured with a laser range finder using the corner of the barge directly above the bar as a target.

Ambient suspended sediment conditions were surveyed on 25 October during both flood and ebb tidal stages prior to the arrival of the tug and barge. Multiple during-knockdown ADCP surveys were conducted from 26 to 28 October, throughout both flood and ebb tidal stages.

Turbidity

Multiple arrays of D&A Instruments optical backscatter (OBS-3A) sensors were deployed during each ADCP survey. The arrays were on a moored buoy (Figure 4) or suspended from the bow of the survey vessel at predetermined depths. Each sensor recorded turbidity in nephelometric turbidity units (NTU) at 15 second intervals.

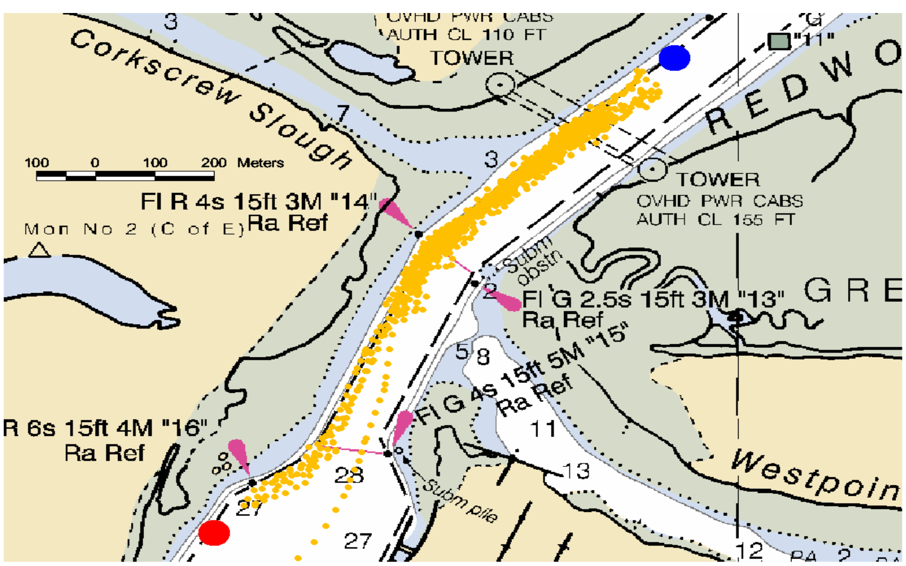

Figure 4. Locations of the bay-side (solid blue circle) and port-side (solid red circle) moored OBS buoys and the knockdown barge tracks (orange circles) on 27 October.

Water Samples

Water samples were collected using a modified General Oceanics 6-Niskin bottle rosette water sampler collected in a horizontal orientation to optimize acoustic data calibration. An OBS-3A unit was mounted on the water sampler to provide real time NTU measurements during the water sampling. The OBS NTU reading and ADCP ensemble number were recorded at the instant of trigger for each individual water sample. Water samples were processed gravimetrically for TSS (mg/L) and optically for turbidity (NTU) using standard laboratory procedures. A single sediment grab sample was collected for grain size analysis to assist in the calibration. Of the 150 water samples taken, 48 were collected during an ebbing tide during ambient conditions prior to the arrival of the knockdown barge. The remaining 102 samples were collected during active knockdown operations; 48 during an ebbing tide and 54 during a flooding tide.

RESULTS

Water Currents

ADCP data revealed no evidence of stratified flow in the water column during any tidal stage. Velocities were generally less than 0.45 m/sec throughout the water column.

Turbidity

As depicted in Figure 5, the relationship between NTU and mg/L values displayed a reasonable degree of scatter (R^2 = 0.7078). Much of the scatter can be attributed to variable conditions within the plume where the higher NTU and mg/L values were obtained. Plumes near the source of re-suspension are very heterogeneous with large changes in concentration occurring on very small spatial scales. Viewed across a large sample population (150 in this data set), a general relationship can be discerned. In Redwood Creek turbidity values of 30, 60, 90, and 120 NTU corresponded to approximate TSS concentrations of 75, 200, 325, and 450 mg/L.

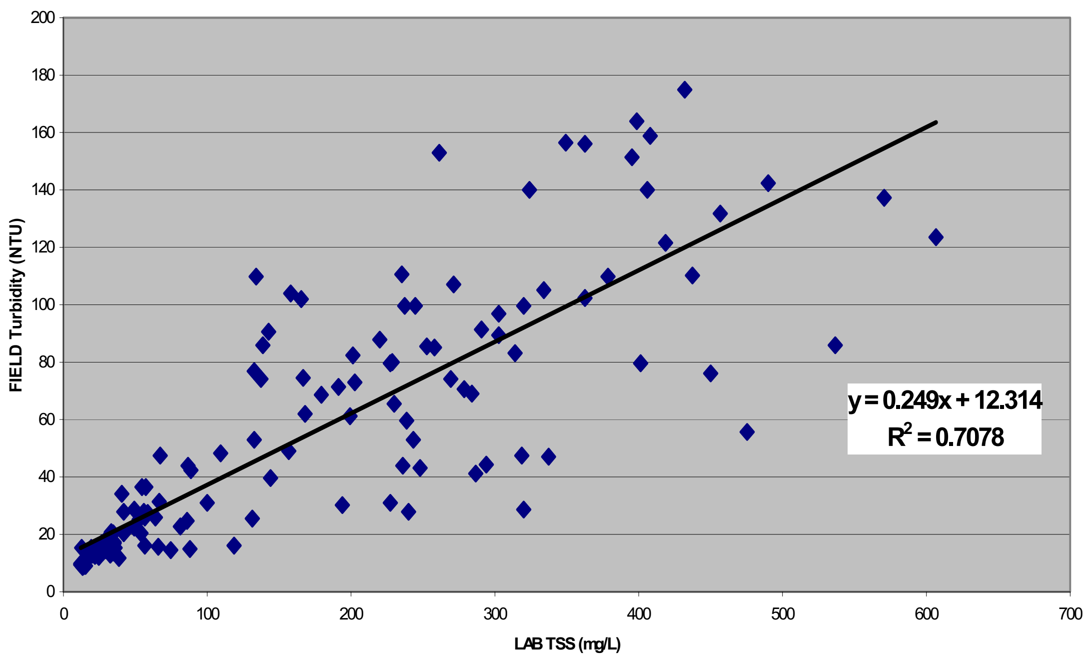

Figure 5. Regression of field turbidity on TSS concentrations for corresponding samples.

Ambient Turbidity

Moored OBS units deployed prior to the arrival of the knockdown barge provided an ebbing tide time series (Figure 6). Turbidities were consistently in the 8 to 22 NTU range, consistent with OBS data collected in tandem with the water samples outside of the influence of plumes. Adjacent to the sloughs during transition from slack to ebbing flows, turbidities were generally higher in the lower portion of the water column. As the tide progressed toward peak ebb, turbidities increased substantially in the upper portion of the water column and actually decreased in the lower water column. Elsewhere turbidities tended to slowly decline from approximately 22 NTU at slack water during high tide to <10 NTU as the tide approached slack low. On ebbing tides silt and detritus-laden waters from the sloughs draining adjacent wetlands enter Redwood Creek at points on opposite shorelines. Ebbing flows in Redwood Creek then carry the turbid water toward San Francisco Bay. Ambient turbidities ranged substantially higher than 22 NTU during certain stages of the tide at various locations in Redwood Creek. Precipitation during the last day of the study also elevated overall turbidities, possibly from increased drainage from the sloughs.

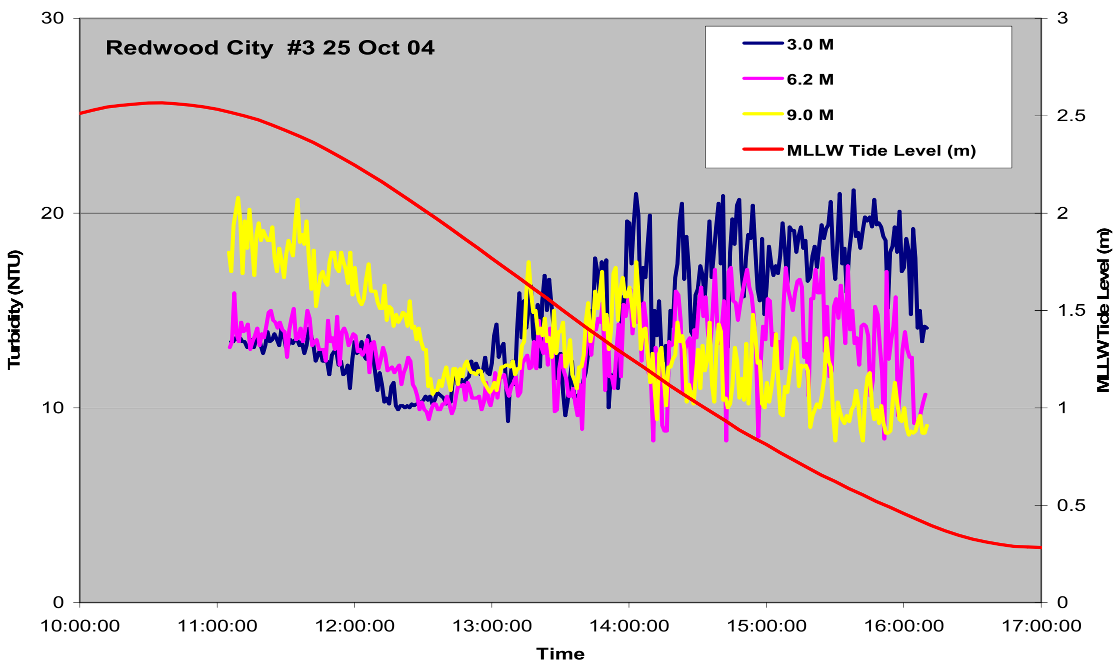

Figure 6. Ambient turbidity conditions at the northernmost moored buoy.

During-Knockdown Turbidity at Moored Buoys

Time series data recorded at a bay-side buoy revealed a pattern of relatively high but decreasing turbidities during the later stages of the flooding tide, followed by a period of low turbidities during slack and early ebb tide, and a period of slightly higher turbidities during the later stages of the ebbing tide (Figure 7). High turbidities at the bay-side buoy during the flooding tide must have been derived from waters entering Redwood Creek from San Francisco Bay, as the water mass was moving toward the project reach rather than arriving from it. Thus turbidities as high as 80 to 90 NTU near the bottom and 30 to 50 NTU near the surface should be considered ambient conditions on that day. Resumption of knockdown operations at 1200 hrs should have allowed suspended sediments to be carried by ebbing currents toward the bay-side buoy. Following slack tide turbidities peaked at 35 to 45 NTU before declining again as the tide slowed. These data may reflect ambient conditions as well, due to the location of the buoy on the opposite bank from the ongoing knockdown. As seen in the ADCP data described below, the bar-induced plumes seldom extended across the channel cross-section.

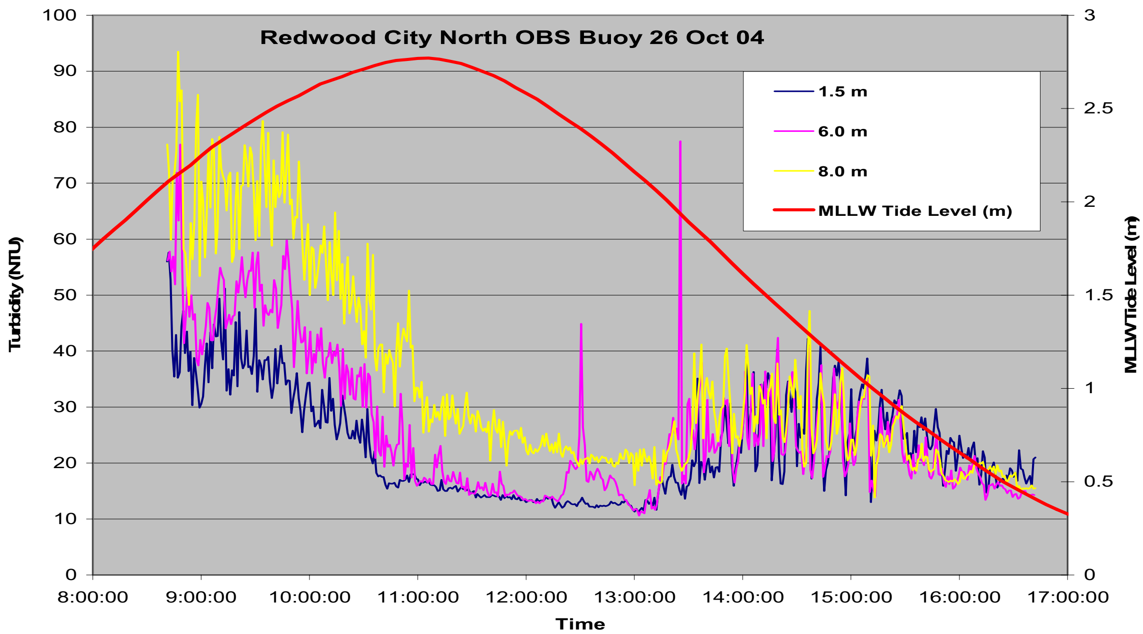

Figure 7. Time series record of turbidity at the bay-side moored buoy during knockdown operations.

The time series record at the port-side buoy on 26 October was very different than that at the bay-side buoy. At the port-side buoy flooding waters should have carried suspended sediments in knockdown plumes to the station's location, whereas ebbing flows should have transported plumes in the project reach away from the buoy. Although turbidities did increase during the later stages of the flooding tide to 45 NTU near the bottom, the barge was not operating during the two hours of peak turbidities. On the ebbing tide turbidities remained low, less than 15 NTU in mid and surface waters and less than 25 NTU near the bottom. Although the barge passed very close to the buoy, this occurred during turns when the bar may have been raised off the bottom.

Both buoys were redeployed on 27 October. The bay-side buoy flooding tide data were similar to those of the preceding day, with peak turbidities ranging as high as 70 NTU and decreasing as the tide progressed to slack water. The water mass moving through the buoy's location would be coming from San Francisco Bay and not the project area during that time period. Turbidities recorded on the ebbing tide at the bay-side buoy were substantially higher. These data probably represented the slight increase in ambient turbidity as observed the preceding day with an additional increment attributable to the knockdown operation. Because the knockdown on 27 October took place along the western side slope of the channel, the bay-side buoy could have been within periodic plumes as the operation moved back and forth in front of Corkscrew Slough. During the ebbing tide the measured peak turbidities at the bay-side buoy ranged from 60 to 200 NTU near the bottom and 50 to 80 NTU at the surface. A closer inspection of the record during the ebbing tide revealed a periodicity in the peaks of high turbidity that suggested a knockdown plume origin (Figure 8). The plumes were largely a lower water column feature, with few spikes above 40 NTU at the upper 1.5 m sensor. Variation in consecutive plume events was likely due to differences in movement of the barge in terms of distance from the toe of the side slope, distance from the buoy when the bar was raised off the bottom and/or a movement of the barge into or against the prevailing current flows. High turbidities observed at the bay-side buoy continued into the slack-water phase of low tide. Peak values in the deep sensor record after 1645 hours are likely due to bottom contacts. At the port-side buoy on 27 October turbidities remained consistently low (< 25 NTU) throughout the tidal cycle with the exception of slightly higher turbidities (> 50 NTU near the bottom) over a two-hour period at slack water. Knockdown plume signatures were expected during the flooding tide as water from the project reach would be moving toward the buoy. The slightly higher slack-water turbidities may have included some residual plume sediments. However, the knockdown operation primarily concentrated on areas north of the turning basin. The location of the port-side buoy against the western side slope in the turning basin may not have been sufficiently close to the operation to be exposed to plumes.

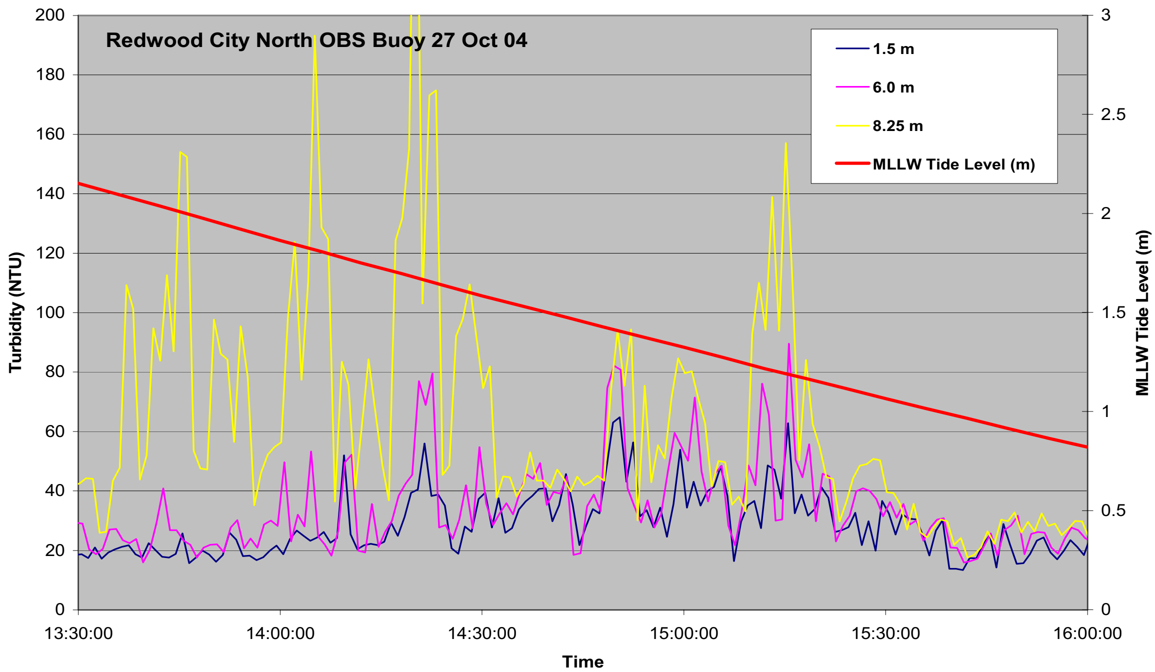

Figure 8. Knockdown plume turbidity signature at bay-side buoy during an ebbing tide on 27 October.

A third deployment during knockdown operations occurred on 28 October. On this date the barge was working primarily along the eastern bank. The data recorded at the bay-side buoy was consistent with that of the preceding two days; turbidities throughout the water column were relatively high during the flooding tide followed by a period of decreasing turbidity during slack water and early ebb tide. Turbidities increased somewhat to 40 to 60 NTU near the bottom and 30 to 40 NTU in surface waters late in the ebbing tide. This pattern may not contain knockdown plume signatures, as the buoy was placed on the opposite side of the channel from the operation. At the port-side buoy turbidities resembled those recorded at that location the preceding day in terms of a general pattern (i.e. generally low throughout the tidal cycle except for a two-hour period during slack tide). On this day the slack-water peaks were substantially higher, reaching 125 NTU near the bottom, 85 NTU in mid water column, and 45 NTU in surface waters. This pattern did not appear to be linked to the knockdown operation, which did not enter the turning basin.

During-Knockdown Turbidity Measured by Mobile Surveys

"Mobile" deployments of OBS units suspended from the bow of the survey vessel allowed data to be collected directly within the knockdown plumes. The ADCP real time display aboard the survey vessel was used to guide transits across the plume acoustic signature while synoptically collecting turbidity data. The turbidities depicted in Figure 9 indicate that the plumes on 27 October during an ebbing tide were relatively diffuse with surface and bottom turbidities generally within a 20 NTU spread. Occasional spikes in turbidity of 80 to 110 NTU at a depth of 6.5 m, 40 to 70 NTU at 5.0 m, and 35 to 55 NTU at 3.5 m occurred for short periods of time. These turbidity spikes may reflect the periodic "digging in" of the knockdown bar as the barge passed over high bottom elevations. The amount of sediment re-suspension may be affected by the increased power applied by the tug operator to pull the bar over the high spots.

Distinct plume signatures are evident in the mobile survey data collected during a flooding tide on 28 October (Figure 10). As the survey vessel intermittently passed through the central portions of the plumes turbidities spiked significantly at depths at or below 6.0 m, but not at depths of 3.0 m or less. Turbidities at a depth of 7.5 m peaked at just over 200 NTU. Turbidities at a depth of 6.0 m ranged from 40 to 100 NTU within the plumes. Turbidities at depths of 3.0 and 1.5 m were consistently in the 20 to 40 NTU range. On this date the data indicated that the plumes were primarily confined to the lower portion of the water column.

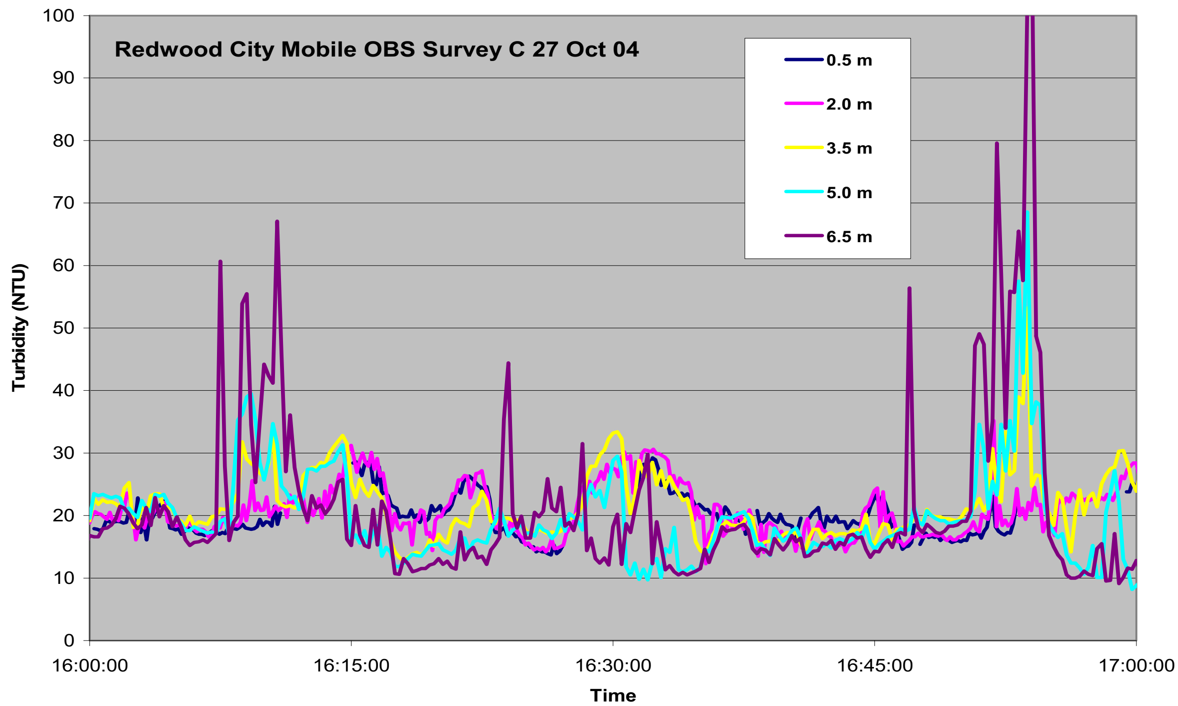

Figure 9. Time series record of turbidities as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge.

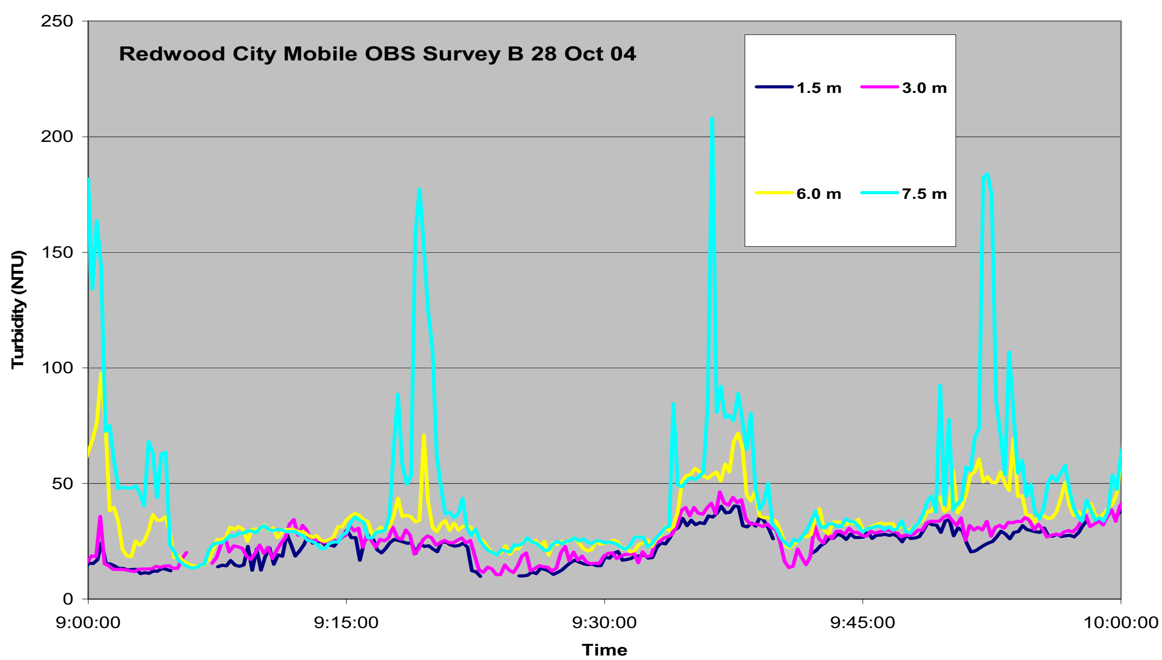

Figure 10. Time series record of turbidities as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge.

ADCP Calibration

Conversion of acoustic backscatter data to estimates of TSS concentration was accomplished by means of a rigorous calibration procedure described by Land and Bray (2000). The quality of the calibration is dependent on the collection of adequate water samples to represent sediments in suspension throughout the water column and across the entire gradient of concentrations occurring in ambient and plume waters. In this study the 150 water samples produced an excellent calibration. When plotted with respect to paired samples (i.e. gravimetric and acoustic measures collected synoptically), a relatively close correspondence is seen for concentrations in the 10 to 600 mg/l TSS range (Figure 11). Some variation was seen for individual pairs at high gravimetric concentrations within the plumes. Observed variation was due to the logistical limitation of sampling gear operating in a plume in which concentrations change rapidly on very small spatial scales.

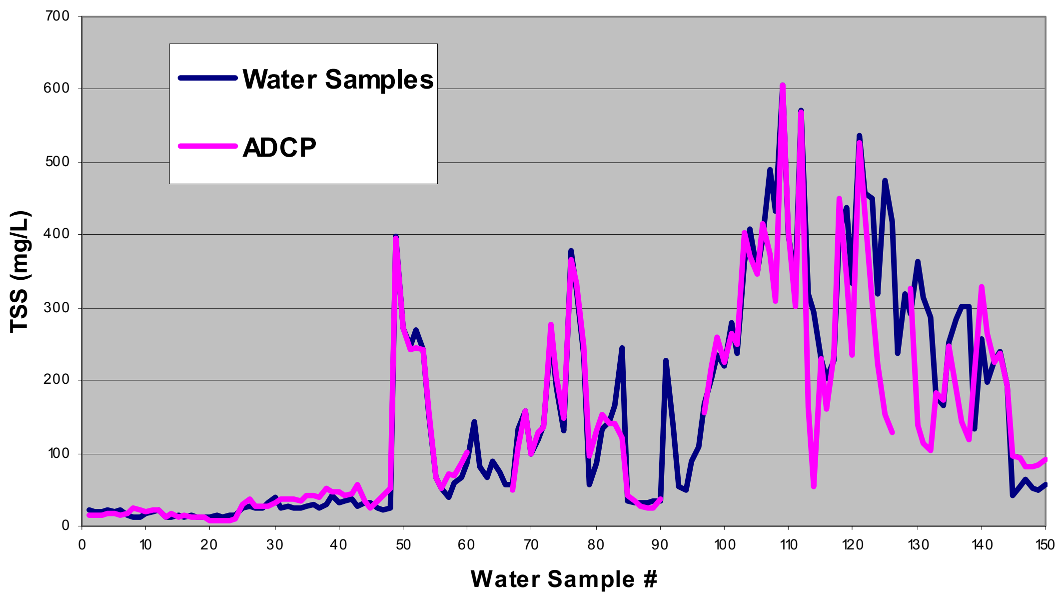

Figure 11. Correspondence between acoustic and gravimetric measures of TSS for matched data pairs.

Acoustic Estimates of TSS Ambient Conditions

On 25 October ADCP surveys were conducted prior to the arrival of the knockdown tug and barge. Figure 12 depicts a typical transect across Redwood Creek during an ebbing tide. The survey vessel moved from relatively clear waters (10 mg/L at the surface to 30 mg/L in the lower water column) along the first 350 m of transect into increasingly higher TSS concentrations, particularly in the upper water column (up to 60 mg/L near the surface and 50 mg/L just above the bottom). This pattern is consistent with input of suspended material from the sloughs, entering the waterway along the shallow banks and dispersing toward San Francisco Bay. A typical transect during a flooding tide on 25 October produced a distinctly different pattern (Figure 13). High concentrations in the 70 to 90 mg/L range occurred extensively in the lower half of the water column, whereas clearer waters in the 20 to 30 mg/L range were detected primarily in the upper water column. This degree of variation was observed along the entire length of the project channel.

Acoustic Estimates of TSS in Knockdown Plumes, Parallel Surveys

In parallel surveys, the survey vessel followed the knockdown barge while maintaining a relatively constant distance between the ADCP transducer and the bar. In all backscatter records the tug's prop-wash was easily identified as an intense signal in the upper 3 to 4 m of the water column. Below the prop-wash distinct plume signatures can be discerned as the bar impacted small high spots in the bottom along the barge's path. The records clearly indicate that re-suspension of bottom sediments by the bar was not uniform along the entire transect, but occurred in pulses as the bar "dug in" on the high spots.

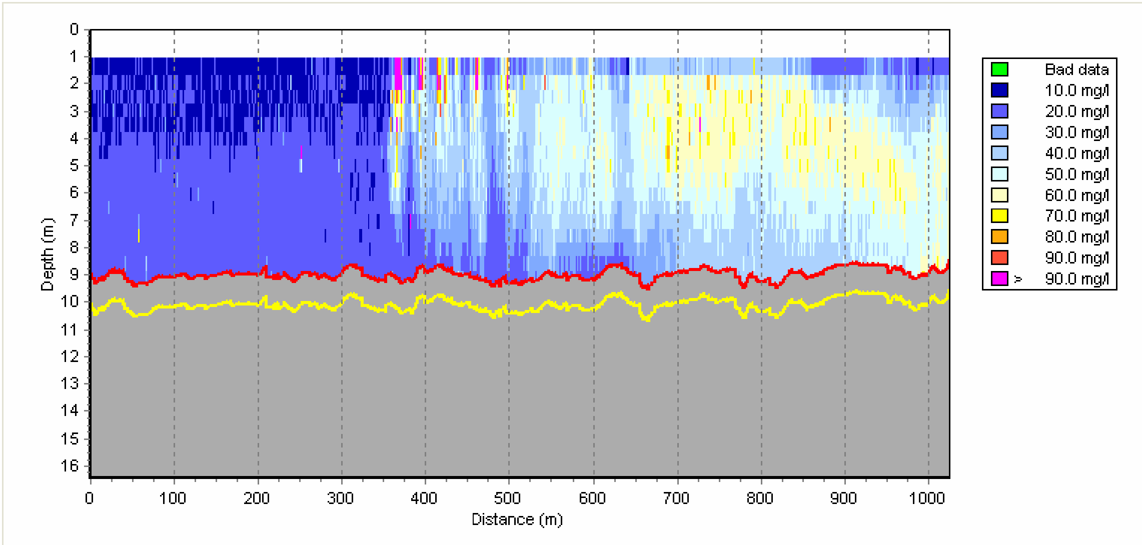

Figure 12. Vertical profile of ambient TSS concentrations across Redwood Creek during an ebbing tide.

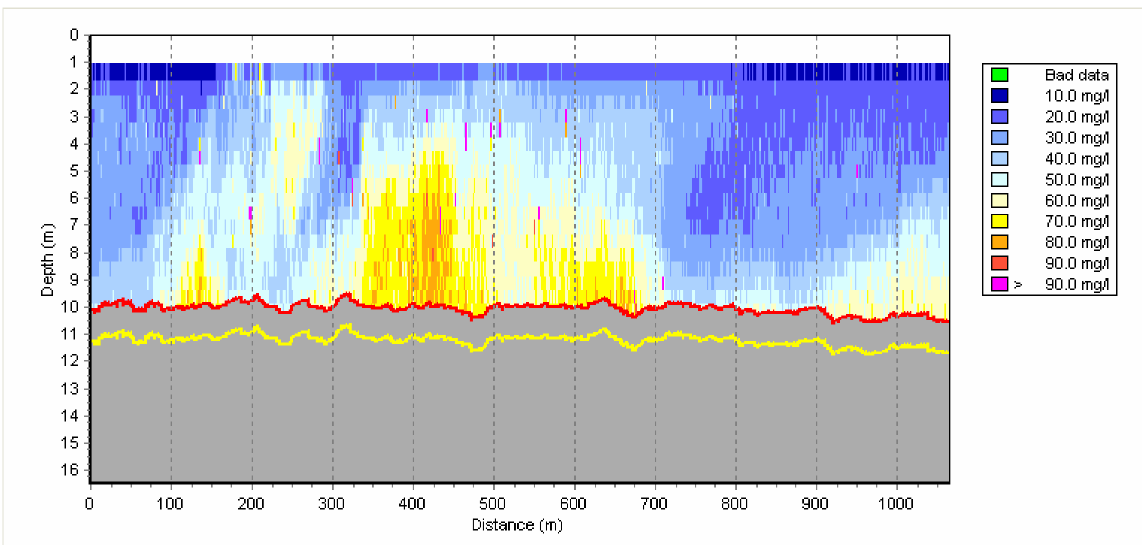

Figure 13. Vertical profile of ambient TSS concentrations across Redwood Creek during a flooding tide.

In one ebb tide survey the transect began against the channel side slope and progressed forward for 900 m. A prominent plume signature was seen at the onset of the record as the bar was pushed along the toe of the side slope. The distance between the barge and the ADCP was approximately 70 m. Further along the transect high concentrations were found in much of the lower half of the water column, with concentrations in the 100 to 175 mg/L range. A portion of these concentrations may be due to ambient suspended sediments. Another ebb tide parallel survey showed an intense and continuous prop-wash signal overlying pulses of plumes over the bottom. The bar created a small plume over the high spot at 650 m along the transect, and a slightly larger plume at 900 m along the transect. The latter plume rose almost 3 m off the bottom.

An additional survey conducted at slack water following an ebb tide (Figure 14), when ambient conditions would consist of clearer waters, yielded a distinct plume signature. At a distance of 50 m behind the barge an intense plume (concentrations > 225 mg/L) was detected below the tug's prop-wash. The plume signature decayed rapidly as the survey vessel moved out of the barge track, noted by the loss of a surface prop-wash signal.

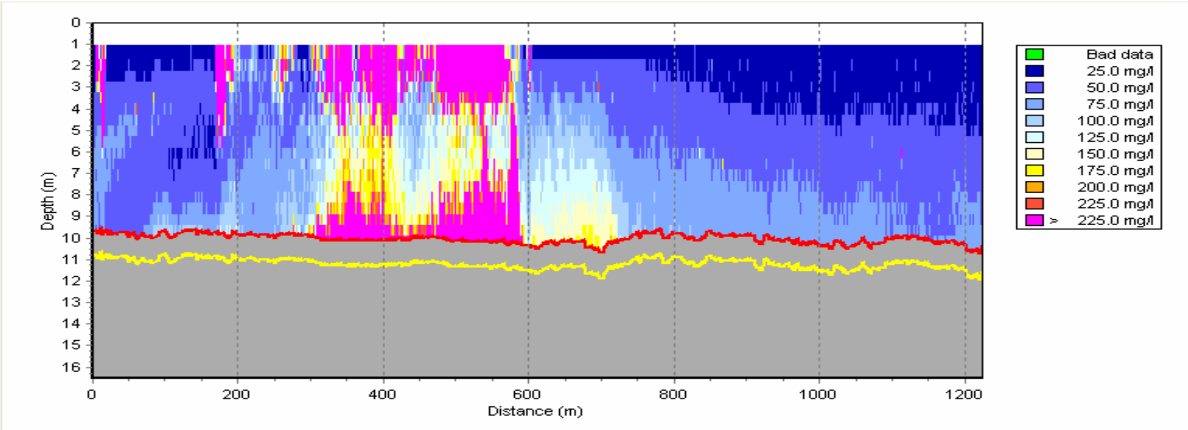

Figure 14. Parallel course on ebbing tide, 50 m directly behind the barge at slack water.

A series of parallel surveys were also conducted during flooding tides (Figures 15 and 16). In each survey the pulsed structure of the knockdown plumes was evident. Distinct plume signatures are shown in Figure 15, when the survey vessel followed the barge at a distance of 55 m. The signatures are less prominent in Figure 16, when the distance to the barge increased to 80 m.

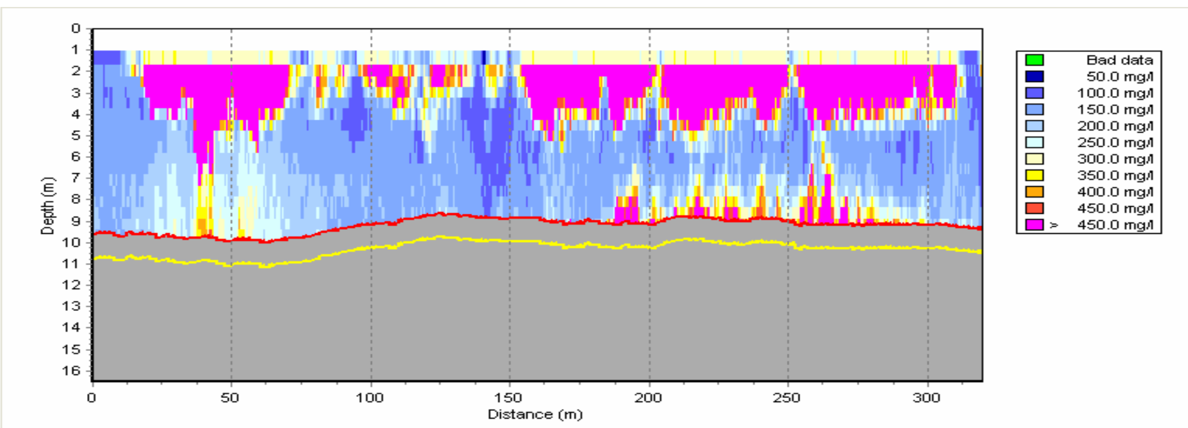

Figure 15. Parallel course on flooding tide, 55 m directly behind the barge.

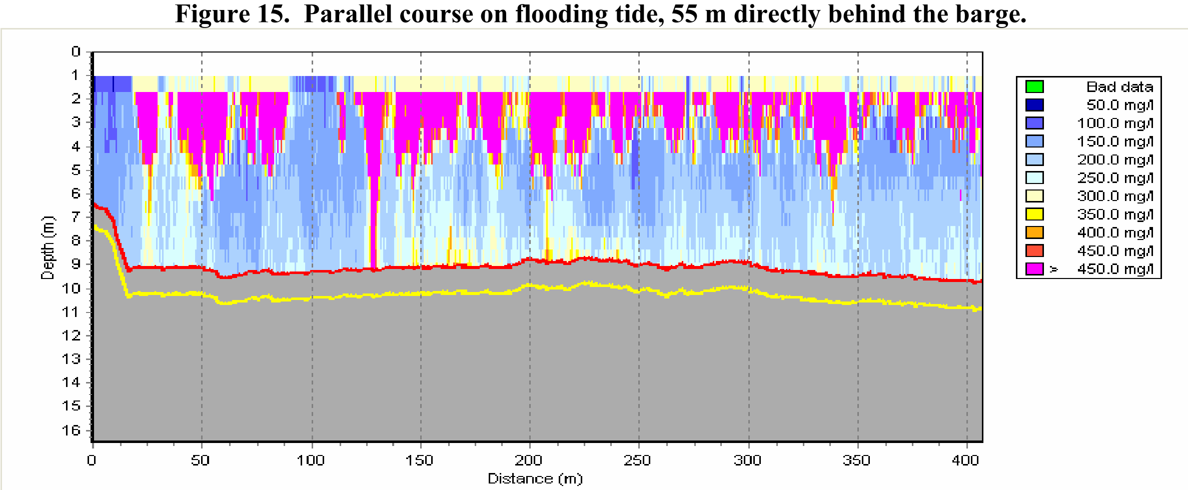

Figure 16. Parallel course on flooding tide, 80 m directly behind the barge.

Acoustic Estimates of TSS Knockdown Plumes, Zigzag Surveys

Zigzag surveys were used to assess variation in knockdown plumes across their entire width at predetermined distances behind the barge. On ebbing tides (Figures 17 to 19), the highly variable signatures of the knockdown plumes between passes (each pass denoted by a strong surface prop-wash signal) are shown at 60, 70, and 90 m behind the barge respectively. Due to the generally low background suspended sediment conditions during the three zigzag surveys, the data clearly show that the knockdown plumes were relatively narrow features, often not as wide as the prop-wash signal. More intense plume signatures were seen at 70 m than at 60 m, and some indication of decay in plumes was seen at 90 m. Several intense surface-to-bottom signatures were seen at 70 m. It appeared that the tug was applying considerably more power to "dig deeper" with the bar or to work against current flows. A combination of a more turbulent prop-wash and more vigorous contact of the bar with the substrate probably produced the merged prop-wash/plume signatures.

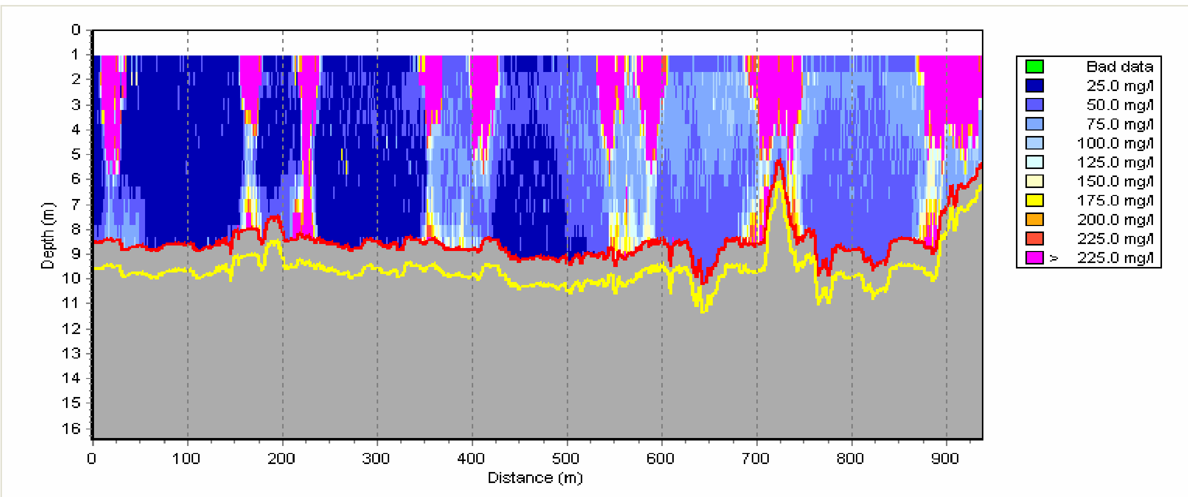

Figure 17. Zigzag course on ebbing tide, 60 m behind barge.

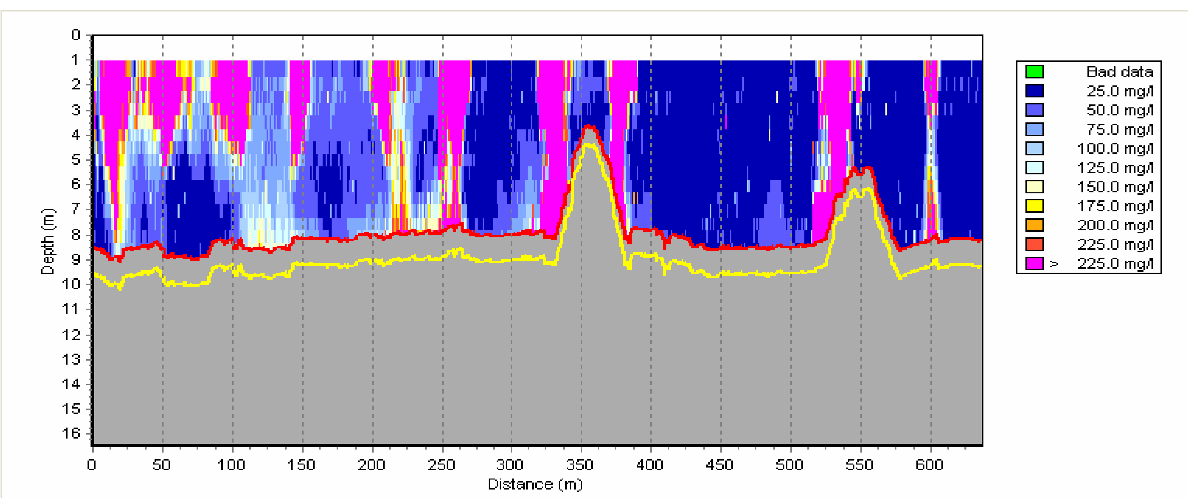

Figure 18. Zigzag course on ebbing tide, 70 m behind barge.

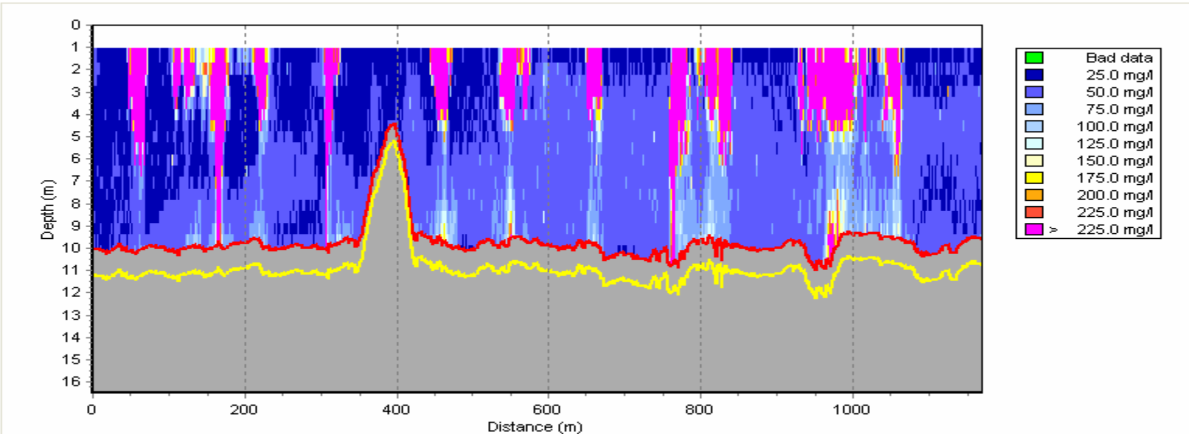

Figure 19. Zigzag course on ebbing tide, 90 m behind barge.

A similar series of zigzag surveys was conducted on flooding tides (Figures 20 and 21). Results were consistent with ebb tide surveys. Intensities of plume signatures among successive passes were highly variable, providing further evidence that re-suspension by the bar was discontinuous. At 45 m behind the barge (Figure 20) intense plumes were seen on 3 of 9 passes, and extend higher than 3 meters above the bottom on only 2 passes. On the 6 less prominent plumes, concentrations generally did not exceed 250 mg/L. At 65 m behind the barge (Figure 21), a very large, intense plume was seen at 400 m along this transect. Here the bottom depth was relatively shallow against the channel side slope, and the bar may have heavily disturbed the substrate. In later passes, where the bottom depth has increased by 50 cm to a meter the plumes were significantly smaller with lower concentration gradients. At 100 m behind the barge (not shown), plumes had weaker signatures with the exception of a single pass at 450 m along this transect, where concentrations near the bottom were as high as 350 mg/L.

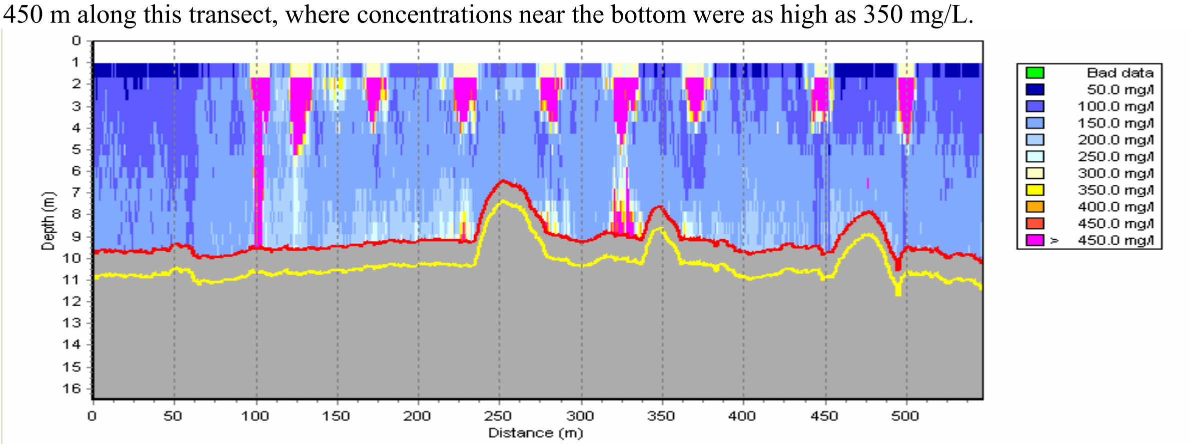

Figure 20. Zigzag course on flooding tide, 45 m behind the barge.

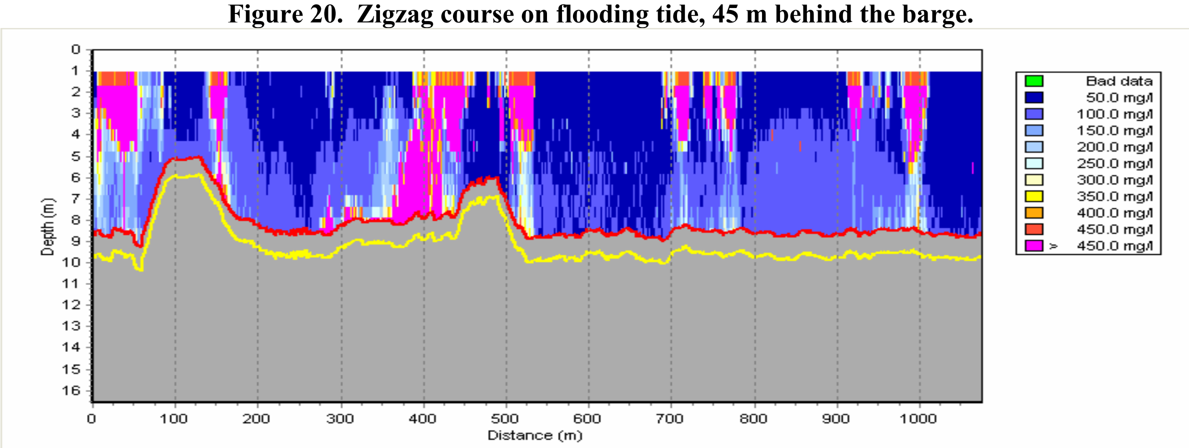

Figure 21. Zigzag course on flooding tide, 65 m behind the barge.

Acoustic Estimates of TSS Knockdown Plumes, Perpendicular Surveys

The design of perpendicular transects across the path of the knockdown barge at the same point in the waterway allowed examination of several characteristics of the knockdown plumes. This approach provided a more accurate determination of the width of individual plumes than the diagonal survey tracks taken in the zigzag surveys. Repetitive transects at the same location as the barge's distance relative to the ADCP changed also allowed observations of the decay rate of the plumes. To interpret the series of transects reported herein, however, the reader must be aware of the operational sequence of events within a knockdown "cycle." In reality, knockdown involves a repetitive process in which the tug and barge move in tandem back and forth in the waterway. The actual path of the bar over the bottom is best described as a "figure-eight" rather than a straight line with distinct start and end points. The tug operator targets the high bottom elevations and adjusts the bar path as necessary. Because the long axis of the figure-eight was typically less than 900 m, the time for completion of a single circuit of the figure–eight ranged from 20 to 30 minutes. This included time for the barge to turn around at each end of the loop. The bar is generally not raised to turn, but adjusted periodically as the tide elevation changes to match the target navigable depth. Considering the above, the plumes can best be characterized in terms of their age in minutes rather than distance from a point of origin. As tidal flows moved in a relatively uniform manner across the perpendicular transect, re-suspended sediments would be carried in the downstream direction. Thus the point of origin of the plume sediments crossing the transect at any time was constantly changing. Considering the age of the plume relative to the positions of the bar and the ADCP allows a composite picture of the plumes to be drawn.

The following descriptions of knockdown plumes were derived from segments of surveys arranged in chronological order, representing a single pass of the tug and barge across the transect's location in Redwood Creek. Seven separate series of perpendicular transects were completed and exemplified herein. Because of specific times allotted to conduct these surveys within the three-day term of the project, all series represent ebbing tide conditions. This was advantageous in light of the observed ambient conditions in Redwood Creek. On ebbing tides highly turbid flows entered the waterway as the adjoining sloughs drained the contiguous wetlands. During the ebb tide, these turbid waters would be transported toward San Francisco Bay and away from survey transects established south of the sloughs. Likewise, turbid San Francisco Bay waters entered the waterway on flooding tides. Highly turbid waters observed periodically during the study period could mask the acoustic signatures of less intense plumes. Thus, surveys located south of the sloughs on outgoing tides provided optimal situations for distinguishing knockdown plumes from ambient conditions.

In examining the series of ADCP records, the reader should also note that the direction of movement across the transect by the survey vessel reverses after each line (i.e. the survey vessel turns and starts a new record moving in the opposite direction). This is readily apparent in successive figures where the channel side-slope change in bathymetry switches from one side of the figure to the next. The apparent shift in location of the plume merely reflects the reversing direction of the survey vessel.

Due to space constraints only a single series is presented in figures (see below) here, although it typifies the entire data set. An initial series consisted of nine transects. The first three transects were run as the barge approached. Some indication of residual plumes was seen over the bottom against the channel side slope. At 40 m from the transect the core of the plume was approximately 15 m wide with a diffuse area of high concentrations extending up the channel side-slope for another 15 m. TSS concentrations rose above 135 mg/L in the core and were primarily in the 60 to 90 mg/L range in the diffuse portion of the plume. Little indication of lateral spread of the plume toward the center of the channel was seen. Each pass of the barge represented the onset of "new" plume measurements, and the corresponding transect was designated as plume reference time zero. Ensuing transects occupied as the barge had progressed 225 m away after an elapsed time of 3 minutes yielded plume signatures very similar to the time zero transect, with an intense lower plume signature and slightly broader (35 to 40 m) diffuse plume. On the next transect, after an elapsed time of 5 minutes, the prop-wash signature has moved further from the bank, and some decay was seen in the plume itself. The plume was 20 to 30 m wide in the lower water column. After 7 minutes of elapsed time, the plume had broadened to 40 m with continued decay in terms of concentration gradients, generally from 45 to 90 mg/L. The plume narrowed after 9 minutes, then expanded once more in the 13 minute transect. After 13 minutes the plume retained TSS concentrations in the 45 to 75 mg/L range.

While the preceding three transects were run, the barge had turned and headed back toward the transect location. Barge passage over the transect initiated a second series of plume measurements. The ensuing transects revealed a similar pattern of plume evolution, although the bottom plume was somewhat weaker at the onset, with very limited spatial coverage of concentrations above 105 mg/L. The plume extended outward about 40 m from the toe of the side slope. After 2 minutes, the plume covered the same cross-sectional area of the channel, again with TSS concentrations largely below 105 mg/L. After 5 minutes of elapsed time, the plume had retained its overall dimensions, but showed further TSS decay near the bottom. After 7 minutes the tug prop-wash signals had almost entirely dissipated and the plume continued to "hug" the bank, extending outward approximately 40 m. The ensuing three transects showed progressive decay of the plume through 9, 11, and 14 minutes of elapsed time. At 14 minutes the plume had diffused laterally, extending outward over 50 m from the bank, and showed concentration decays to below 60 mg/L along its interior channel perimeter. The plume had not completely dissipated upon the arrival of the barge crossing the transect in the opposite direction.

A third series began with a similar time zero prop-wash and plume signature as the preceding series. At time zero some residual plume remained in the upper water column 50 to 80 m from the bank. A relatively intense knockdown plume was observed after 1 minute had elapsed, which expanded to 60 m at 4 minutes. However, the ensuing transects revealed a rapidly decaying plume, both in terms of concentration gradient and lateral spatial dimensions. At 11 minutes the portion of the plume containing concentrations above 60 mg/L continued to hug the bank, with a diffuse plume characterized by TSS concentrations under 45 mg/L extending outward over 70 m into the channel.

In a fourth series of perpendicular transects generally stronger plume signatures were seen in the time zero and 3 minute transects. Very strong tug prop-wash signals indicated that the operator was applying lots of power in pushing the barge forward. The bottom plume at 3 minutes contained concentrations well over 150 mg/L in a 40 m wide swath. The prop-wash signal was almost completely lost at 6 minutes, with a very reduced plume in terms of concentration gradients. At 8 minutes the plume had decayed to concentrations less than 125 mg/L and broadened to a 70 m wide diffuse feature throughout the water column.

A fifth series of perpendicular transects began with very strong merged prop-wash and plume signatures. Operating against the toe of the channel side slope, the tug had apparently applied substantial power in pushing the barge. The acoustic signatures at time zero and 2 minutes were very narrow, less than 20 m wide. At 5 and 7 minutes respectively, the prop-wash signal diminished, leaving clear signatures of bottom plumes primarily in the 150 to 175 mg/L TSS concentration range. During this series the tug had turned after progressing only 200 m away from the transect. Thus the sixth series of transects began while there was still a relatively strong plume signature remaining from the fifth series.

A sixth series of perpendicular transects (Figures 22 to 28) included very strong initial prop-wash signals at time zero and 2 minutes. The intense acoustic signature at 2 minutes elapsed time dissipated significantly by 5 minutes (Figure 24). The plume at 5 minutes was broad, with TSS concentrations greater than 100 mg/L extending almost 65 m into the channel. TSS concentrations of 150 mg/L were largely confined to a band less than 20 m wide. Two minutes later (Figure 25), the plume had largely dissipated, with a few areas of TSS concentrations approaching 100 mg/L in the residual plume along the bank and scattered laterally across the bottom. This pattern persisted in the 9, 11, and 13 minute transects. Small prop-wash signals in the 9 minute record (Figure 26) were created by the survey vessel. An indication of a residual plume was seen at 13 minutes (Figure 28) following an almost complete loss of a plume signature in the 11 minute transect (Figure 27). This return of a plume signature may reflect the pulsed nature of the knockdown process, as waters over high spots that receive re-suspended sediments are interspersed with pockets of water where the bar had less contact with the substrate.

The seventh and final series of perpendicular transects produced a similar succession of acoustic signatures. Initially the signals extended from surface to bottom in narrow, 20 m wide bands, until the prop-wash dissipated sufficiently to reveal a clear plume signature at 6 minutes elapsed time. At 8 minutes the signal again extended from surface to bottom, probably reflecting another intermittent application of power by the tug operator. The final transect, at 9 minutes elapsed time, was typical of a dissipating prop-wash signal revealing a lower plume of relatively high TSS concentrations in the 150 to 200 mg/L range, with a diffuse band of a generally low concentration plume spreading laterally about 70 m outward from the bank.

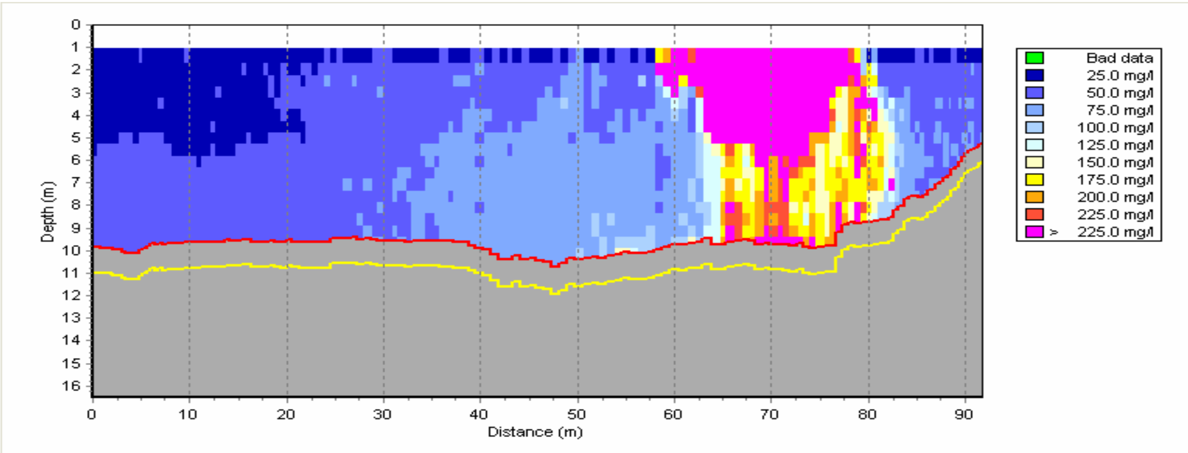

Figure 22. Perpendicular course on ebbing tide, barge passes 60 m beyond transect. Time reference = zero.

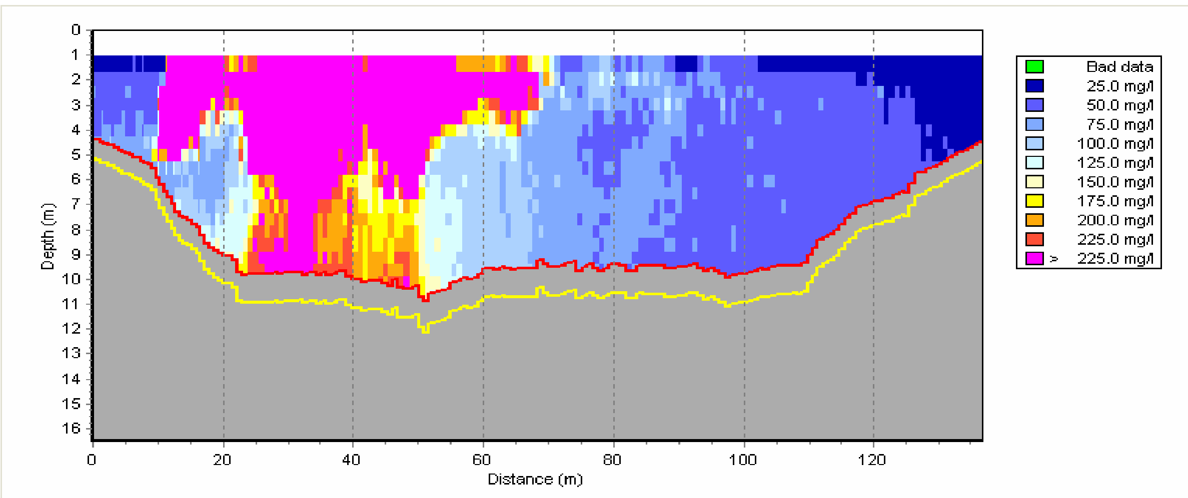

Figure 23. Perpendicular course on ebbing tide, barge 200 m from transect. Time reference = 2 minutes.

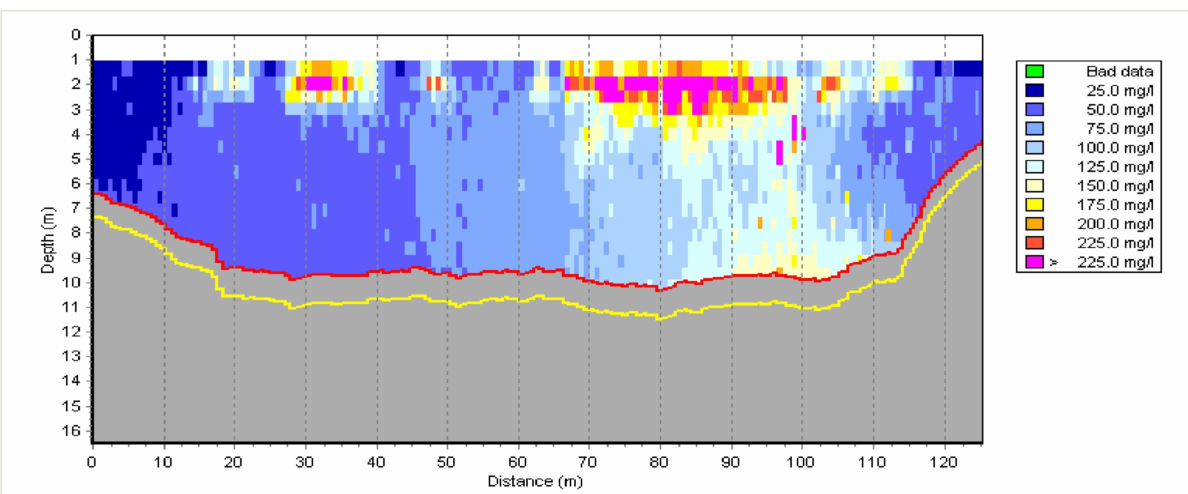

Figure 24. Perpendicular course on ebbing tide, barge 235 m from transect. Time reference = 5 minutes.

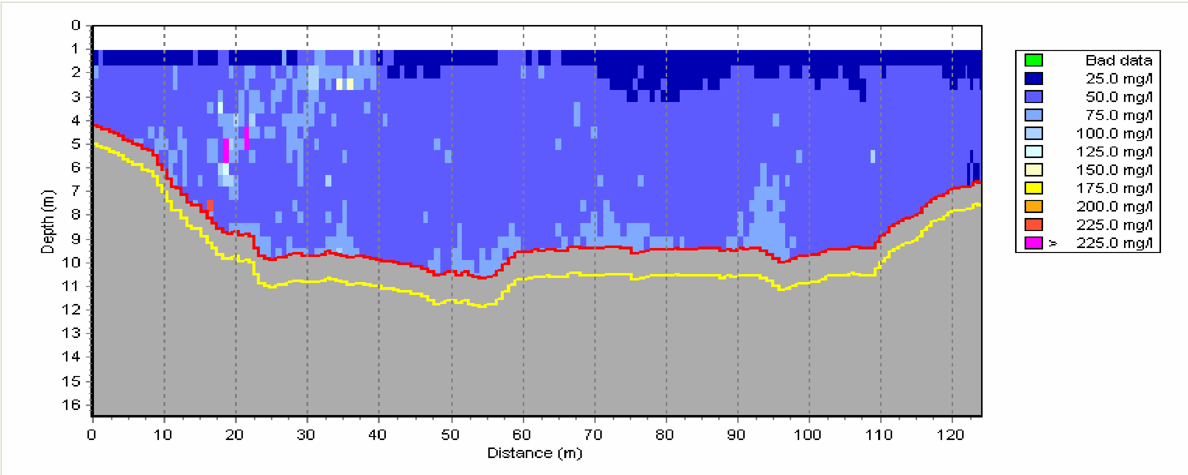

Figure 25. Perpendicular course on ebbing tide, barge 300 m from transect. Time reference = 7 minutes.

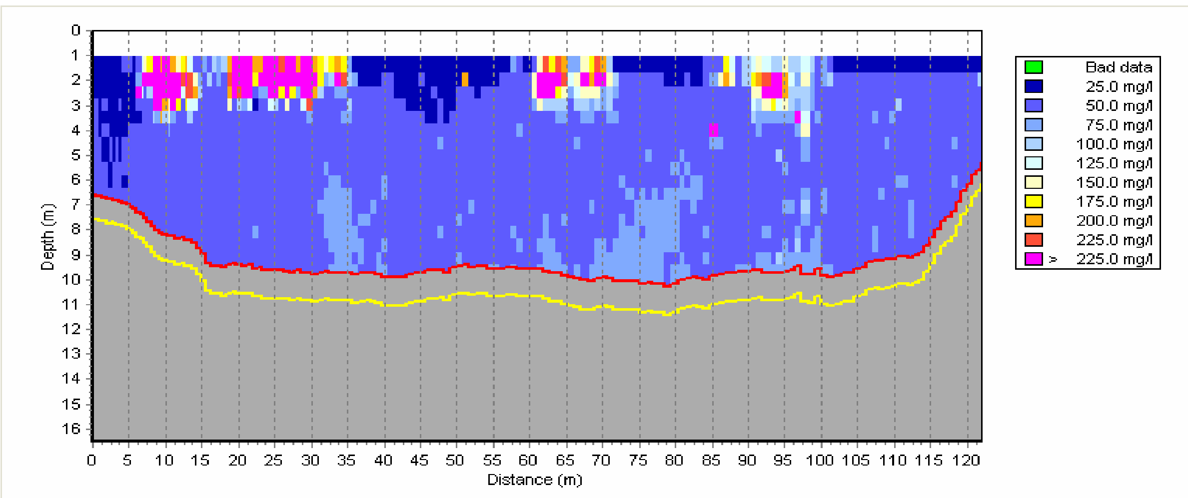

Figure 26. Perpendicular course on ebbing tide, barge approaching. Time reference = 9 minutes.

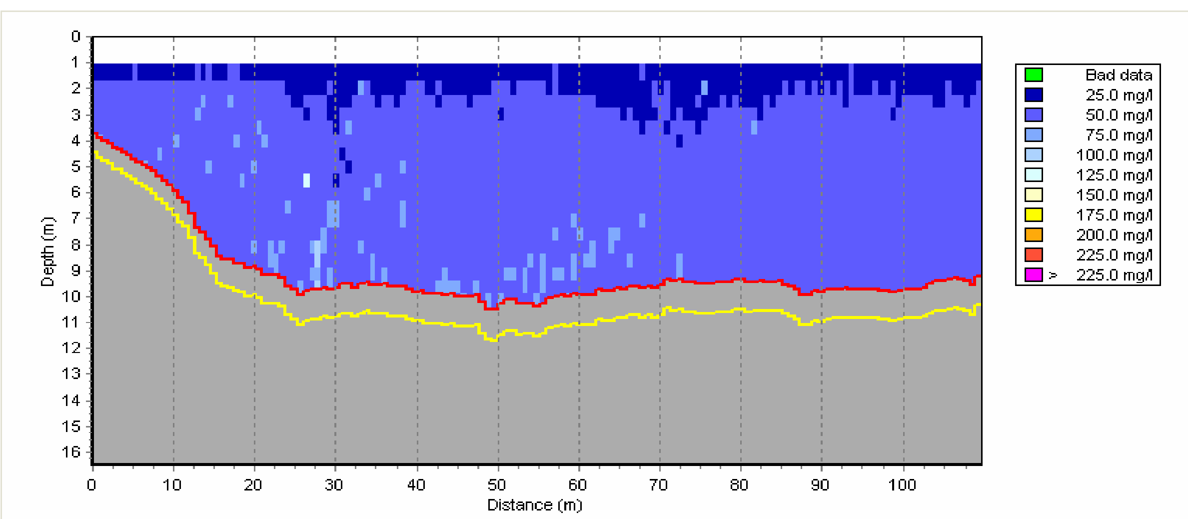

Figure 27. Perpendicular course on ebbing tide, barge approaching. Time reference = 11 minutes.

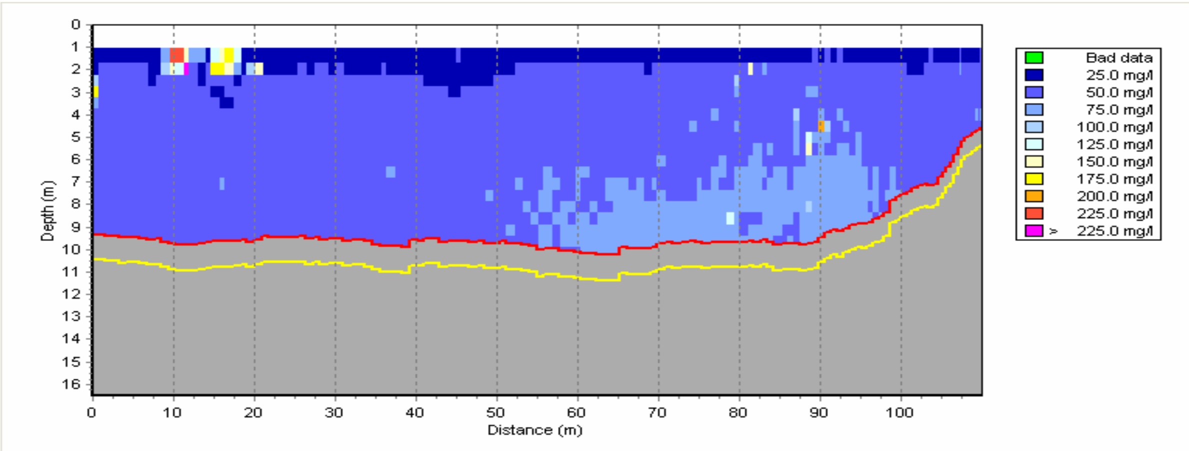

Figure 28. Perpendicular course on ebbing tide, barge approaching. Time reference = 13 minutes.

DISCUSSION

Re-suspension of sediments from the substrate and re-settlement are governed by physical properties of the *in situ* sediment, prevailing hydrodynamics of the overlying waters, and the mode of disturbance. Coarse sediments, unless held in suspension by turbulent forces, quickly settle back to the bottom. Consolidated silts and clays, if cohesion is not disrupted, will behave as aggregates and also settle relatively quickly. In the case of unconsolidated, disaggregated fine sediments, however, particles can remain in suspension for long periods of time even in minimal current flows. Knockdown is considered to be a cost effective means to establish navigable depth when bottom depth contours are uneven. Positioning dredges to remove small isolated shoals or high spots may not be cost effective due to comparatively higher mobilization/demobilization, personnel, fuel, and equipment maintenance costs than tug/barge/bar options. For this reason knockdown, or bed leveling, is often performed following dredging projects to remove peaks and ridges left behind by conventional dredging methods. Consequently, knockdown is seldom used when *in situ* sediments have high water contents, behave in a fluid manner, and tend to migrate into lower elevations.

In the present study, knockdown operations produced suspended sediment plumes that were highly variable in a temporal context, but consistently predictable in a spatial context. The intermittent "pulsed" characteristics of the observed knockdown plumes were not surprising given the manner in which knockdown occurs. Removal of high bottom elevations along the toe of the channel side slope generally produced the highest TSS concentration gradients within the plumes. Additionally, more intense plumes appeared to be linked to hitting the high spots with the bar while the tug applied more power, as indicated by intensified prop-wash signals. Because the bar was maintained at the predetermined navigable depth and adjusted only to compensate for changes in tidal elevation, the bar was occasionally only lightly in contact with the bottom or not at all.

Part of the temporal variability seen in the knockdown plumes was attributed to the "back and forth" nature of the operation. Some indication was seen of more intense plumes as the barge was pushed into the current as opposed to with the current. This effect may also be linked to increased power used by the tug to maintain forward speed. Each leg of the back and forth routine varied somewhat in time as the tug operator turned the barge to return to identified high spots. As discerned from the multiple series of perpendicular surveys, TSS concentrations sometimes returned to near ambient levels prior to the bar sweeping through that point in the waterway again, and sometimes a residual plume remained as the bar crossed that point again.

Three-dimensional spatial "footprints" of generic knockdown plumes can be described based on the cumulative data derived from parallel, zigzag, and perpendicular ADCP transects. The width of the bar represented a finite limit on the width of sediment disturbance on any given pass. In all cases the plume observed close to the bar's point of contact with the bottom was a relatively narrow feature, in some records not wider than the bar itself. Lateral spread of the plume appeared to be slow, as the plume was generally limited by uniform tidal flows. With passage of time plumes diffused to features 20 to 25 m wide, or approximately twice the width of the bar. As the plume continued to age larger variations in widths of plume signatures were observed. On several occasions lateral expansion of the plume may have been promoted by turbulence in the area of the water column influenced by the tug's prop-wash as well as by the repetitive passage of the tug and barge. In several surveys the plume expanded laterally to 70 or more meters from the bank.

Concentration gradients within the plumes also varied greatly. As evidenced by both water samples and acoustic measures, concentrations ranged as high as 600 mg/L, primarily directly behind the path of the bar and in the lower half of the water column. Concentrations generally decayed to less than 200 mg/L within 5 to 6 minutes of bar passage, and to 100 mg/L within 7 to 9 minutes. Residual plumes with concentrations in the 50 to 100 mg/L range persisted for 13 minutes or longer.

In many respects knockdown plumes were similar ambient conditions in Redwood Creek. In sections of the waterway south of the sloughs ambient turbidities and TSS concentrations generally ranged from 10 to 20 NTU and 30 to 45 mg/L respectively. Tidal circulation carried turbid slough and bay waters into Redwood Creek, approaching 40 to 65 NTU as the tide ebbed and 100 to 120 NTU as the tide flooded following a precipitation event. These turbidities were comparable to TSS concentrations as high as 420 mg/L.

During knockdown operations, in portions of the waterway, organisms undoubtedly could be exposed to high turbidities and TSS concentrations. Assessing the degrees of risk posed by knockdown operations would require knowledge of the behavior, distribution, and tolerance of specific organisms. For example, fish that occupy the upper portion of the water column would be unlikely to encounter substantially elevated turbidities or TSS concentrations, particularly as compared to ambient conditions. Plumes tended to diffuse laterally behind the barge, but predominantly in the bottom half of the water column. The tug operator concentrated bar passes along a single bank on a given day and alternated banks on successive days, therefore the plumes did not occur along both banks on any given day. Plumes of high turbidities and TSS concentrations did not extend from bank to bank, although residual plumes of much lower values were often broadly spread across the lower channel cross-section.

The results of the present study provide a base of knowledge upon which to prepare future environmental assessments of knockdown operations. Modifications to the manner in which the bar is maneuvered across the bottom, very fine *in situ* sediments, or very different hydrodynamics at a given project site could potentially produce plumes of different dynamics than those observed in Redwood Creek. However, these results should be applicable to many knockdown scenarios.

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