SUSPENDED SEDIMENT PLUMES ASSOCIATED WITH MECHANICAL DREDGING AT THE PORT OF OAKLAND, CALIFORNIA

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ABSTRACT

Suspended sediment plumes associated with dredging operations continue to be a source of concern for regulators. In San Francisco Bay, California, protection of sensitive biological resources has been prioritized by the Long Term Management Strategy (LTMS) stakeholder forum. One critical data gap identified by the LTMS forum is knowledge of the spatial and temporal dynamics of plumes during the conduct of dredging in waterways seasonally occupied by juvenile salmonids (*Oncorhynchus* spp.), Pacific herring (*Clupea pallasii*), and other fishery resources. Ultimately, such knowledge can contribute to prudent management of dredging projects by application of best management practices, including environmental windows when necessary.

This study entailed plume characterization during removal of maintenance sediments from Oakland Outer Harbor by a 12-cubic yard closed bucket at a channel depth between 12 and 13 m. An acoustic Doppler current profiler was used to survey water current structure and suspended sediment concentration gradients during ambient conditions and periods of active dredging on both flooding and ebbing tides. Fifty-five water samples analyzed gravimetrically provided a calibration data set for conversion of acoustic backscatter to suspended sediment concentration.

Plumes were driven by relatively weak currents, generally less than 25 cm/sec, during both flood and ebb tidal stages. Ambient suspended sediment concentrations ranged from 10 to 15 mg/l at the surface and 25 to 50 mg/l at the bottom. Weak currents, in combination with a closed bucket, produced plumes that were largely bottom-oriented with acoustic signatures that decayed to background conditions within 400 m from the source. Loss of sediment via resuspension was predominantly confined to the lower water column, with few indications of a surface plume component. Pulses of elevated concentration coincided with repetitive cycles of bucket impact with the substrate. Concentrations exceeding 275 mg/l were measured only in immediate proximity to the source, and with increasing distance concentrations greater than 100 mg/l were observed only in relatively small pockets of water that dispersed along the bottom.

At this location, if similar dredging equipment were used, it appears unlikely that transient fishes in mid to upper portions of the water column would be exposed to suspended sediment concentrations exceeding ambient for even short durations. Bottom-oriented fishes would likely receive higher dosages of suspended sediment, although encounters with plume pulses would be limited to a relatively small spatial scale.

Keywords: Resuspended sediments, turbidity plumes, acoustic Doppler current profiler

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INTRODUCTION

Suspended sediment plumes associated with dredging operations continue to be a source of concern for regulators. Hypothetical impacts attributed to sediment resuspension and deposition are frequently cited during the interagency coordination process. In San Francisco Bay, California, protection of sensitive biological resources is a primary objective of the Long Term Management Strategy (LTMS) stakeholder forum. One critical data gap identified by the LTMS forum is knowledge of the spatial and temporal dynamics of plumes during the conduct of dredging in waterways seasonally occupied by juvenile salmonids (*Oncorhynchus* spp.), Pacific herring (*Clupea pallasii*), and other fishery resources. Ultimately, such knowledge can contribute to prudent management of dredging projects by application of best management practices, including environmental windows when necessary.

Dredging occurs in the San Francisco Bay estuary in many locations that represent a variety of geo- morphologic and hydrodynamic settings. Dredging also entails the use of a variety of equipment and operational measures. Given this broad spectrum of dredging project scenarios, it has proven difficult for regulatory agencies to assess the relative risk posed by individual projects based on existing knowledge of plume dynamics. The objective of this study was to characterize in detail the spatial and temporal dynamics of plumes in an area that requires frequent maintenance dredging. These data would form the basis for examining how decisions for protective measures could be linked to a better understanding of the dredging process.

This study entailed plume characterization during removal of maintenance sediments from the Port of Oakland's Outer Harbor complex (Figure 1) by a 12-cubic yard closed bucket, operated by the Dutra Group, at a channel depth between 12 and 13 m.

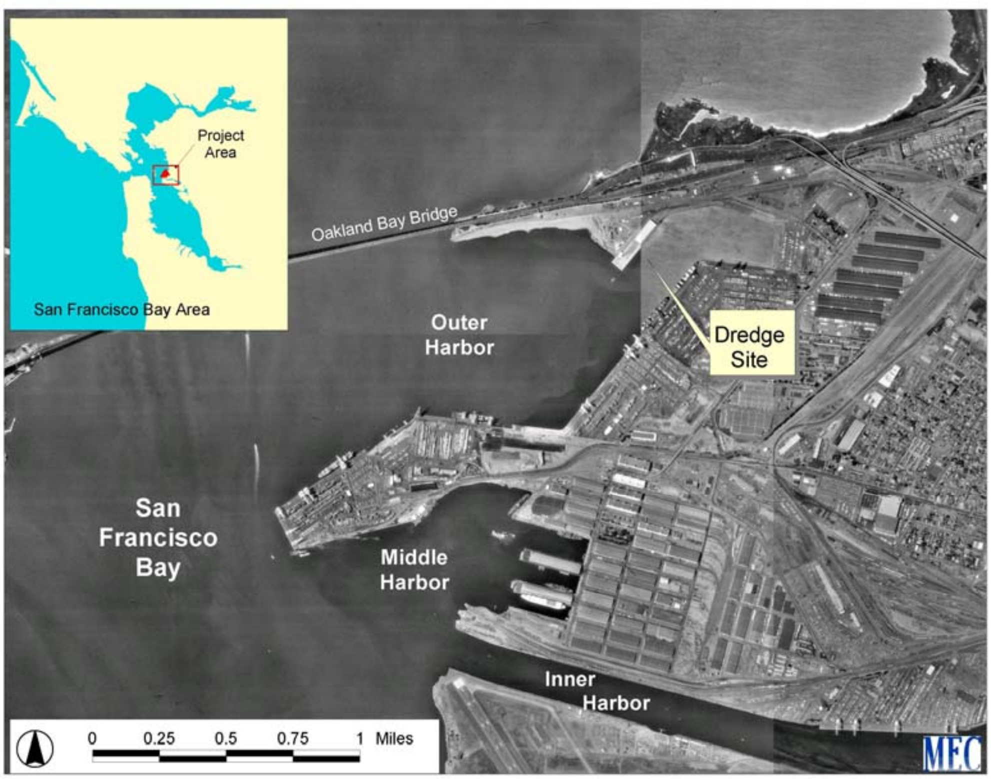

Figure 1. The study area (inset) with an aerial view of the Outer Harbor portion of the Port of Oakland. The approximate location of the dredge during sampling is indicated.

METHODS

Current Structure and Suspended Sediment Plume Acoustic Signatures

An RD Instruments 600-kHz Mariner Workhorse Series Acoustic Doppler Current Profiler (ADCP) was used to collect current velocity, direction, and acoustic backscatter data. Navigation data received from a differential Global Positioning System were collected synoptically and integrated during post-processing. ADCP acoustic backscatter data were analyzed using Sediview Software provided by Dredging Research Ltd. The Sediview Method (Land and Bray 2000) derives estimates of suspended solids concentration in each ADCP data bin by converting relative backscatter intensity to concentration. This process requires collection of a field data set consisting of discrete water samples analyzed gravimetrically. The sample population represents the concentration gradient prevailing at the study site, and is used to "groundtruth" the acoustic data. The calibration samples are collected at known locations within the insonified portion of the water column, so that individual gravimetric samples can be directly compared with acoustic estimates of concentration for the same unit volume of water. An example of acoustic methodologies for plume characterization can be found in Reine et al. (2002). All ADCP surveys were similarly designed, with roughly parallel transects established perpendicular to the channel's long axis at spacing intervals selected to capture the entire spatial extent of fully developed plumes.

Water Sampling

Water samples were collected for gravimetric analysis of total suspended solids (TSS) with a rosette sampler consisting of 9 remotely triggered Niskin bottles. The instrumentation synoptically collected water quality data, including salinity and transmissivity.

RESULTS

Current Structure

Current velocities during ebbing tides were relatively slow throughout the study area, generally less than 25 cm/sec. No indication of strongly increasing or decreasing flows at any depth in the water column was seen as surveys progressed through the early to late stages of the tide. Likewise, all flood flow velocities were relatively slow, but somewhat higher than those observed in the ebb surveys. Flood flow velocities were generally less than 40 cm/sec. No indications of stratified flows with respect to direction or velocity were observed with respect to either surface or bottom waters during any tide stage.

Acoustic Concentration Data Calibration

The acoustic backscatter to concentration calibration data set consisted of a total of 55 water samples. In Figure 2 the populations of gravimetric and acoustic concentration measurements are compared. For data collected at Outer Oakland Harbor the relationship between gravimetric and acoustic measures had a relatively high degree of correspondence, with acoustic concentrations tending to be slightly higher than gravimetric concentrations in the 0 to 90 mg/l range, and slightly lower than gravimetric concentrations in the 90 to 400 mg/l range.

Ambient Suspended Sediment Concentrations

Because the dredging project began prior to the initiation of monitoring, ambient suspended sediment concentrations were estimated on the basis of data collected well outside of the area influenced by plumes, and while the dredge was inactive. A plan-view layout of the Outer Harbor study area with locations of ambient survey transects is given in Figure 3. This ambient survey consisted of 11 transects established in roughly parallel orientation at approximately 100 m intervals following the long axis of the navigation channel. Each transect extended across the entire channel cross-section within the 3 m depth contours with adjustments of the transect widths where necessary to accommodate locations of the dredge, tenders, and barges. Transects were enumerated in series beginning with Transect 1 at the bay-ward extremity of the survey area to Transect 11 at the innermost section of the harbor.

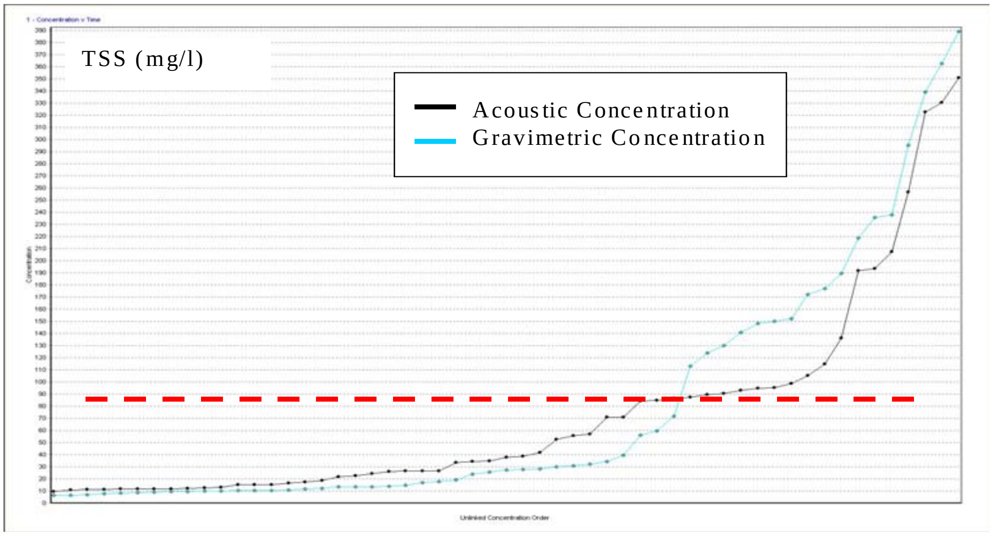

Figure 2. Comparison of acoustic and gravimetric measurements of suspended sediment concentration in rank order.

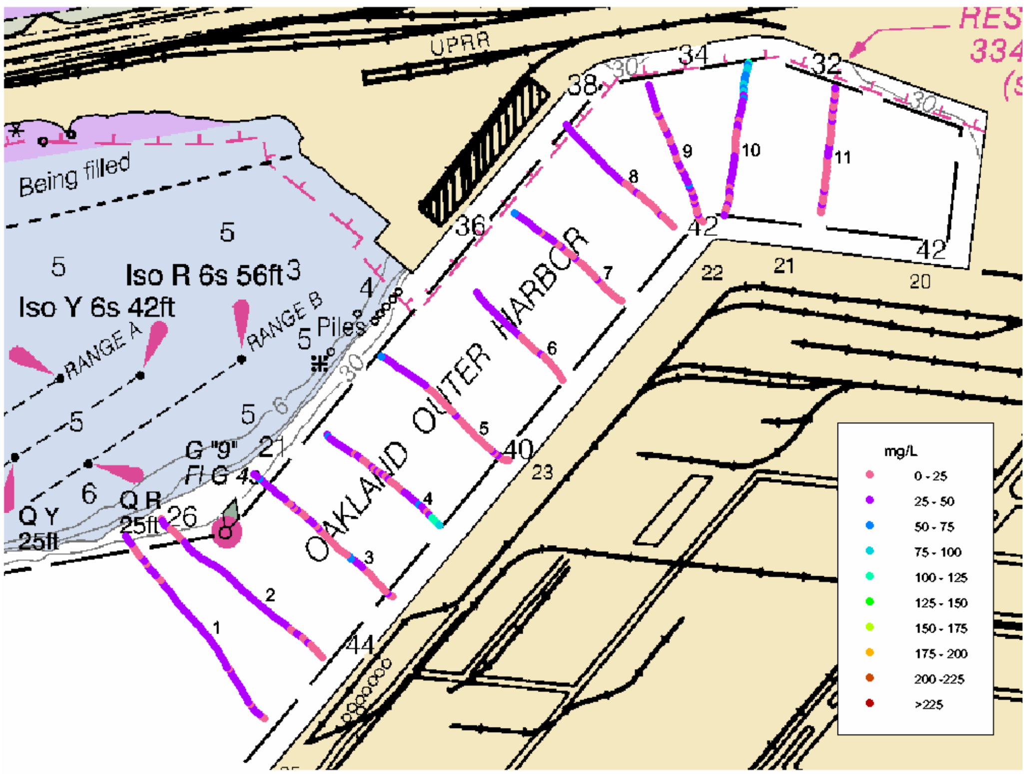

Figure 3. Depth-averaged acoustic estimates of suspended sediment concentrations during a period of dredging inactivity on an ebbing tide.

As seen in Figure 3, ambient suspended sediment concentrations were generally below 50 mg/l throughout the study area with the exceptions of small localized pockets of elevated concentration at ends of Transects 4 and 10. These occurrences of high concentration may have been linked to passage of commercial ship traffic through the harbor. A typical vertical profile of ambient suspended sediment concentrations is exemplified by Transects 1 in Figure 4. On this transect, closest to open bay waters, a distinct increase in suspended sediment concentration with increasing depth was apparent. Concentrations as high as 100 mg/l were found at depth in the channel basin. Concentrations in waters less than 8 m deep were generally below 25 mg/l.

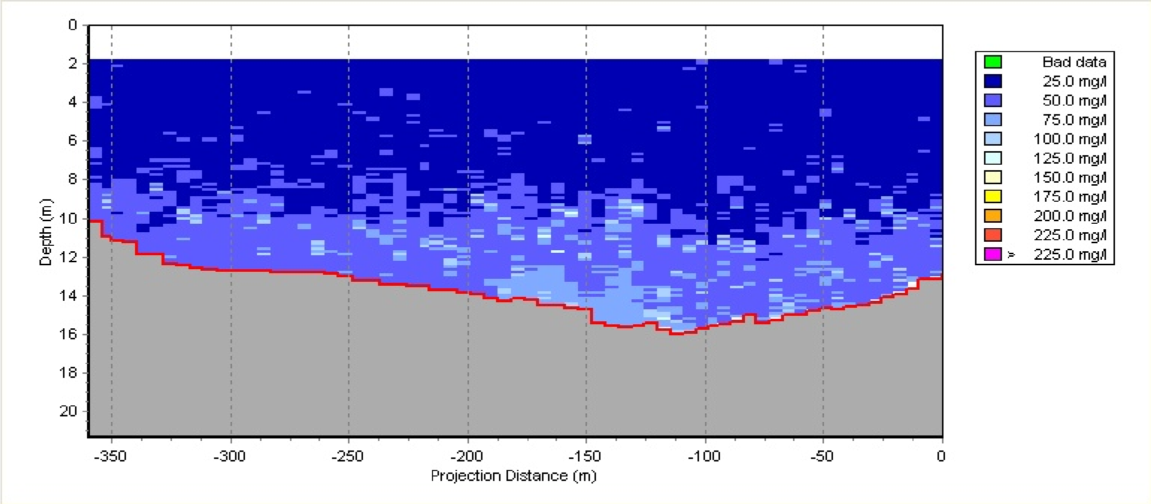

Figure 4. Vertical profile of ambient TSS on Transect 1 during an ebbing tide survey.

Ebb Tide Plume Characterizations

Two during-dredging ebb tide ADCP surveys (ODEC and ODED) were conducted. In these surveys the dredge had been in full production mode for sufficient time to generate a fully developed plume with maximum concentration gradients and spatial dispersion. A plan-view of transects in Survey ODEC is shown in Figure 5. Transects 7 and 8 were shortened due to barriers created by the locations of the operating dredge and barge. A clear depth-averaged plume signature can be discerned on portions of Transects 5 through 11. Although the plume would logically be expected to disperse bay-ward by ebbing flows, most of the plume "footprint" extended laterally and into the harbor from the dredge's position at that time. This lack of bay-ward dispersion likely reflects the low overall flow velocities throughout the study area. The portion of the plume on the inner harbor side of the dredging operation may represent plume remnants of bucket cycles during transition through he previous flood stage.

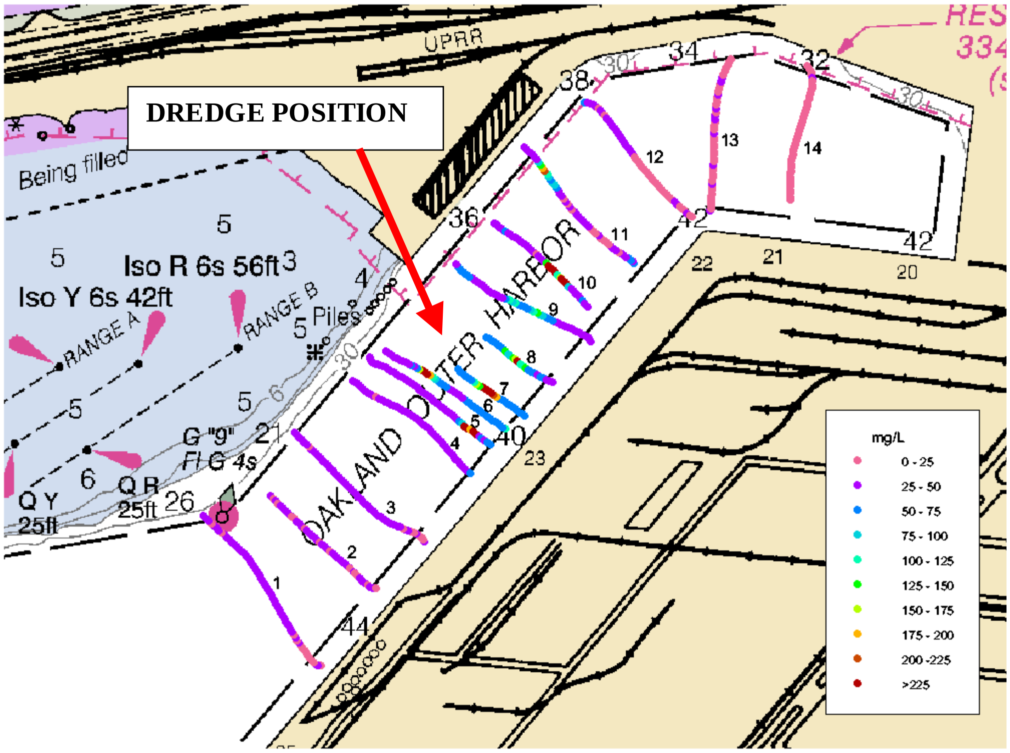

Figure 5. ADCP Survey ODEC transects during an ebbing tide. The dredge was operating adjacent to Transects 7 and 8. Depth-averaged acoustic concentration estimates are indicated by color-coded dots.

A selected series of vertical cross-sectional profiles representative of the ebb survey are given in Figures 6 through 10. Transects 1 through 3 were unremarkable in that they resembled ambient conditions, with concentrations above 25 mg/l confined to depths below 8 m. On Transect 3 (Figure 6) a more diffuse distribution of concentrations was seen, extending higher into the water column. These slightly elevated mid-water concentrations may be associated with the outer margin of re-suspended plume sediments. The first indication of a distinct plume acoustic signature can be seen on the bottom on Transect 4 (Figure 7). A band of suspended sediments about 120 m wide and up to 4 m off the bottom extends over the eastern portion of the transect, with concentrations primarily in the 75 to 100 mg/l range, but as high as 150 mg/l. The same basic pattern, with slightly lower concentrations, was seen on Transect 5. On Transect 6, which crosses the channel immediately adjacent to the point at which the dredge bucket was transiting the water column, a very distinct, intense acoustic signature of rising gas bubbles was present (Figure 8). A separate signature of a diffuse bottom plume dispersing laterally in the lower half of the water column can also be seen. Air is entrained as the bucket is lowered through the surface of the water. In currents as slow as those present at the study sites, air bubbles have been shown to dissipate within 100 m or less of the source. On Transect 7 a diffuse plume covered the entire lower column below a depth of 7 m, with concentrations as high as 125 mg/l. Note that this transect began in mid-channel because of obstructing dredging equipment. Transect 8 is interesting in that two distinct plume "pulses" are evident, one relatively intense and a second rather diffuse (Figure 9). The intense pulse was located approximately 150 m from the source, with concentrations up to 200 mg/l, whereas concentrations in the second pulse, about 100 m further away, do not exceed 125 to 150 mg/l. With distance, the plume had settled deeper in the water column. These acoustic signatures clearly illustrate the non-uniform structure of the plume generated by a bucket dredge, which in this case was a closed bucket. Each impact of the bucket on the substratum produced a pulse of suspended sediment, which slowly drifted downcurrent. The intervening time interval between bottom impact and winching up, unloading, and winching down again is on average 50 to 70 seconds for most bucket dredging operations. Thus a new pulse was created roughly every 60 seconds. The intense pulse decayed with movement away from the source as coarser fractions settled out. A residual plume of fine sediments can persist for an indefinite period based on hydrodynamics and bathymetry at the site. Transects 9 and 10 retained this pattern of double signatures, with decaying concentrations with increasing distance. Again, it is noteworthy that these plume components were located on the harbor side of the dredging operation, although the tide was ebbing. The acoustic plume signatures were almost entirely lost on Transect 11 (Figure 10), although concentrations that may be part of the residual plumes were distributed widely in the water column. Background concentrations also appeared to decay progressing from Transect 12 to 14. Essentially the entire water column had concentrations in the 0 to 25 mg/l range on Transect 14. This may reflect the fact that current speeds at the "dead end" of the harbor channel are sufficiently slow to create an effective settling basin.

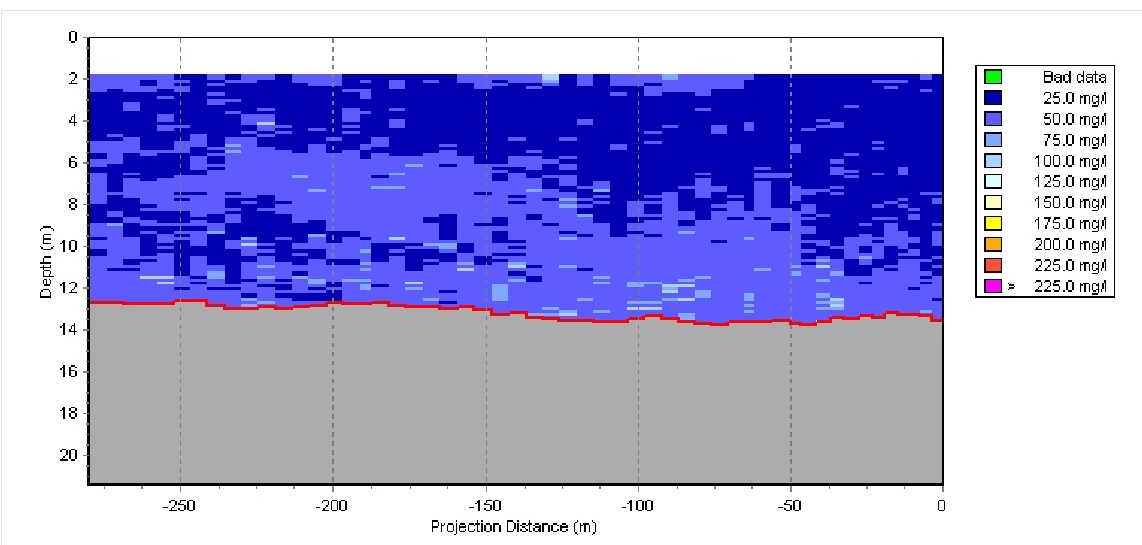

Figure 6. Vertical profile of TSS on Transect 3 during an ebbing tide survey (ODEC).

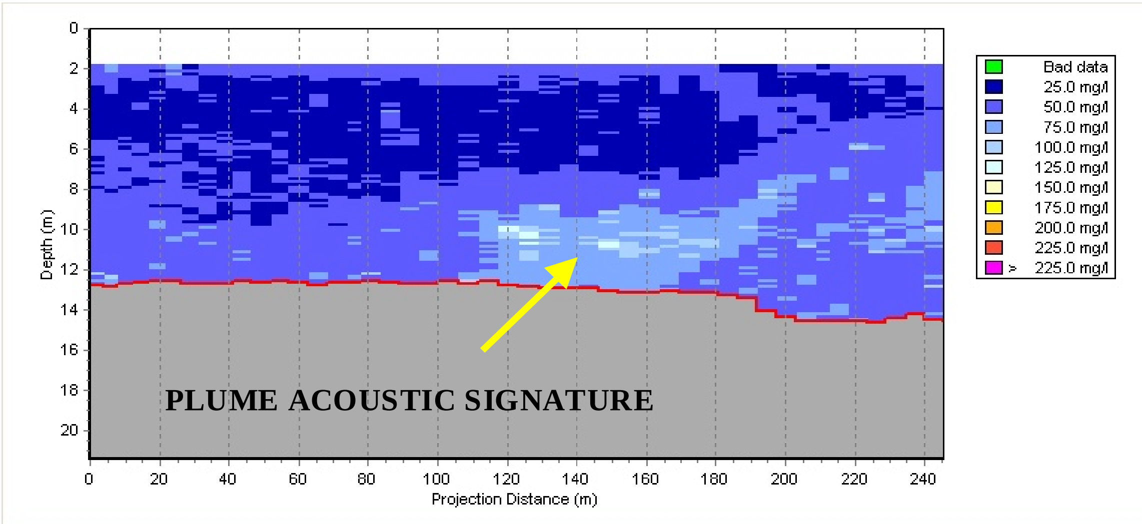

Figure 7. Vertical profile of TSS on Transect 4 during an ebbing tide survey (ODEC).

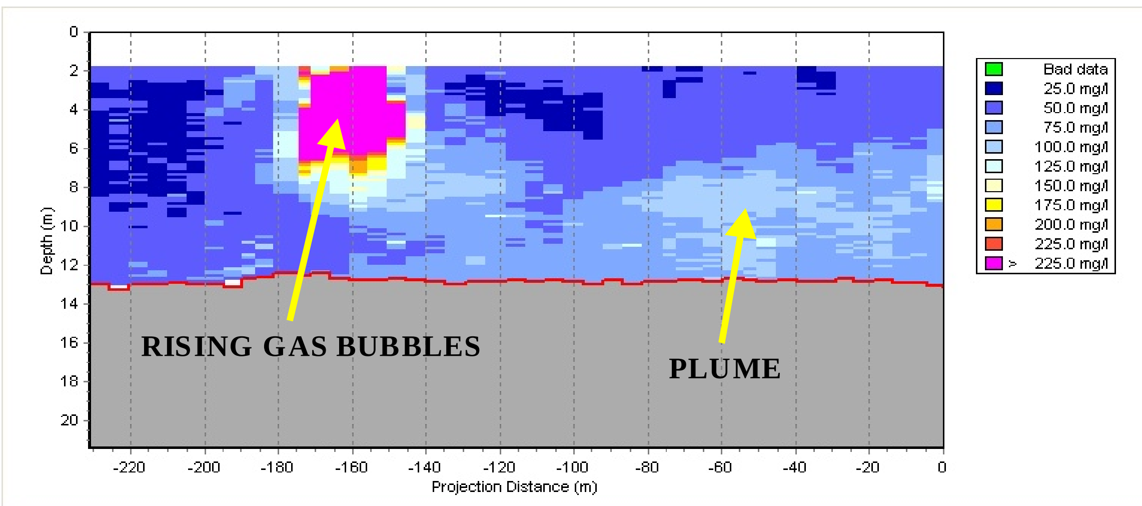

Figure 8. Vertical profile of TSS on Transect 6 during an ebbing tide survey (ODEC).

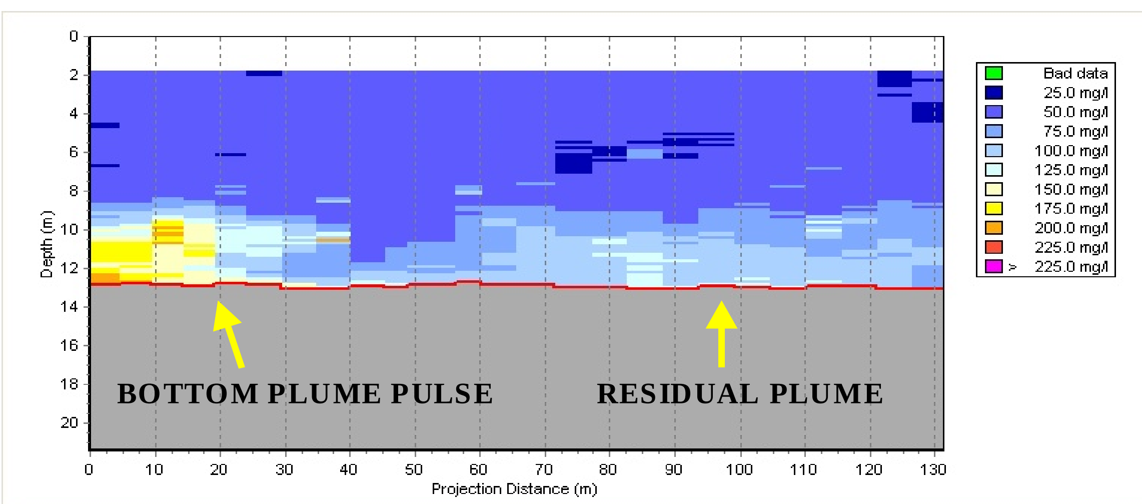

Figure 9. Vertical profile of TSS on Transect 8 during an ebbing tide survey (ODEC).

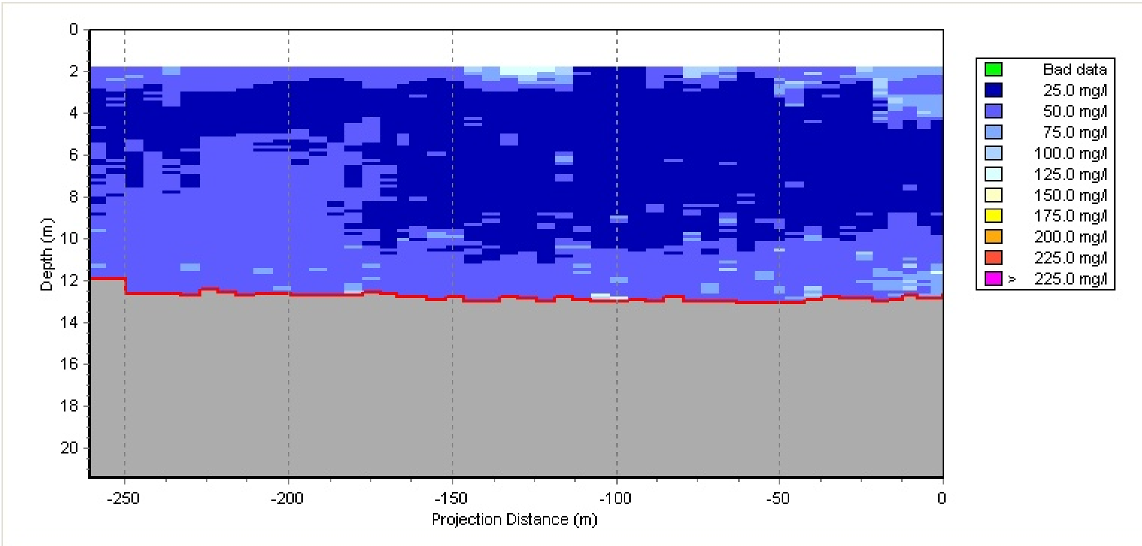

Figure 10. Vertical profile of TSS on Transect 11 during an ebbing tide survey (ODEC).

A second during-dredging ebb tide survey (ODED) produced very similar results. Distances between parallel transects were reduced to gain better resolution of plume features near the source. Examination of the vertical cross-sectional profiles comprising the survey again indicated that the plume was a heterogeneous feature, with pulses of re-suspended sediment moving away from the source. Outer, bay-ward transects showed consistent occurrence of concentrations in the 25 to 50 mg/l range. In this survey some appearance of a mid-water plume was found on Transects 3 and 4 downcurrent from the dredge. A band of elevated concentrations (up to 125 mg/l) approximately 125 m wide and 5 to 9 m deep occurred in the central portion of the channel. Intense gas bubble acoustic signatures were evident on both Transects 5 and 6, which crossed the channel on the immediate downcurrent side of the dredge. A less intense plume signature was seen in the lower portion of the water column on Transect 5, about 125 m wide, and containing concentration up to 125 mg/l. Lateral to the dredge, a relatively intense (up to 200 mg/l) bottom plume signatures occurred on Transects 7 and 8. The plume was confined largely to depths below 8 m on Transect 8. Double plume pulses just above the substrate were seen on Transect 9, with concentrations decayed to approximately 125 mg/l. More diffuse bands of elevated concentration were evident along Transects 10 and 11, generally restricted to depths greater than 10 m. A double plume pulse reappeared on Transect 12, including a small signature of concentration as high as 200 mg/l. A small plume signature was detected on the final transect (Transect 13), where a central pulse showed signs of decay to concentrations in the 75 to 100 mg/l range. This transect, on the harbor side of the dredge, was approximately 200 m from the source. Likewise, the plume was detected approximately 200 m away from the dredge on the bay side. Currents again appeared too weak to carry the plume substantial distances.

Flood Tide Plume Characterizations

Two during-dredging ADCP surveys (ODFC and ODFD) were completed during flooding tides. A plan-view layout of transect locations for ODFC is given in Figure 11. Depth averaged acoustic estimates of suspended sediment concentrations indicate the presence of a plume between Transects 3, just bay-ward of the dredge, and Transect 10, where the channel turns into the inner harbor area. Vertical cross-sectional profiles of suspended sediment concentration are presented in Figures 12 through 16.

Transects 1 and 2 generally resembled ambient conditions with the exception of a small plume signature (concentrations up to 100 mg/l) on the bottom at the western end of Transect 2. The plume signature expanded over the western half of the water column in Transects 3 (Figure 12) and 4, with concentrations primarily in the 100 to 150 mg/l range. An intense bottom plume pulse, about 80 m wide and confined below a depth of 8 m, was found on Transect 5 (Figure 13), which extended laterally from the dredge location. A diffuse plume across a broad extent of the channel bottom, with concentrations approaching 125 mg/l, was seen on Transect 6 (Figure 14). Diffuse plume signatures persisted on Transects 7 and 8 (Figure 15), rising into surface waters. Signs of plume decay were evident on Transects 9 and 10 (Figure 16), where concentrations remained in the 75 to 100 mg/l range. Concentrations continued to decay to ambient levels on Transects 11 and 12. Concentrations throughout the water column on

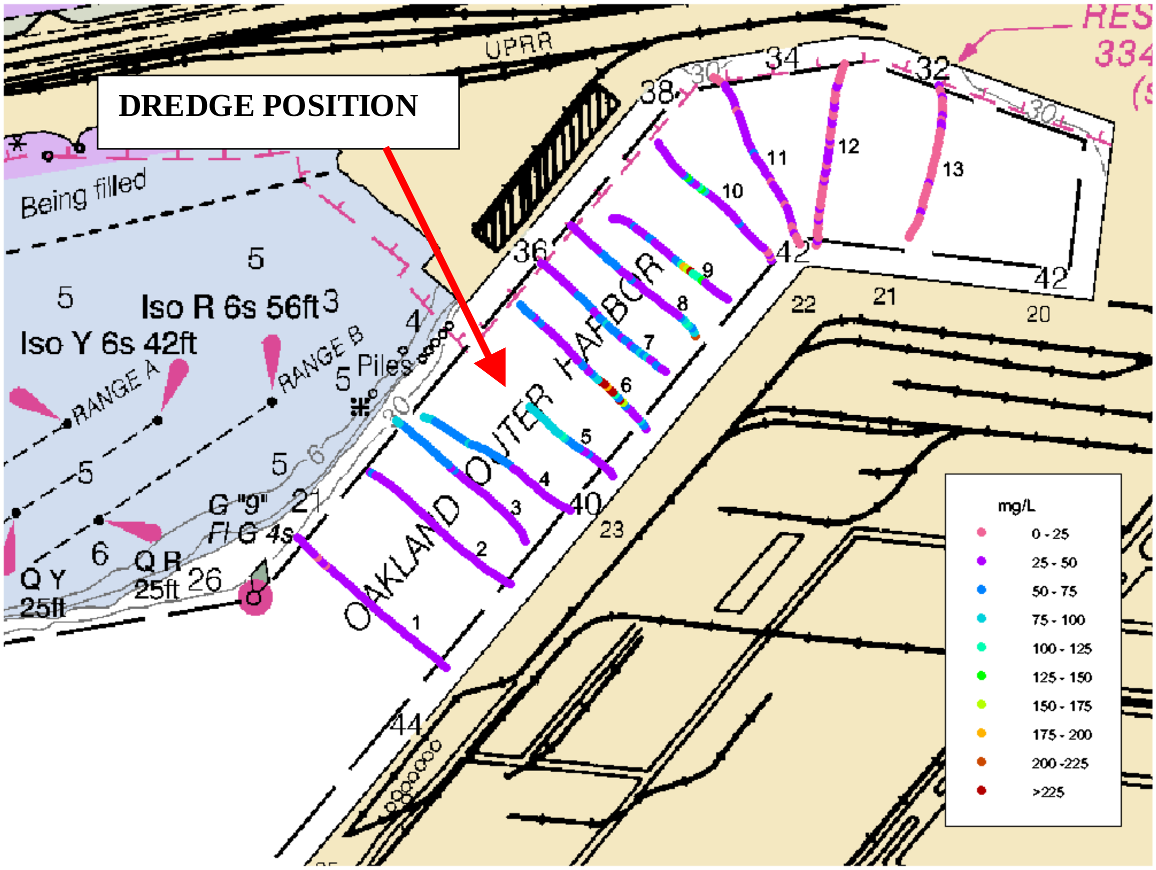

Figure 11. Locations of ADCP Survey ODFC transects during a flooding tide. The dredge was operating adjacent to Transect 5. Depth-averaged acoustic concentration estimates are indicated by color-coded dots.

Transect 13 were very low, generally below 25 mg/l. This is consistent with data for ebb survey ODEC, again indicating that currents were sufficiently weak to allow settlement of fine sediments.

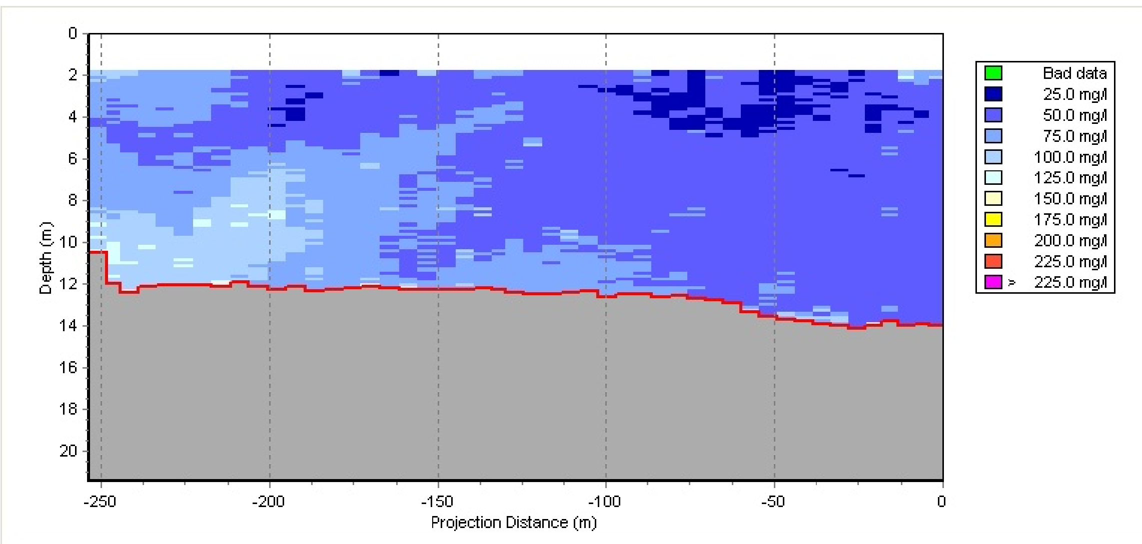

Figure 12. Vertical profile of TSS on Transect 3 during a flooding tide survey (ODFC).

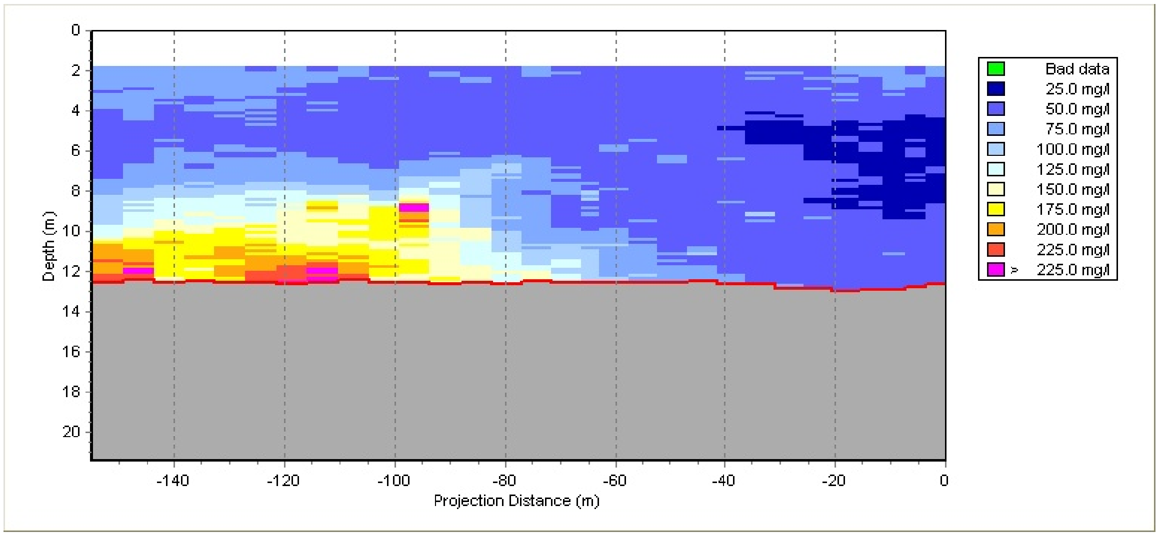

Figure 13. Vertical profile of TSS on Transect 5 during a flooding tide survey (ODFC).

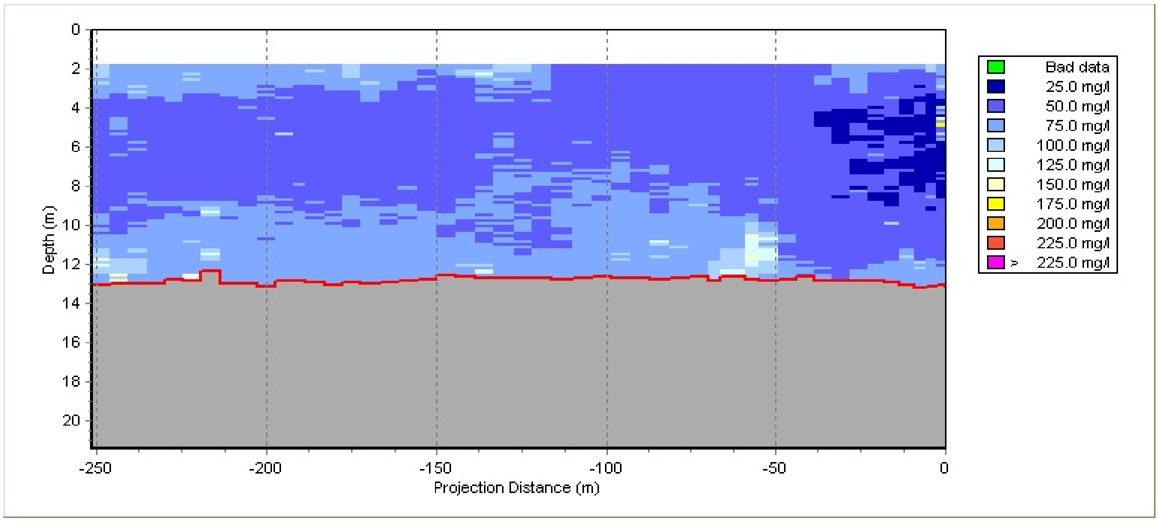

Figure 14. Vertical profile of TSS on Transect 6 during a flooding tide survey (ODFC).

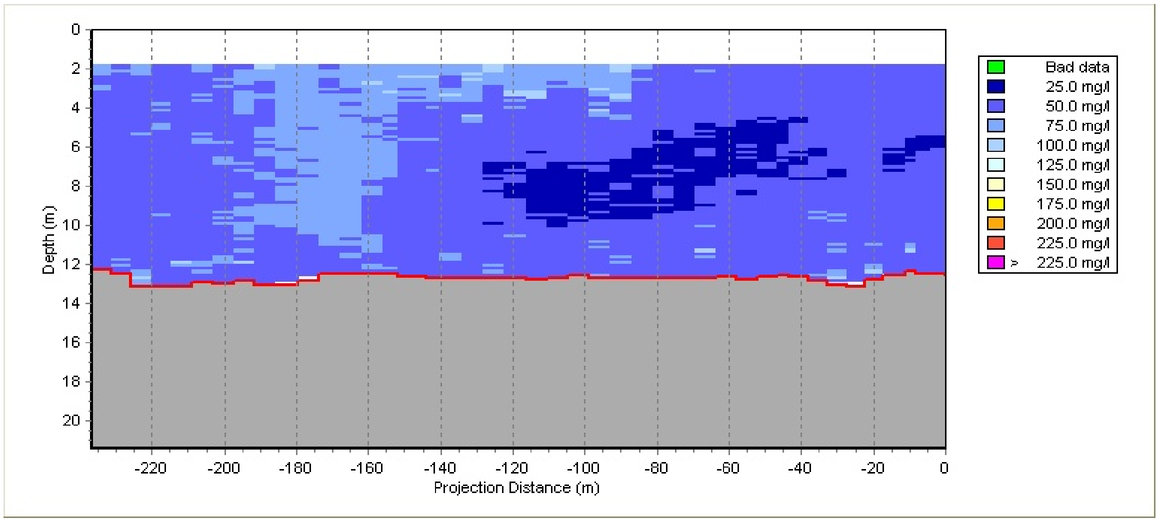

Figure 15. Vertical profile of TSS on Transect 8 during a flooding tide survey (ODFC).

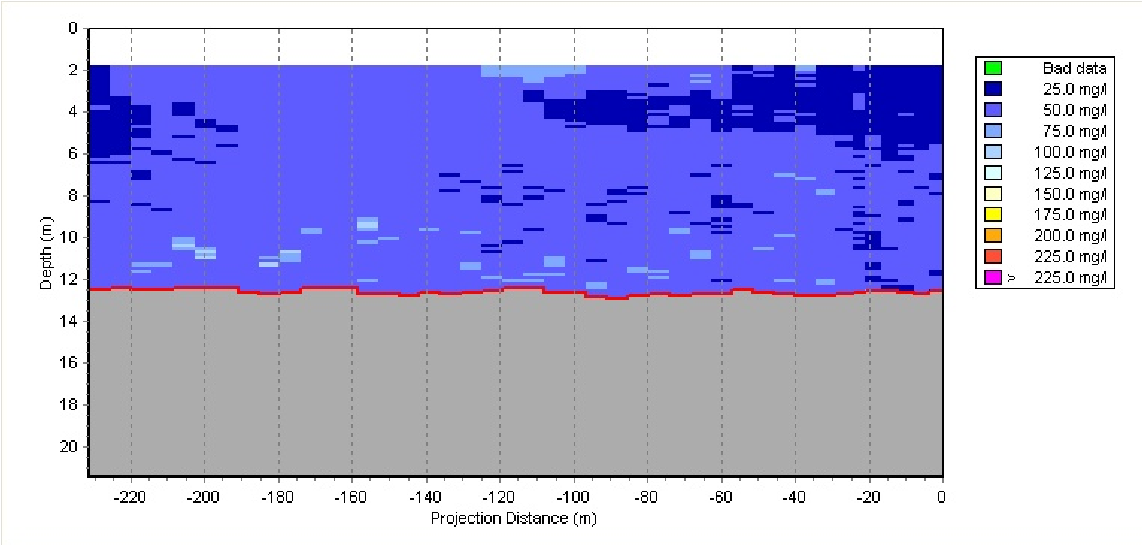

Figure 16. Vertical profile of TSS on Transect 10 during a flooding tide survey (ODFC).

An additional during-dredging ADCP survey (ODFD) was conducted during a flooding tide. A plan-view layout of transect locations is given in Figure 17. Representative vertical cross-sectional profiles of suspended sediment concentration are presented in Figures 18 through 24. Transect 1 resembled ambient conditions observed in the other surveys. A small bottom plume acoustic signature, with concentrations up to 150 mg/l, was present on Transect 2 (Figure 18). A broad bottom plume with concentrations in the 100 to 125 mg/l range was evident on Transect 3 (Figure 19). On Transect 4 a very intense gas bubble signature extended upward through the water column, and a separate, intense bottom plume with concentrations as high as 225 mg/l dispersed laterally (Figure 20). The surface gas bubble plume persisted on Transect 5, with the separated bottom plume now expanded in mid-depths and decaying to peak concentrations near 175 mg/l (Figure 21). Intense plume signatures dissipated on Transect 6, where remnants of a surface plume remained visible (Figure 22). On Transects 7 and 8 (Figure 23) diffuse areas of slightly elevated concentration extended across the bottom below a depth of 8 m. Indications of a surface plume, perhaps with some bubble components, were present. On Transects 9 through 13 a progression was seen in decay of concentrations and settlement of the diffuse plume lower in the water column (Figure 24 represents Transect 12). Generally low concentrations occurred on Transect 13, which was located near the harbor channel "dead end."

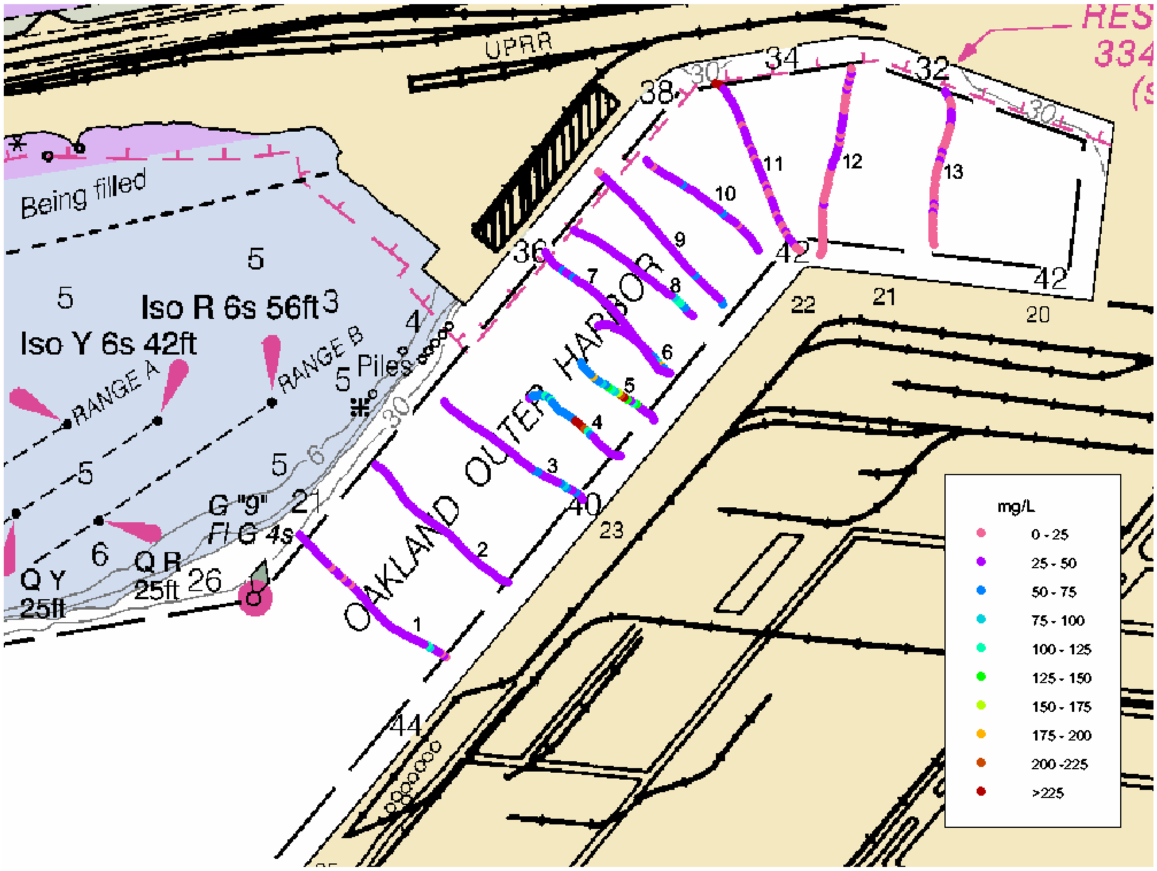

Figure 17. Locations of ADCP Survey ODFD transects during a flooding tide. The dredge was operating adjacent to Transects 4 and 5. Depth-averaged acoustic concentration estimates are indicated by color-coded dots.

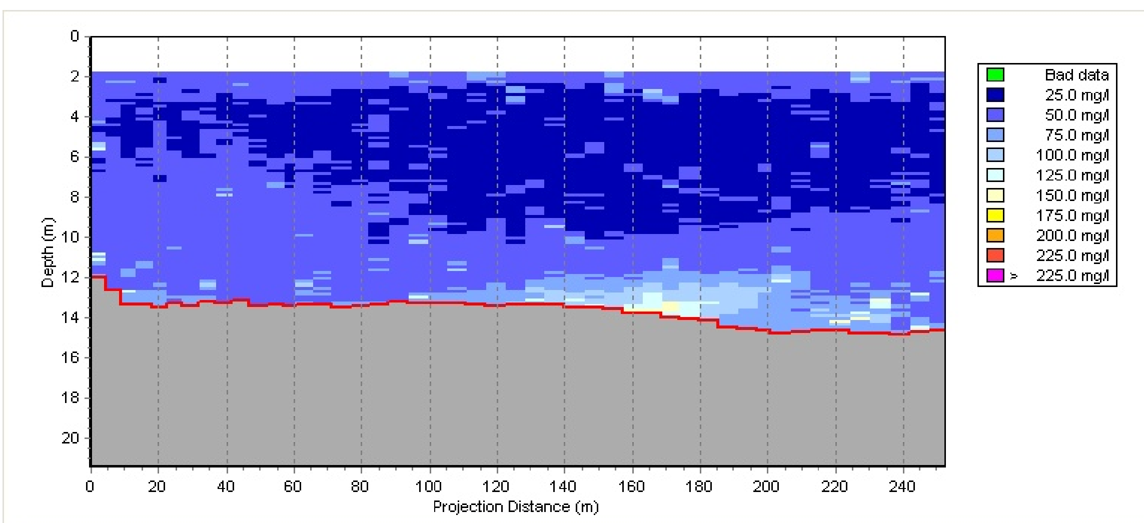

Figure 18. Vertical profile of TSS on Transect 2 during a flooding tide survey (ODFD) Harbor.

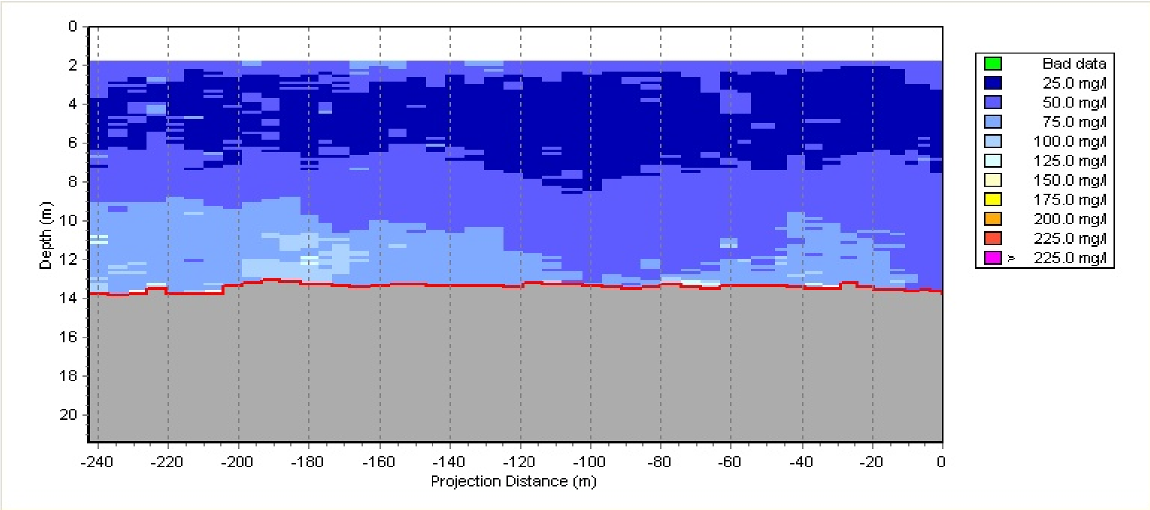

Figure 19. Vertical profile of TSS on Transect 3 during a flooding tide survey (ODFD).

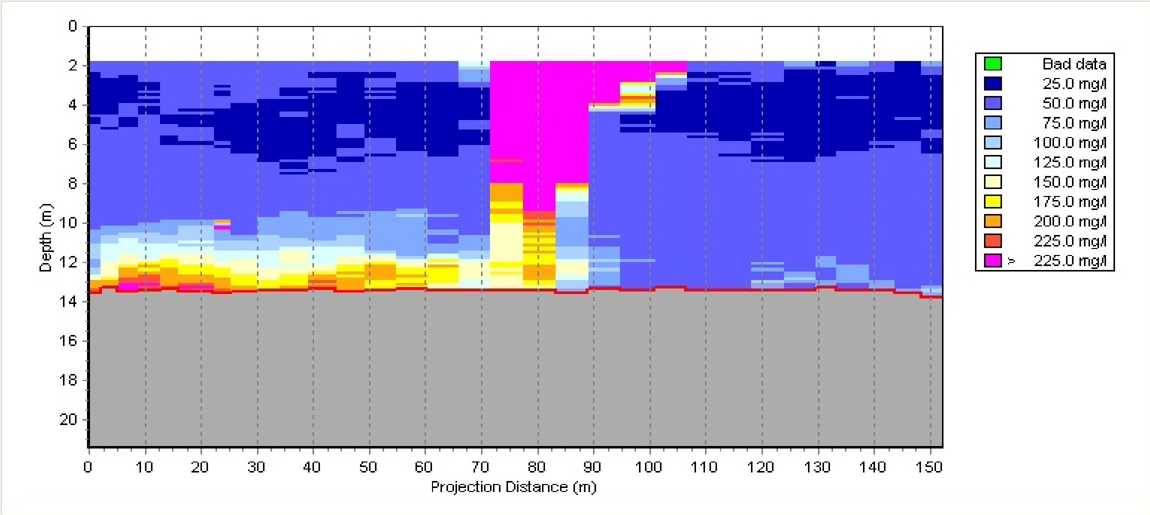

Figure 20. Vertical profile of TSS on Transect 4 during a flooding tide survey (ODFD).

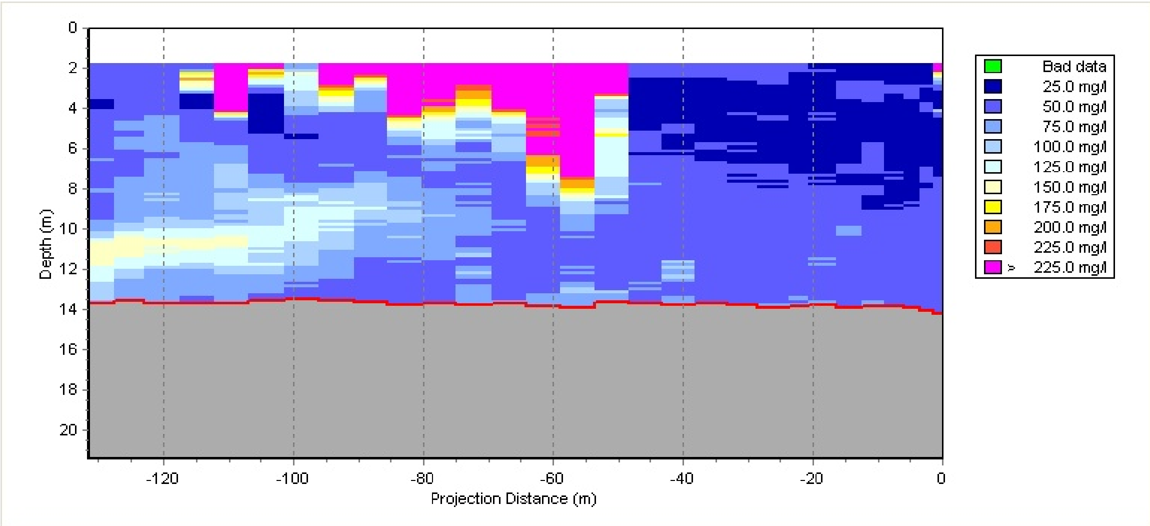

Figure 21. Vertical profile of TSS on Transect 5 during a flooding tide survey (ODFD).

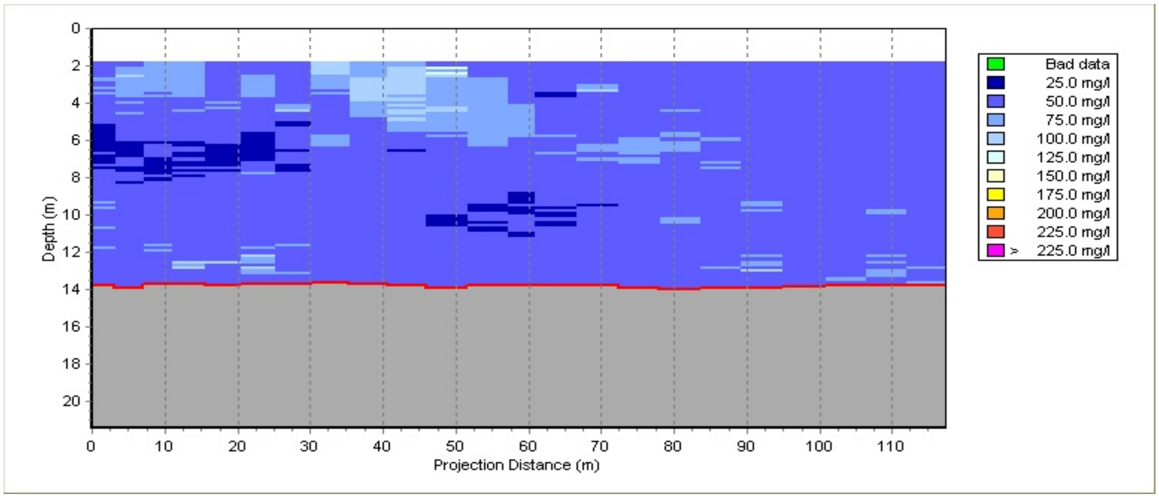

Figure 22. Vertical profile of TSS on Transect 6 during a flooding tide survey (ODFD).

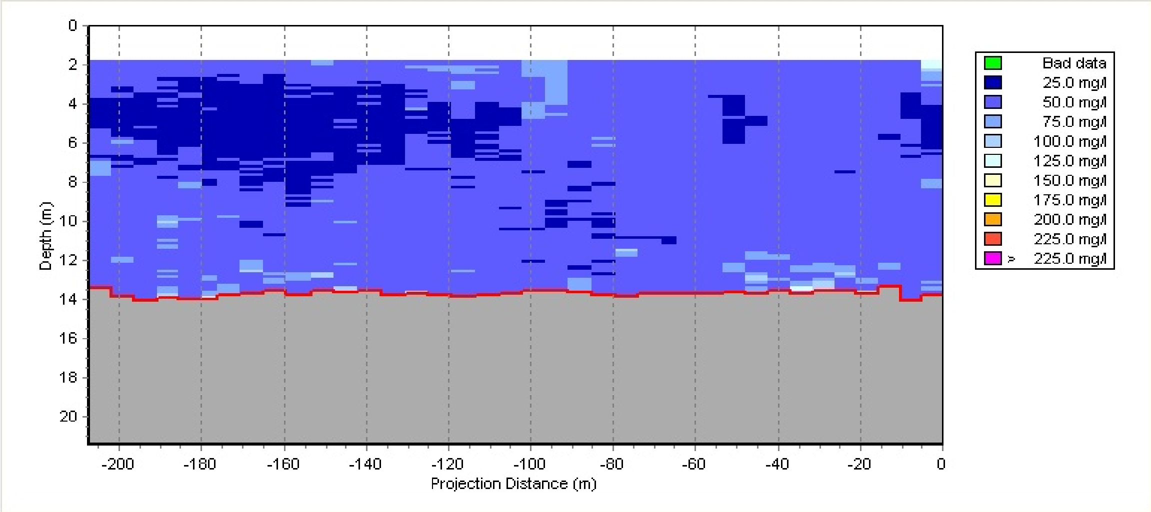

Figure 23. Vertical profile of TSS on Transect 8 during a flooding tide survey (ODFD).

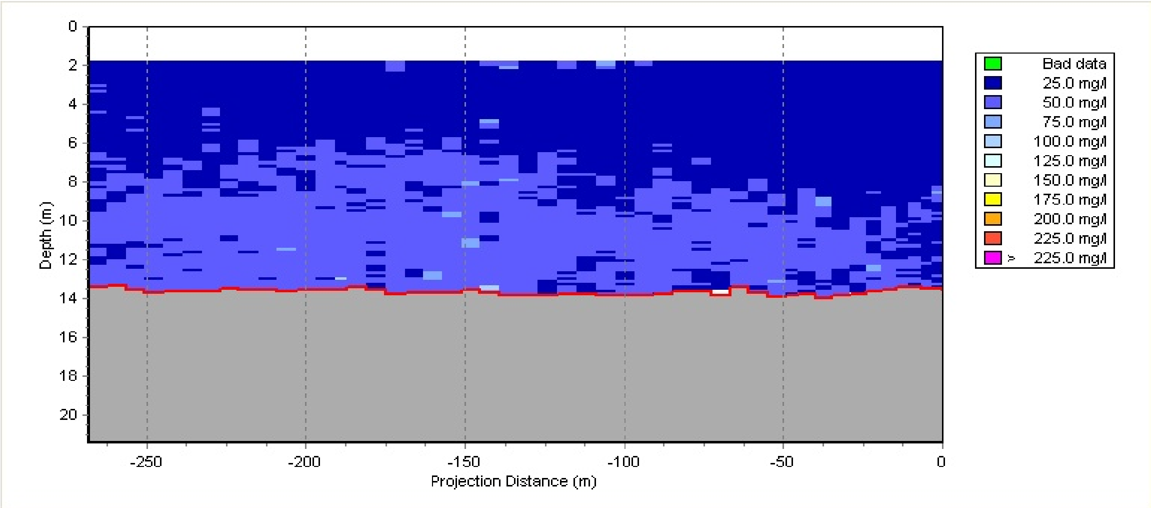

Figure 24. Vertical profile of TSS on Transect 12 during a flooding tide survey (ODFD).

CONCLUSIONS

ADCP surveys effectively characterized suspended sediment plume structure for bucket dredging operations in the Port of Oakland Outer Harbor navigation channel. Plumes were driven by relatively weak currents during both ebb and flood tidal stages. The fact that a closed bucket was used in this project clearly influenced the spatial and temporal dynamics of plumes in the study area. Few indications of surface components of plumes were detected, as the major loss of sediment via re-suspension appeared limited to the lower water column. Plumes were very heterogeneous, consisting of pulses of elevated concentration generated primarily by repetitive bucket impact with the substrate. Net flux of plume-borne sediments appeared to be toward the harbor rather than toward open bay waters, even during ebbing tides. The weak current flows, however, did not extend to the innermost portion of the harbor navigation channel. Suspended sediment concentrations, as observed in ambient and during-dredging surveys, were consistently lowest in the “dead end” area, where flows apparently allowed settlement of fine sediments.

Plumes generated by the dredge in this study were characterized by relatively narrow bands of elevated concentrations that decayed within short distances from the source. In both ebb and flood surveys, acoustic plume signatures were distinct above background concentrations for distances up to 400 m from the source. Plume trajectories were dynamic, extending laterally and both up- and down-current from the operation, as residual plume components from preceding cycles of the bucket persisted in the near-field surrounding the dredge. Concentrations exceeding 275 mg/l were measured only in immediate proximity to the source. Suspended sediment concentrations tended to decay fairly rapidly with increasing distance. In general, concentrations above 100 mg/l were distributed in small pockets that primarily flowed just above the bottom, but occasionally dispersed into mid-water depths.

It would be instructive to conduct comparative ADCP surveys at the study site to characterize plumes generated by a comparably sized conventional bucket. Given the lack of dispersion of plumes demonstrated in this study, some measure of performance in terms of plume reduction by deployment of the closed bucket could be achieved. Likewise, it should be noted that the results of this study are site-specific, i.e. plume dynamics would vary significantly elsewhere in the San Francisco Bay system based on hydrodynamics, geomorphology, and numerous other factors. These data, however, should provide insights into the types and magnitudes of risks to environmental resources posed by dredging at the Outer Oakland Harbor site, and how best to manage those risks.

Data derived from acoustic surveys of plumes provide a much more detailed “picture” of plume dynamics at a given project site than conventional approaches to water quality compliance monitoring. In fact, where questions related to protection of specific target resources (e.g., migratory fishes) are the primary focus of regulatory concern, it is difficult to envision how routine compliance monitoring can apply. Infrequent measurements of almost any water quality parameter at fixed points in the water column at locations presumed to fall within a highly dynamic plume offer few reliable insights into actual degrees of risk of exposure. Acoustic data can potentially remove a great deal of uncertainty from the assessment of probabilities of a target species encountering a plume and the relative degrees of exposure to high or low concentrations of suspended sediment. In the present study, for example, plumes tended to be entrained in bottom waters. This finding would support a conclusion that fishes transiting the study area in the upper water column or along the periphery of the waterway would experience a relatively low risk of exposure. In contrast, bottom-oriented fishes would be more likely to encounter the plume, at least intermittently. Combining accurate knowledge of plume dimensions with that for fish temporal and spatial distributions would insert higher levels of confidence into environmental assessments and promote consideration of reasonable management practices.

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