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

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INTRODUCTION

Background

Re-suspension of sediments during dredging projects, both at the dredging and dredged material disposal sites, has been a persistent concern of regulatory agencies charged with protection of environmental resources. Potential effects on fish, shellfish, and submerged aquatic vegetation are frequently cited as justifications for decisions to place restrictions (e.g., environmental windows, spatial buffer zones) on dredging projects or to require precautionary operational measures (e.g., silt curtains, modified equipment) (Wilber and Clarke 2001). However, restrictions and other precautionary measures can significantly inflate the cost of a dredging project, and the actual effectiveness or need for specific measures is often unknown. 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. The challenge of maintaining navigation infrastructure while providing adequate protection of key 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 dredging project coordination. In almost every case, however, reasonable decisions can be made if a 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. A major portion of the volume of sediment dredged on an annual basis is accomplished by mechanical (e.g., bucket) and hydraulic (e.g., cutterhead, hopper) dredges. Other less conventional equipment designs exist, but generally are used only where the project necessitates special handling of the sediments. The large range in production rates obtained with mechanical or hydraulic dredges is largely achieved through plants of various sizes, not by changes in design. Given the generic nature of the dredging process, efforts to characterize sediment re-suspension characteristics of various dredges have focused on these three main categories of dredge plant.

With respect to sediment re-suspension one common aspect of the maintenance dredging process has not been examined in detail. In most navigation channels sedimentation rates over time infill the entire channel basin on small or large spatial scales, or shoals may form periodically that create topographic "highs" or ridges. In the former case conventional dredging plants are routinely used to re-establish authorized navigable depth. In the latter case, however, a specific process called "knockdown", or "bed leveling" may be used. 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. Although high resolution positioning technologies have greatly improved the ability of dredgers to completely sweep a channel to specified depth, invariably some isolated peaks and ridges remain. Rather than attempt to remove all high spots by keeping expensive dredge plants on site, dredging contractors have developed gear to rapidly and efficiently remove peaks and ridges. 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 I-beams welded together or be configured with a leading edge that acts as a plough.

Although knockdown or bed leveling operations have been conducted frequently throughout the United States for several decades, the process has only recently been identified by regulatory agencies as deserving further attention. In the San Francisco Bay area, sediment plumes associated with knockdown were acknowledged as a knowledge gap by various agencies and stakeholders engaged in the Long-Term Management Strategy (LTMS) forum. The LTMS participants seek better management of dredging projects by supporting initiatives to address priority concerns with scientific investigations. The present study evolved from discussions within LTMS working groups and was supported by the San Francisco District of the U.S. Army Corps of Engineers (USACE).

In October of 2004 an opportunity to study sediment re-suspension during a knockdown operation arose in conjunction with a project at Redwood City, California. A joint effort by the U.S. Army Engineer Research and Development Center (ERDC) and Weston Solutions was coordinated with staff at the San Francisco District. The objectives of this study were to: 1) describe the knockdown operation to the extent that it represented the manner in which similar operations occurred in San Francisco Bay, and 2) characterize in detail the suspended sediment plumes created by the knockdown operation in terms of spatial extent, temporal variation, and total suspended solids (TSS) concentration gradient structure.

Project Location

The Port of Redwood City is located approximately 35 km (18 mi) south of San Francisco and is the only deepwater port in southern San Francisco Bay (Figure 1). The Port facilities handle liquid, dry and neo-bulk cargo for industries such as metal recycling, cement and gypsum import. The Port facilities accommodate both deep-draft shipping and tug and barge traffic. The entrance to the Port is via Redwood Creek.

The Redwood Creek navigation channel is approximately 6 km in length, extending in a general north-south direction from the San Francisco Bay to the Port facilities. The northern 4 km (2.5 mi) of the channel is 92 m (300 ft) wide and is maintained at a depth of 8.5 m (28 ft). The southernmost portion of Redwood Creek, adjacent to the Port facilities, has two turning basins, each approximately 325 m (1,066 ft) wide. The channel is bordered along most of its length by tidal flats. Mean tidal amplitude at the project site is 1.8 m (6.2 ft). Two sloughs intersect Redwood Creek: Corkscrew Slough from the west and Westpoint Slough from the east (Figure 2). Neither slough is maintained for navigation.

The area involved in knockdown operations was approximately 0.8 km long, located immediately north of the northern turning basin (Figure 1). Mounds, or high spots, up to 0.6 m (2 ft) above grade were scattered throughout this reach in an alignment roughly parallel with the axis of the navigation channel. An estimated 2,300 m^3 (3,000 cubic yards) of sediment were to be re-distributed by knockdown operations.

METHODS

General

Field activities were conducted at Redwood Creek between 24 and 28 October 2004. Knockdown dredging operations in Redwood Creek commenced on the morning of 26 October. The dredging contractor, Dutra Dredging Company, performed the knockdown operations using the tug T/V *Sharon Brusco* (Figure 3) in tandem with a barge mounted with a winch-lowered bar. The knockdown operations consisted of the tug pushing the barge with the bar lowered from the stern of the barge. The bar (Figure 4) consisted of two 30 ft long I-beams welded together such that the total dimensions of the bar were approximately 3 ft high x 2 ft wide x 30 ft long. The bar was suspended from two winch cables at opposite corners of the stern of the barge. Depth of the bar could then be adjusted as needed. Separate cables connected the ends of the bar to the respective forward corners of the barge, thereby holding the bar in optimal orientation perpendicular to the axis of forward movement and limiting the position of the bar while in contact with the bottom to a point directly below the stern.

The knockdown operations occurred on three consecutive days. On each day the bar was used to level sediment primary along the western or eastern toes of the channel side-slopes. Time series records of the barge's DGPS positions for each day (Figure 5) illustrate the footprint of channel bottom area involved in the project.

Plume monitoring operations were conducted from the 44 ft survey vessel R/V *Shearwater* (Figure 6), equipped with a stern-mounted A-frame for deployment of water quality instrumentation. A Trimble NT300D differential global positioning system (DGPS) aboard the survey vessel provided navigation and position data to an accuracy of ±1.0 m (3.2 ft). Vessel mobilization and gear testing occurred on 24 October and demobilization occurred when knockdown operations ceased on 28 October 2004. A Garmin GPS 76 placed on the T/V *Sharon Brusko* each day continuously recorded the tug's position accurate to 5 m (16 ft). These data were downloaded at the end of each day and used to determine the origin of the suspended sediment plume at selected times during all knockdown surveys.

Acoustic Doppler Current Profiler

Surveys were conducted with an RD Instruments 600kHz Workhorse Mariner Acoustic Doppler Current Profiler (ADCP) mounted amidships on the port side of the survey vessel (Figure 6). The ADCP transducer head was mounted 33 cm (13 in) below the water's surface. Data acquisition was performed by RD Instruments' WinRiver software running on a laptop computer. The ADCP was used to collect current velocity, direction, and acoustic backscatter data. Data were collected with a bin resolution of 0.5 m (1.6 ft) and a total of 35 vertical bins for all transects. The instrumentation package calculated and recorded vessel and current direction in three-directional axes to an accuracy of ±0.2 cm/sec. 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. An internal fluxgate compass allowed the instrument to correct ADCP current vectors for vessel speed and orientation. Navigation data received from the DGPS were collected synoptically and integrated during post-processing.

ADCP acoustic backscatter data were analyzed by the ERDC 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 field data set consisting of discrete water samples collected at known locations within the insonified portion of the water column and analyzed gravimetrically, as described below. Individual gravimetric samples can thereby be directly compared with acoustic estimates of TSS concentration for the same unit volume of water. The sample population represented the concentration gradient prevailing at the study site, and was used to "groundtruth" the acoustic data. An example of the acoustic methodologies for plume characterization can be found in Reine et al. (2002).

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. Survey transects were not pre-established due to the nature of knockdown operations. Because the knockdown process involved active towing of a bar across the bottom, the source of sediment re-suspension was not at a fixed point in space, but continuous along the path of the barge. This occurred primarily parallel to the long axis of the navigation channel. 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. As discussed below, prop-wash did not pose a major impediment to plume detection.

In this study plume detection was optimized using several survey designs. One survey design consisted of transects that were run in a "zigzag" fashion astern of the knockdown barge while maintaining a consistent distance from the stern of the barge (Figure 7). Zigzag transects were run at distances ranging from approximately 50 to 100 m behind the barge. Zigzag transect sampling was designed to measure the width of the plume at various distances behind the knockdown barge. Another transect design involved following directly behind or slightly to the side of the path of 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 (Figure 8). These transects were designed to measure variation in plume intensity at a consistent 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 (Figures 9 and 10) 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.

ADCP surveys were conducted to characterize ambient and during-knockdown conditions. 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, thoughout both flood and ebb tidal stages. Knockdown operations were completed in Redwood Creek on 28 October.

Turbidity

Arrays of optical turbidity sensors were deployed during each ADCP survey. The arrays consisted of D&A Instruments optical backscatter sensors (OBS-3A) placed on a moored buoy or suspended from the bow of the survey vessel at predetermined depths. Each sensor was set to log turbidity measurements every 15 seconds. All OBS data were measured in nephelometric turbidity units (NTU). An array of 5 equally spaced OBS units was placed near the center of the study area during ambient surveys on 25 October, with sensors placed at approximately 3 m (10 ft), 4.5 m (15 ft), 6 m (20 ft), 7.5 m (25 ft) and 9 m (30 ft) below the water surface. On that date additional arrays were deployed at opposite ends of the project channel reach with sensors at depths of approximately 3 m (10 ft), 6 m (20 ft), and 9 m (30 ft) to measure near-surface, mid-water, and near-bottom turbidities upstream and downstream during both flooding and ebbing tides. During knockdown operations on 26, 27 and 28 October moored buoys were placed at the southern and northern extents of the project in the morning and retrieved in the evening. No buoy was placed in the mid-reach to avoid creating an obstacle in the path of the knockdown barge. An additional array consisting of 5 OBS units was deployed from the bow of the survey vessel on 28 October, allowing data to be collected at points throughout the project boundaries.

Water Samples

For calibration of the raw ADCP acoustic backscatter data conversion to TSS concentrations a total of 150 water samples was collected, using a General Oceanics 12-bottle vertical rosette water sampler. To optimize calibration procedures the water sampler was modified such that samples could be collected in a horizontal orientation (Figure 11). Six Niskin water bottles were used in this configuration. Each bottle had a capacity of 8 liters. An OBS-3A unit, identical to those used for the turbidity surveys, was mounted on the water sampler. The OBS unit continuously recorded measurements of depth, temperature, conductivity and turbidity. This OBS unit was connected via cable to a laptop computer aboard the survey vessel, thereby providing real time NTU measurements during the water sampling. The sampler was manually triggered to close dependent on the observed backscatter signal from the ADCP and turbidity measurements from the OBS unit. All water samples were transferred to the Weston Solutions laboratory in Carlsbad, California for processing. 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. This sample was processed according to procedures established by Plumb (1981).

Of the 150 water samples taken, 48 were collected during an ebbing tide on 25 October during ambient conditions prior to the arrival of the knockdown barge. The remaining 102 samples were collected during active knockdown operations, of which 48 were collected on 27 October 2004 during an ebbing tide and 54 were collected on 28 October during a flooding tide. Samples were taken during knockdown operations by lowering the water sampler to a specified depth and waiting for the knockdown barge to pass the survey vessel position. The survey vessel then moved into position as closely as safely possible directly behind the barge after it passed. The water sampler was then triggered 6 times over an approximately 2 minute period of time. The OBS NTU reading and ADCP ensemble number were recorded at the instant of trigger for each individual water sample.

RESULTS

Water Currents

ADCP data provided characterizations of prevailing water circulation in Redwood Creek during all surveys. During the study period no evidence was seen of strong density stratification in the water column or the occurrence of stratified flows. Examples of typical ebb tidal flows are given in Figures 12 and 13, which depict depth-averaged flow direction and velocity vectors in plan view and a vertical profile across the same transect respectively. Velocities were generally less than 0.45 m/sec throughout the water column. Similar results were observed for flood tidal flows.

Turbidity

Optical measures of turbidity are influenced by properties of the sediments in suspension, therefore direct comparisons of turbidity and TSS concentration cannot be made without synoptic samples obtained from the same sampled water volume. Collection of an adequate calibration data set in this study supported such comparisons. As depicted in Figure 14, the relationship between NTU and mg/L values displayed a substantial degree of scatter ($R^2 = 0.7078$). Much of the scatter can be attributed to the highly variable conditions within the plume where the higher NTU and mg/L values were obtained. Plumes, particularly near the source of re-suspension, are very heterogeneous with large changes in concentration occurring on very small spatial scales. This variation can also be seen in Figure 15, which plots the NTU - mg/L data pairs in order of sample collection. The initial series of samples, taken outside of the plumes, yielded relatively consistent values, whereas later samples taken within the plumes showed much greater variability. The distance between the OBS unit and the water sample bottle at the instant of triggering, less than 0.5 m, alone can account for considerable variation. However, 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.

Ambient Turbidity

Ambient turbidities can be assessed from several of the collected data records. Moored OBS units (Figure 16) deployed on October 25, prior to the arrival of the knockdown barge, provided time series measurements as an ebbing tide progressed (Figures 17 and 18). Turbidities were consistently in the 8 to 22 NTU range. This range was also observed for OBS data collected in tandem with the water samples outside of the influence of plumes. An interesting trend was apparent in the northernmost (Figure 16) moored OBS data as early in the record, during tidal transition from high-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. This pattern was not seen in the mid-reach moored OBS data (Figure 17) (or for the southern moored OBS data, not graphed) for the same time period. At this station turbidities tended to slowly decline from approximately 22 NTU at slack water during high tide to 5 to 10 NTU as the tide approached slack low. The lowermost OBS unit, at a depth of 9.2 m, recorded periods of generally higher turbidity in the latter stages of the ebbing tide, but these spikes may be caused by the sensor coming in contact with the substrate. One logical explanation for the comparatively higher turbidities observed at the northernmost station is linked to its position in proximity to the two sloughs that intersect Redwood Creek. On an ebbing tide an incursion of silt and/or detritus laden waters from the sloughs draining adjacent wetlands enters Redwood Creek at points on opposite shorelines near the moored buoy. Ebbing flows in Redwood Creek proper then carry the turbid water toward San Francisco Bay. The overall pattern and range of ambient turbidities in Redwood Creek were generally consistent with expected values for waterways characterized by unconsolidated sediments and bounded by tidal flats where moderate tidal flows prevail. Additional insights on ambient conditions can be obtained from examination of data collected during knockdown operations as described below. In brief, ambient turbidities appeared to range substantially higher than the 22 NTU level during certain stages of the tide at various locations in Redwood Creek. Precipitation during the last day of the study also seemed to elevate overall turbidities, possibly by causing greater drainage through the sloughs emptying into the waterway and increasing suspended sediment concentrations typically associated with stormwater runoff.

During-Knockdown Turbidity at Moored Buoys

Knockdown operations began on the morning of 26 October. The original tug assigned to the project by Dutra Dredging Company shut down due to mechanical problems at 0915 hrs, less than one hour after commencing knockdown operations. After several attempts to repair the tug the T/V *Sharon Brusko* arrived and resumed knockdown operations at 1155 hours.

From the time series data recorded at the northern moored buoy on 26 October (location shown in Figure 19), a pattern of relatively high but decreasing turbidities during the later stages of the flooding tide in the morning hours was 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 in late afternoon (Figure 20). High turbidities at the northern 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. The resumption of knockdown operations at 1200 hrs should have allowed suspended sediments to be carried by ebbing currents toward the northern buoy. Following slack tide turbidities at the northern buoy did increase to 35 to 45 NTU before declining once again as the tide returned to slack water. 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.

The time series record at the South Buoy (Figure 21) on 26 October was very different than that at the North Buoy. At the South 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 tracks in Figure 19 indicate that the operation passed very close to the buoy, this occurred during turns when the bar may have been raised off the bottom. The spike in turbidity at the end of the data record for the deep sensor occurred when the OBS unit came in contact with the bottom (confirmed by the instrument's depth data) at extreme low tide.

The North and South Buoys were redeployed on 27 October (Figure 22). The North Buoy data recorded during the flooding tide during morning hours were very 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 (Figure 23). 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 North 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 North 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 North 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 (as seen in Figure 24) revealed a periodicity in the peaks of high turbidity that suggested a knockdown plume origin. 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 North Buoy continued into the slack-water phase of low tide. Most of the peak values seen in the deep sensor record after 1645 hours are likely due to bottom contacts. At the South 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 (Figure 25). 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 South Buoy against the western side slope in the turning basin may not have been sufficiently close to the operation to be exposed to plumes. Again, the spike in the bottom sensor record at extreme low tide represents the sensor coming in contact with the substrate.

A third deployment during knockdown operations occurred on 28 October (Figure 26). On this date the barge was working primarily along the eastern bank. The data recorded at the North 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 began to increase later in the ebb tide (Figure 27). 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 South Buoy (Figure 28) 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 (Figures 29 to 32). 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 plume was repeatedly bracketed in zigzag fashion as the survey vessel maintained a consistent distance behind the barge. The turbidities depicted in Figures 29 and 30 indicate that the plumes on 27 October during an ebbing tide were relatively homogeneous with ranges of turbidities between surface and bottom sensors generally less than 20 NTU. 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.

Clear plume signatures are evident in the mobile survey data collected during a flooding tide on 28 October (Figures 31 and 32). 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.

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 degree of confidence that can be placed in the estimates of concentration is proportional to the strength of the calibration data set. 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 a very good calibration. In Figure 33 the entire population of gravimetric measurements derived from water samples and acoustic estimates derived from ADCP backscatter are arranged in rank order. The graph shows a relatively close relationship between the two measures throughout the 10 to 600 mg/L TSS concentration range. When plotted with respect to paired samples (i.e. gravimetric and acoustic measures collected synoptically), some variation was seen for individual pairs. This variation was most evident for samples representing high gravimetric concentrations within the plumes (Figure 34). This was due to the logistical limitation of sampling gear operating in a plume in which concentrations change rapidly on very small spatial scales. The acoustic data were very adequate representations of TSS concentrations for the purposes of plume characterizations in this study.

Acoustic Estimates of TSS

Ambient Conditions

In waterways where ambient TSS conditions change substantially within and between tidal cycles, a full understanding of those ambient conditions is critical to support characterizations of input from anthropogenic sources such as dredging or knockdown. Redwood Creek is typical of a small peripheral tributary to a large estuarine system. On 25 October ADCP surveys were conducted prior to the arrival of the knockdown tug and barge. Figure 35 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 would be consistent with input of suspended material from the sloughs, entering the waterway along the shallow banks and carried toward San Francisco Bay. A typical transect during a flooding tide on 25 October produced a distinctly different pattern (Figure 36). 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. In Figure 37, TSS concentrations were relatively high throughout the water column while ambient water samples were being collected from the drifting survey vessel on an ebbing tide. This contrasts with the water column ADCP record taken during water sample collection within and adjacent to a plume (Figure 38) on a flooding tide. Here the plume signature at 50 to 200 m along the transect was similar to background concentrations as observed in Figure 36, illustrating the difficulty in differentiating between plume and ambient conditions. In Figure 39, the plume signature was distinct against low background TSS concentrations that occurred on an ebb tide, but similar conditions were not the general case in Redwood Creek.

Knockdown Plumes, Parallel Surveys

In parallel surveys, the survey vessel followed the knockdown barge while maintaining an approximately uniform distance between the ADCP transducer and the bar. For example, the backscatter record shown in Figure 40 represents an ebb tide survey in which the barge's relative position was held at a distance of 60 m in front of the ADCP. The tug's prop-wash was easily identified as the intense signal in the upper 3 to 4 m of the water column as the barge advanced a distance of approximately 1,000 m. Below the prop-wash distinct plume signatures can be discerned as the bar impacted small high spots in the bottom at 375 m and 825 m along the transect. Concentrations in the 175 to 225 mg/L range were associated with those plumes and were largely confined to the bottom 2 m of the water column. The record indicated that re-suspension of bottom sediments was not uniform along the entire transect, but present in pulses as the bar "digs in" on the high spots. Toward the end of the transect the barge was pushed closer to the side slope of the channel, as noted by the rising bottom trace at the right of Figure 40.

In the ebb tide survey depicted in Figure 41, 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 example of an ebb tide parallel survey is given in Figure 42, which shows 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.

A separate survey conducted at slack water following an ebb tide (Figure 43), 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.

A series of parallel surveys were also conducted during flooding tides (Figures 44 through 46). In each survey the pulsed structure of the knockdown plumes was evident. Distinct plume signatures are shown in Figure 44, when the survey vessel followed the barge at a distance of 55 m. The signatures are less prominent in Figure 45, when the distance to the barge increased to 80 m, but remained detectable in Figure 46, when the distance increased to 130 m.

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 47 to 50), 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, 90, and 75 m behind the barge respectively. Due to the generally low background suspended sediment conditions during the first 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. In Figure 50, however, intense surface to bottom signatures were seen at 75 m on all passes through the plume. In this survey it appeared that the tug was applying considerably more power than in other surveys, possibly 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 produced the merged prop-wash/plume signatures.

A similar series of zigzag surveys was conducted on flooding tides (Figures 51 through 53). 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 51) 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 52), 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 (Figure 53), 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.

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 look at 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 continuous 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 the transect. 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 are presented to describe knockdown plumes. 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 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 a figure to the next.

Series No. 1 consisted of nine transects (Figures 54 to 62). The initial three transects were occupied as the barge approached. Some indication of residual plumes were seen over the bottom against the channel side slope. The short prop-wash signals in Figures 54 and 55 were caused by the survey vessel and not the tug. In Figure 57 the barge has passed through the transect, creating a very intense prop-wash signal. 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 is seen. Because this transect represents the onset of "new" plume measurements, it was designated as plume at time zero. The next transect (Figure 58), occupied as the barge had progressed 225 m away after an elapsed time of 3 minutes, was 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 (Figure 59), 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 (Figure 60), 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 again as shown in the 9 minute old plume (Figure 61), then expanded once more in the 13 minute old plume (Figure 62). 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. Passage over the transect initiated a second series of plume measurements, with time zero represented by Figure 63. 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 (Figure 64). After 5 minutes of elapsed time, the plume had retained its overall dimensions, but showed further TSS decay near the bottom (Figure 65). After 7 minutes the tug prop-wash signals had almost entirely dissipated (survey vessel prop-wash noted in the upper left of Figure 66), and the plume continued to "hug" the bank, extending outward approximately 40 m. The ensuing three transects (Figures 67 to 69), showed progressive decay of the plume through 9, 11, and 14 minutes of elapsed time. In the final transect of the series (Figure 69) the survey vessel has created a strong prop-wash signal as it turned against the bank. 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. This third series began with a similar time zero prop-wash and plume signature as the preceding series (Figure 70). At time zero some residual plume can be seen in the upper water column 50 to 80 m from the bank. A relatively intense knockdown plume is seen in Figure 71, after 1 minute had elapsed, which is further amplified at 4 minutes, as seen in Figure 72. A plume over 60 m wide had been created at that point in time. However, the ensuing transects (Figures 73, 74, and 75) reveal 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 the fourth series of perpendicular transects generally stronger plume signatures were seen in the time zero and 3 minute transects (Figures 76 and 77 respectively). The very strong tug prop-wash signals indicate that the operator was applying lots of power in pushing the barge forward. The bottom plume at 3 minutes contains 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 (Figure 78). At 8 minutes (Figure 79), the plume has decayed to concentrations less than 125 mg/L and broadened to a 70 m wide feature throughout the water column.

A fifth series of perpendicular transects (Figures 80 to 83) included very strong, initially 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 (Figures 82 and 83), 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.

The sixth series of perpendicular transects (Figures 84 to 90) included very strong initial prop-wash signals at time zero and 2 minutes. Note however that the X-axis distance scale is slightly shorter than for other transects, somewhat “stretching” the images. The intense acoustic signature at 2 minutes elapsed time dissipated significantly by 5 minutes (Figure 86). 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 87), 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 88) were created by the survey vessel. An indication of a residual plume was seen at 13 minutes following an almost complete loss of a plume signature in the 11 minute transect. 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 (Figures 91 to 95) 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 (Figure 93). 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 (Figure 95), 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.

DISCUSSION

The Redwood City study represented the first extensive monitoring of suspended sediment plumes created during knockdown operations. Monitoring efforts that included optical measures of turbidity as well as acoustic and gravimetric estimates of TSS concentration were designed to produce a detailed characterization of knockdown plumes. The essence of a knockdown operation in terms of sediment re-suspension, is very different than conventional dredging methods for managing navigable depth in a waterway. Whereas dredging involves the removal of sediment from the local system, knockdown merely relocates sediment within the local system.

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 larger particles and also settle relatively quickly. In the case of unconsolidated fine sediments, however, particles can remain in suspension for long periods of time even in minimal current flows. Knockdown is generally considered as an 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. This is the reason why knockdown, or bed leveling, is often performed following dredging projects to remove peaks and ridges left by conventional dredging methods. Consequently, knockdown will seldom be 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 in Redwood Creek 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 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 the same 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 as close as possible 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 expanded to features 20 to 25 m wide, or approximately twice the width of the bar. As the plume aged in terms of elapsed time the records showed large variations in widths of plume signatures. Plume expansion and contraction likely reflected the bottom contact pulse. 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 water samples collected directly within the plumes and analyzed gravimetrically, concentrations reached at least 600 mg/L. Comparable concentrations were also seen acoustically, 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.

Interpretation of the results of the present study should also consider the temporal and spatial scales of sediment re-suspension induced by knockdown operations in relation to ambient conditions in Redwood Creek. In sections of the waterway south of the sloughs ambient turbidities and TSS concentrations generally ranged between 10 to 20 NTU and 30 to 45 mg/L respectively. Elsewhere in Redwood Creek tidal currents circulate waters of substantially higher turbidities and TSS concentrations. For example, turbidities near the outlet of Corkscrew Slough on 28 October (Figure 29), following a period of precipitation, approached 40 to 65 NTU as the tide ebbed and 100 to 120 NTU as the tide flooded. These turbidities were comparable to TSS concentrations as high as 420 mg/L.

As revealed by surveys of ambient conditions during this study, fish and shellfish in Redwood Creek would encounter periods of relatively high turbidity and TSS concentration regardless of the occurrence of knockdown operations. During knockdown operations, in portions of the waterway, organisms undoubtedly could be exposed to significantly higher 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 the bar passes along a single bank on a given day and alternated banks on successive days, therefore the plumes would did 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 do 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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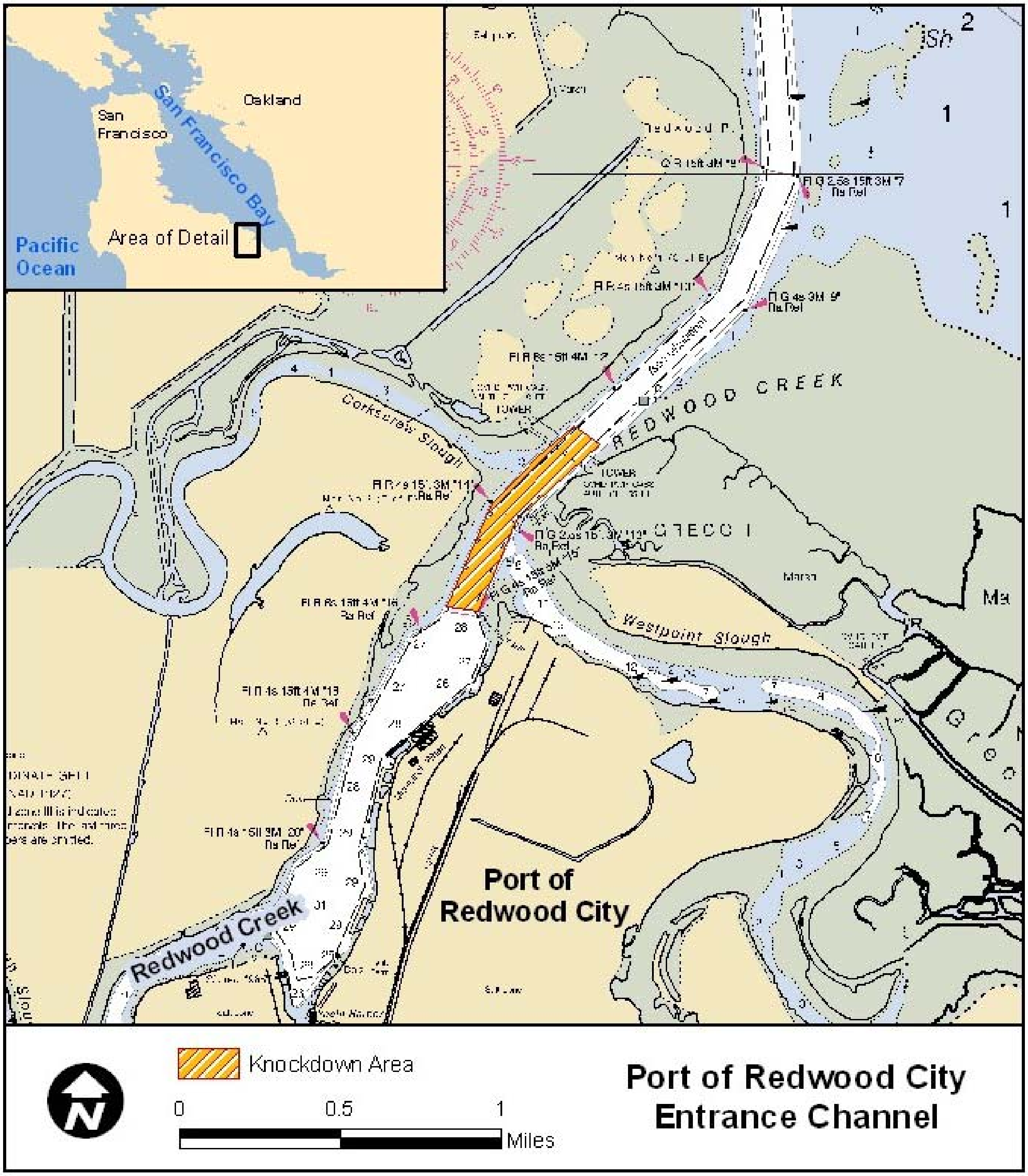

Figure 1. Study location in relation to San Francisco Bay (inset), and detail of Redwood creek navigation channel leading into the Port of Redwood City facilities, where the navigation channel expands into turning basins and berthing areas.

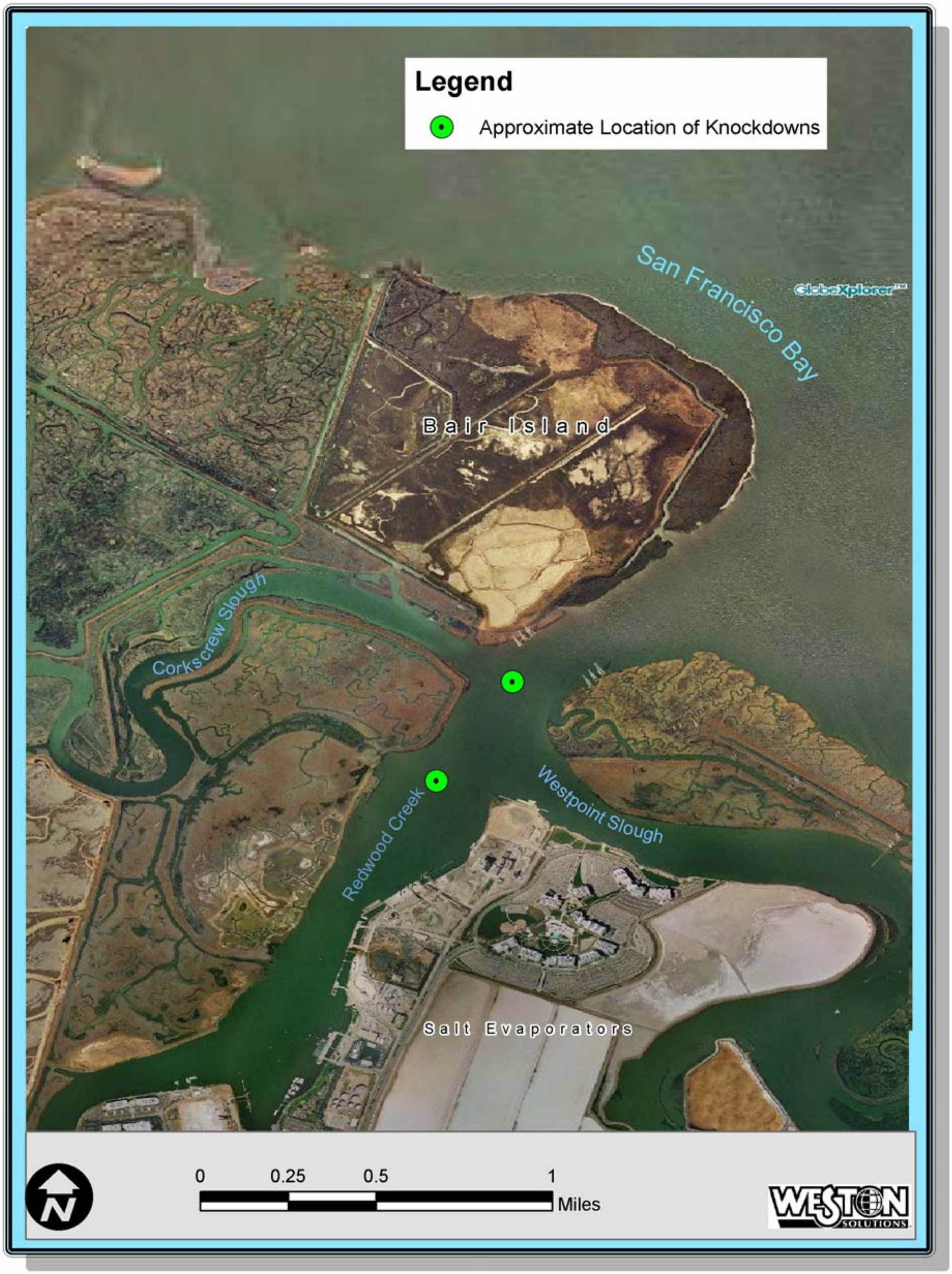

Figure 2. Aerial view of the study location showing the reach of Redwood Creek subject to knockdown and the points of confluence with Corkscrew Slough to the west and Westpoint Slough to the east.

Figure 3. The Dutra Dredging Company T/V *Sharon Brusko* pushing the knockdown barge in Redwood Creek.

Figure 4. The knockdown bar suspended from the barge at the water surface.

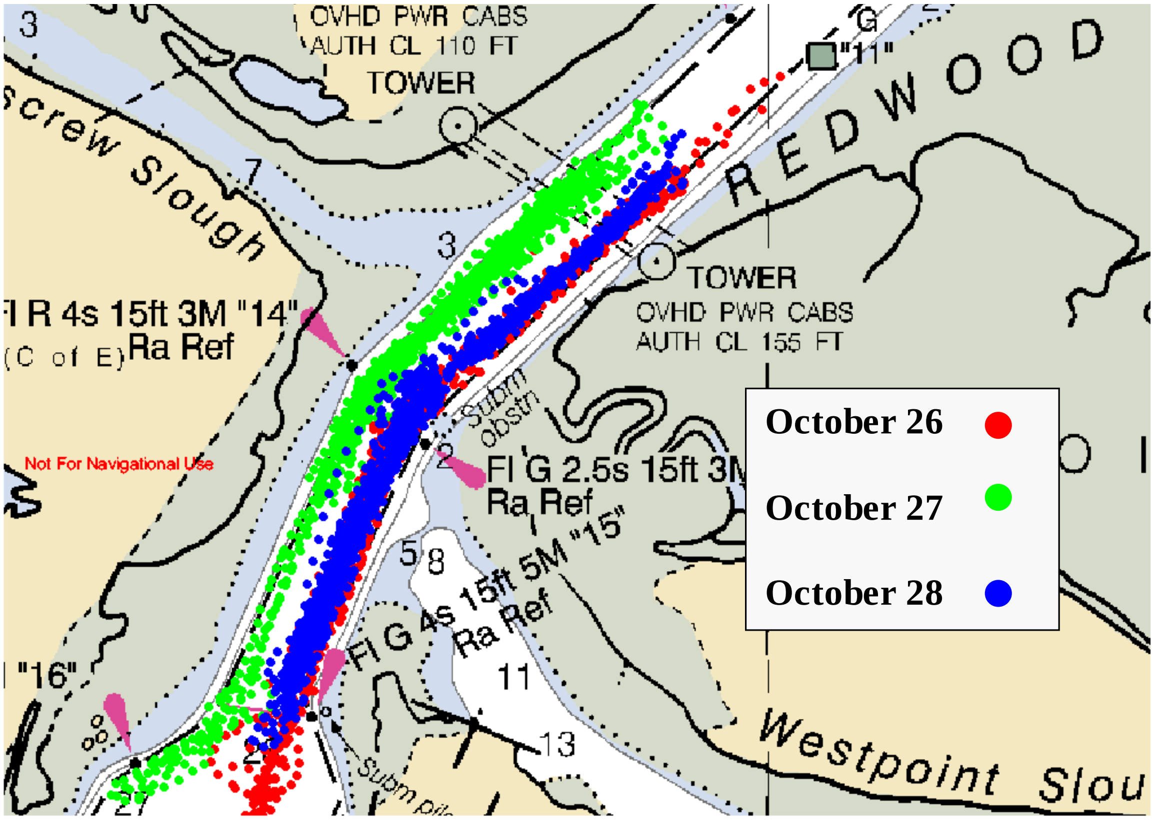

Figure 5. Time series record of DGPS positions of the knockdown barge on consecutive days.

Figure 6. Survey vessel R/V Shearwater, showing ADCP-integrated DGPS mounted on the port side with transducer assembly riding just below the surface of the water.

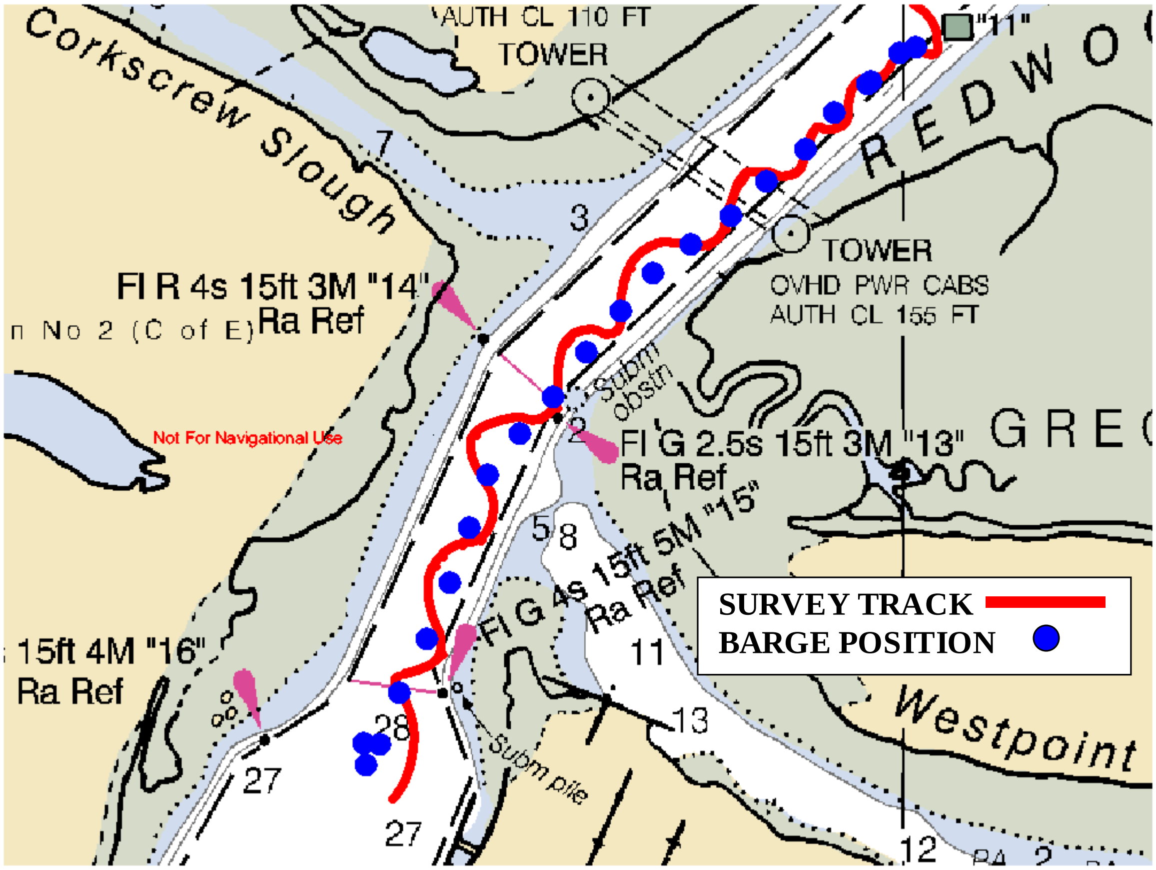

Figure 7. An example of track lines from a zigzag ADCP survey showing the path of the survey vessel crossing behind the barge as it progressed northward along the waterway.

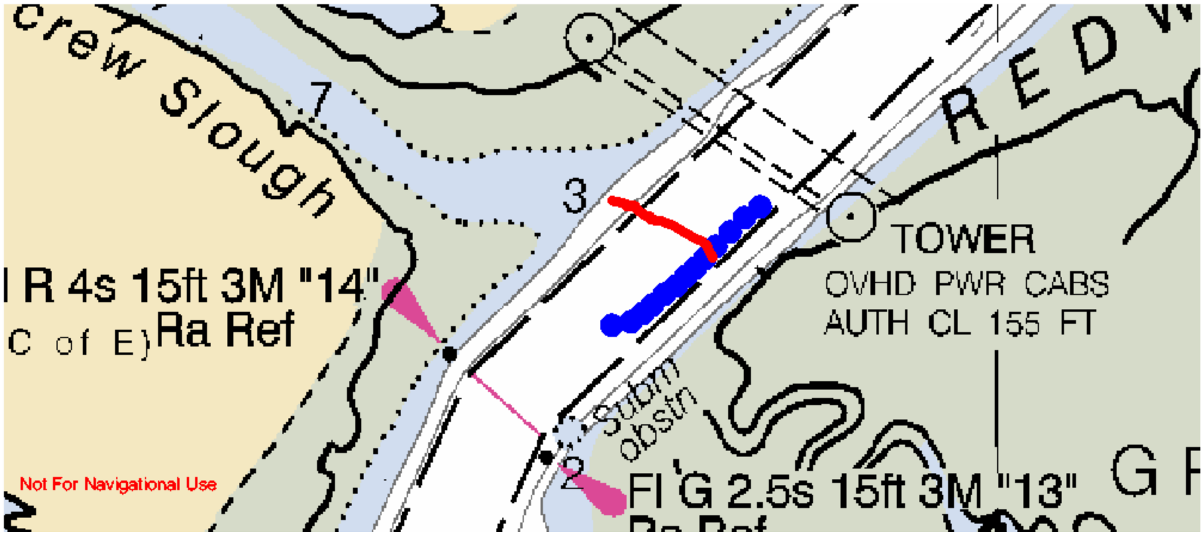

Figure 8. An example of track lines for a transect perpendicular to the path of the barge. The same transect was re-run as the barge progressed at increasing distances from the transect location.

Figure 9. Running a parallel ADCP transect directly behind the knockdown barge.

Figure 10. Running a perpendicular ADCP transect behind the stern of the tug pushing the knockdown barge.

Figure 11. Modified rosette water sampler with OBS unit attached (indicated by arrow).

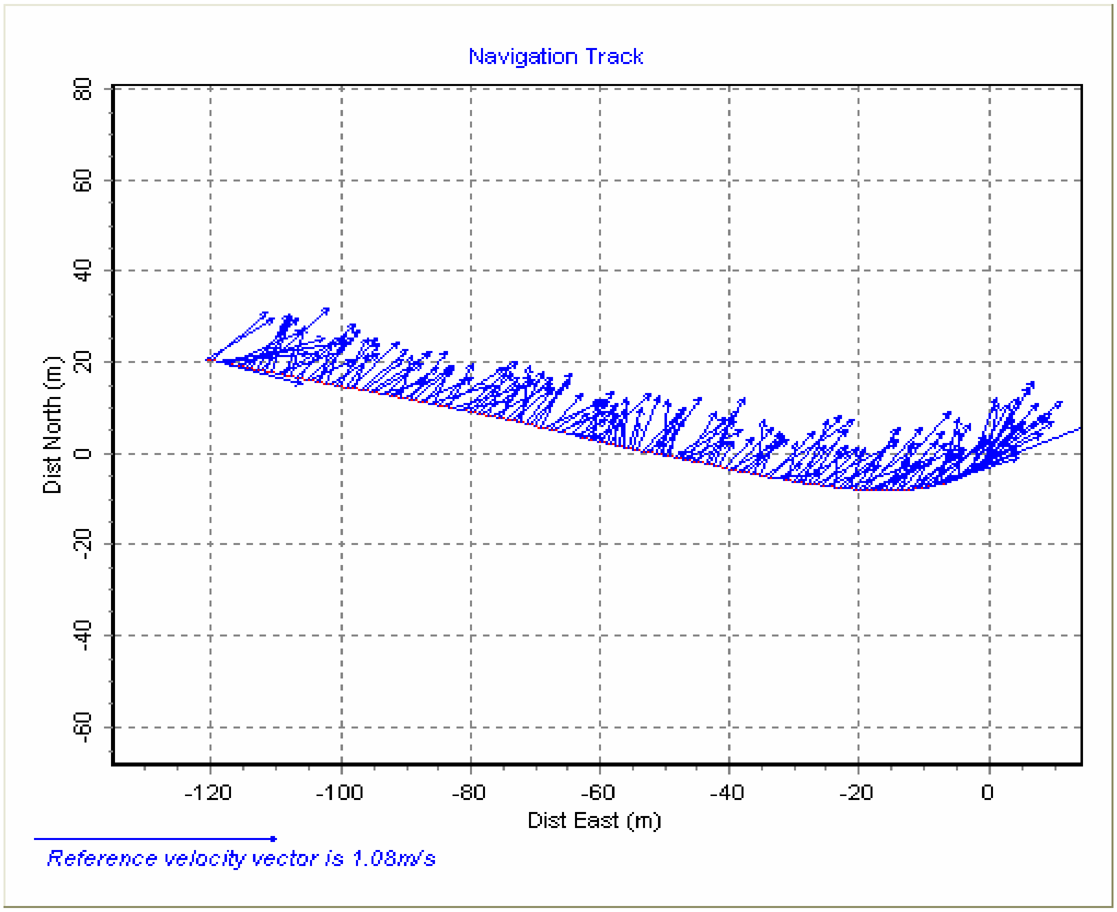

Figure 12. Current velocity and direction vectors for a transect across Redwood Creek during an ebbing tide.

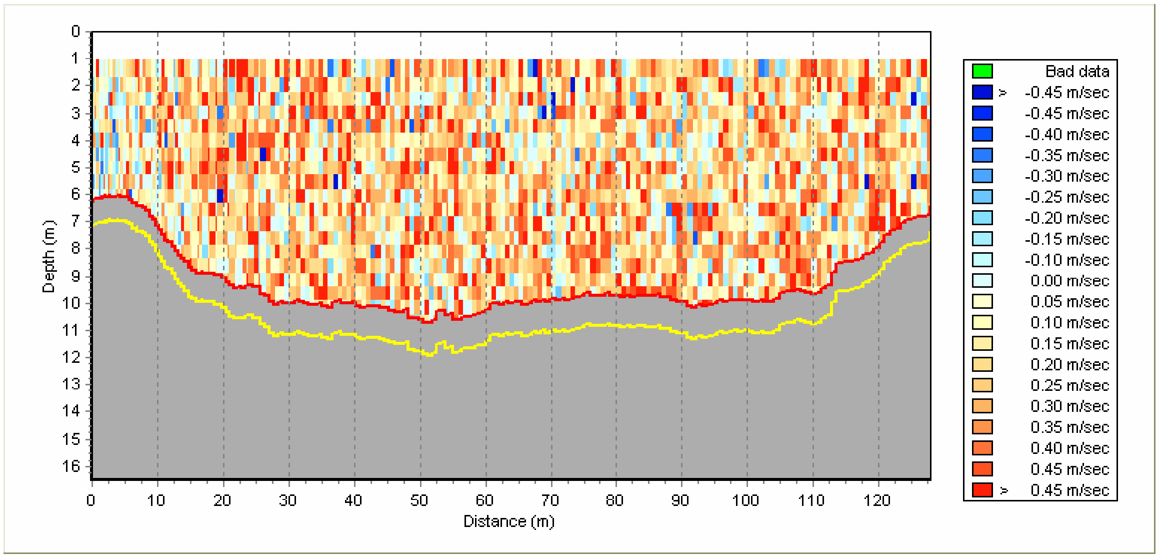

Figure 13. Vertical profile of current velocities across Redwood Creek during an ebbing tide.

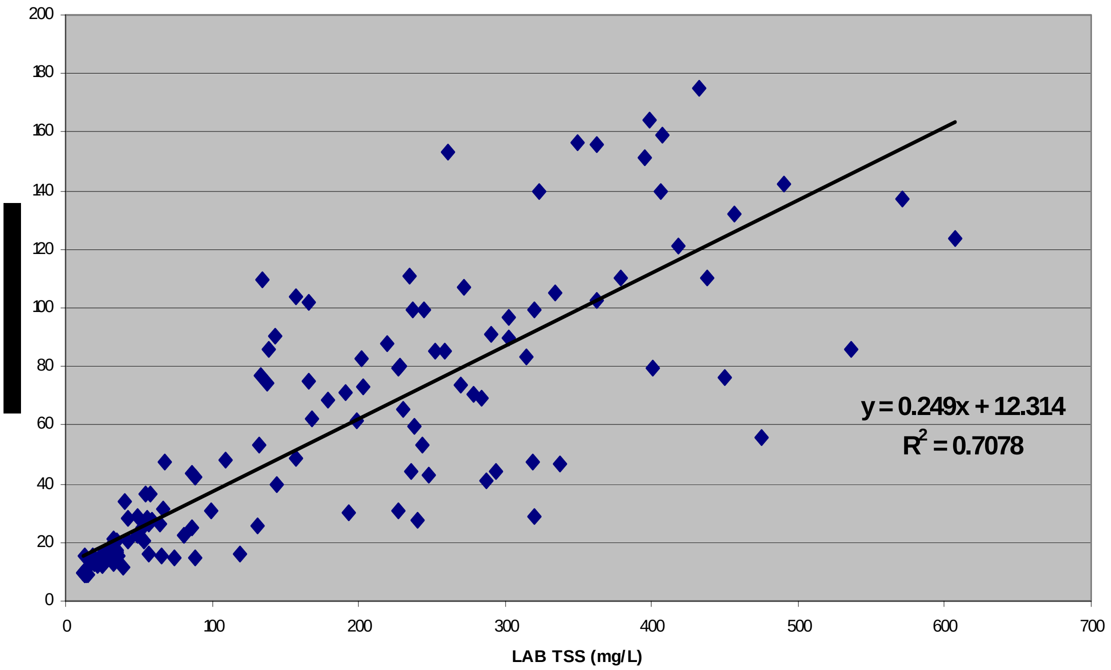

Figure 14. Regression of field turbidity values on TSS concentrations for corresponding samples.

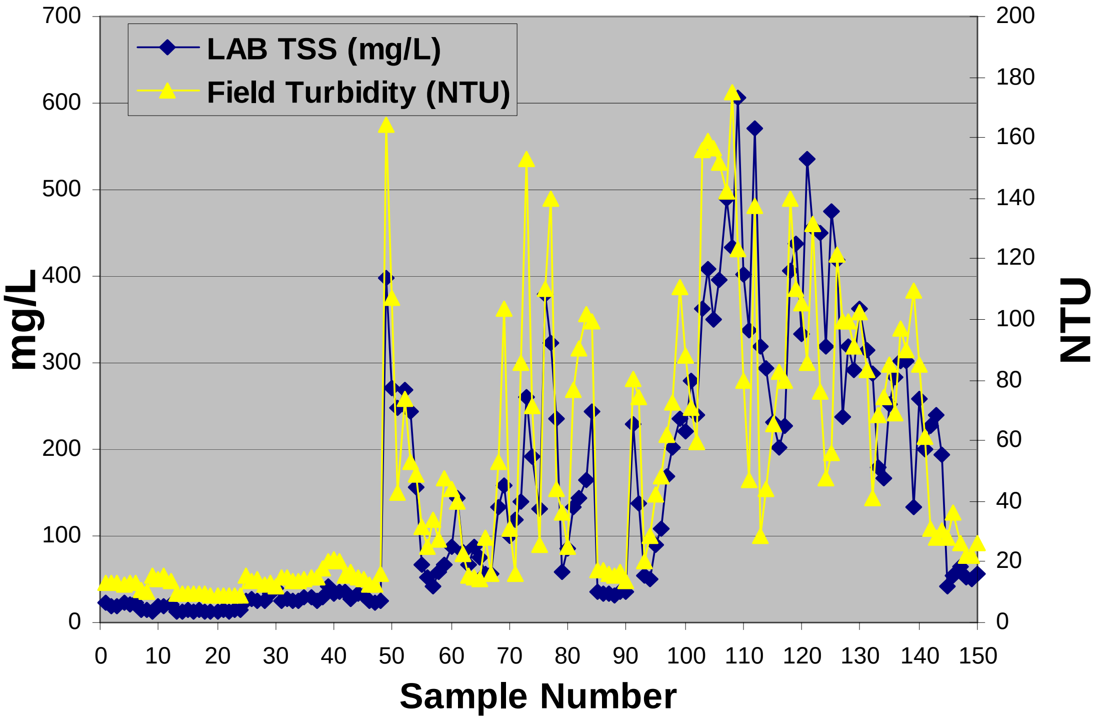

Figure 15. Relationship between turbidities measured in the field and laboratory determined TSS concentrations for the same water samples.

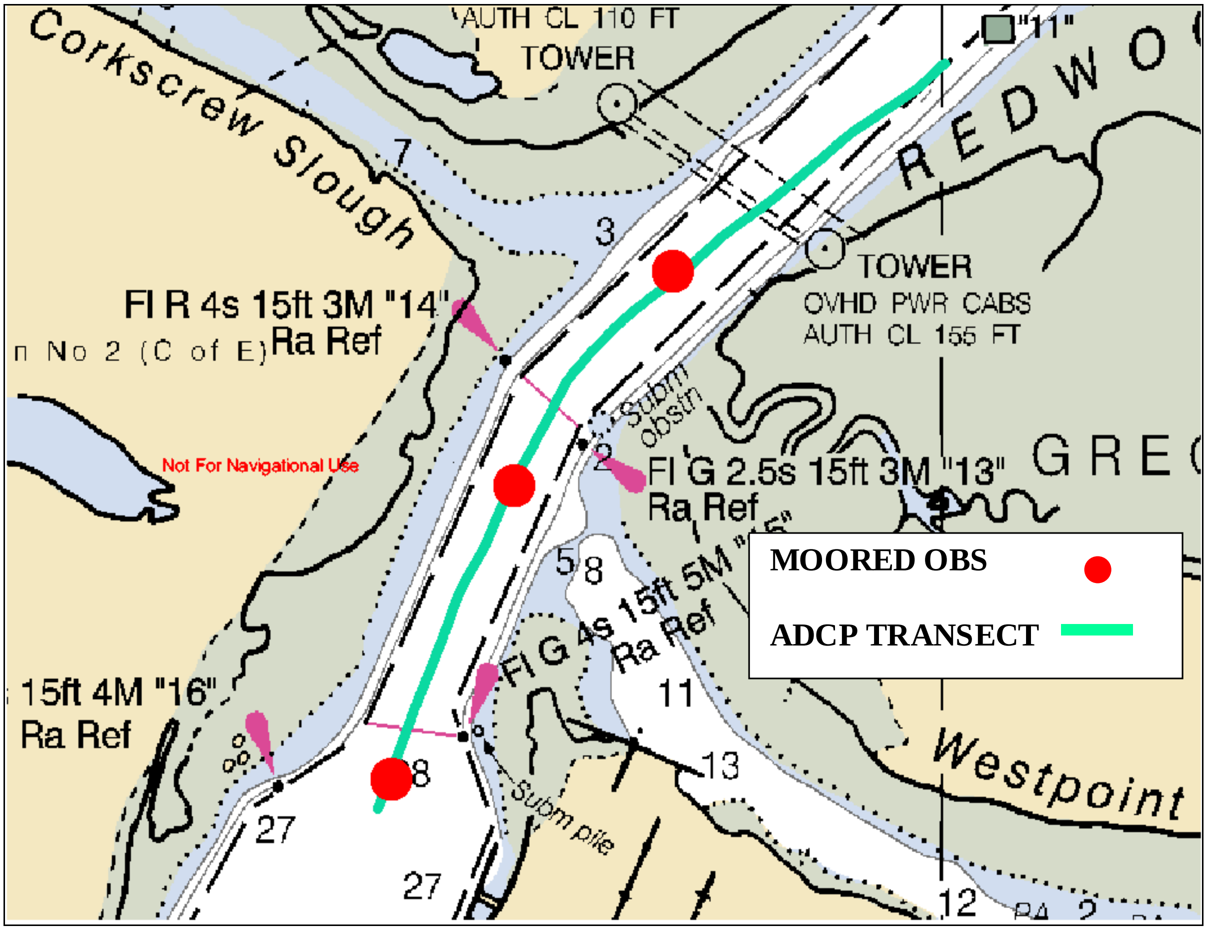

Figure 16. Locations of moored buoys with OBS units and ADCP transects during ambient measurements in Redwood Creek on 25 October 2004.

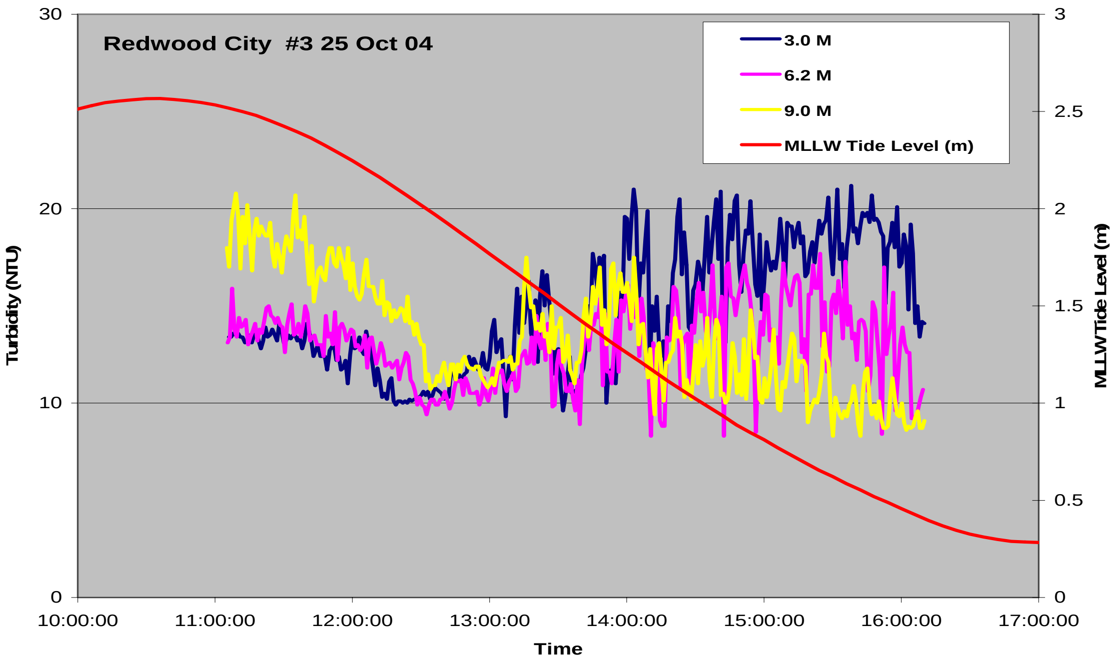

Figure 17. Ambient turbidity conditions at the northernmost moored buoy.

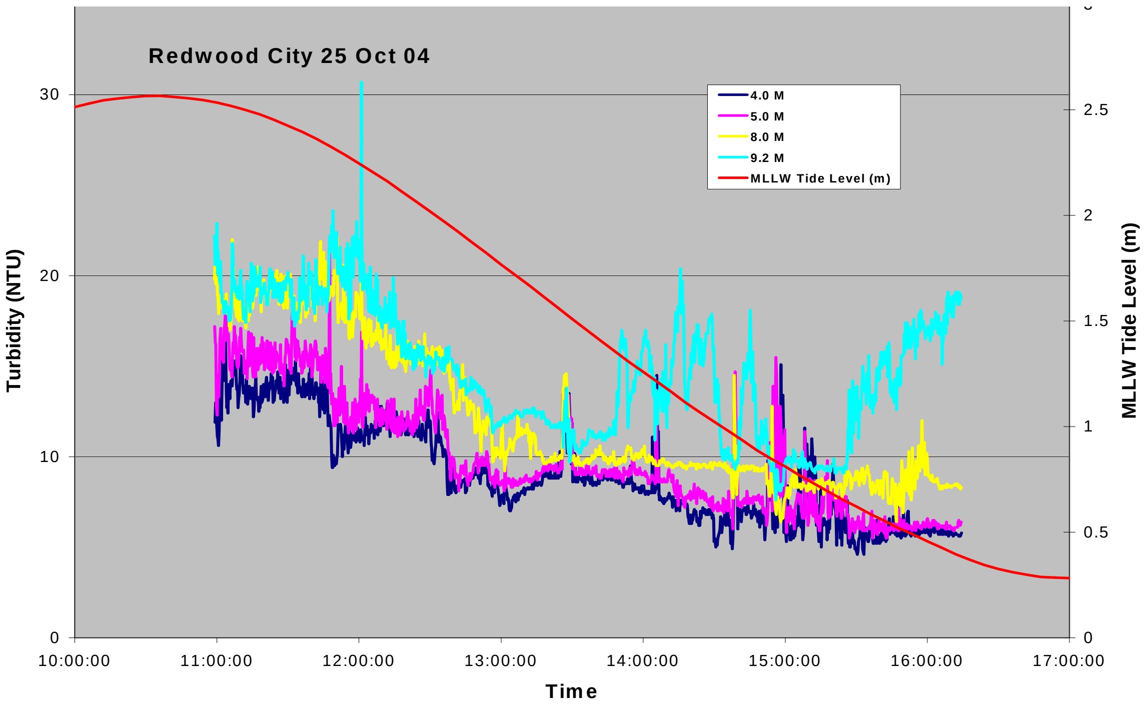

Figure 18. Ambient turbidity conditions at the mid-reach moored buoy.

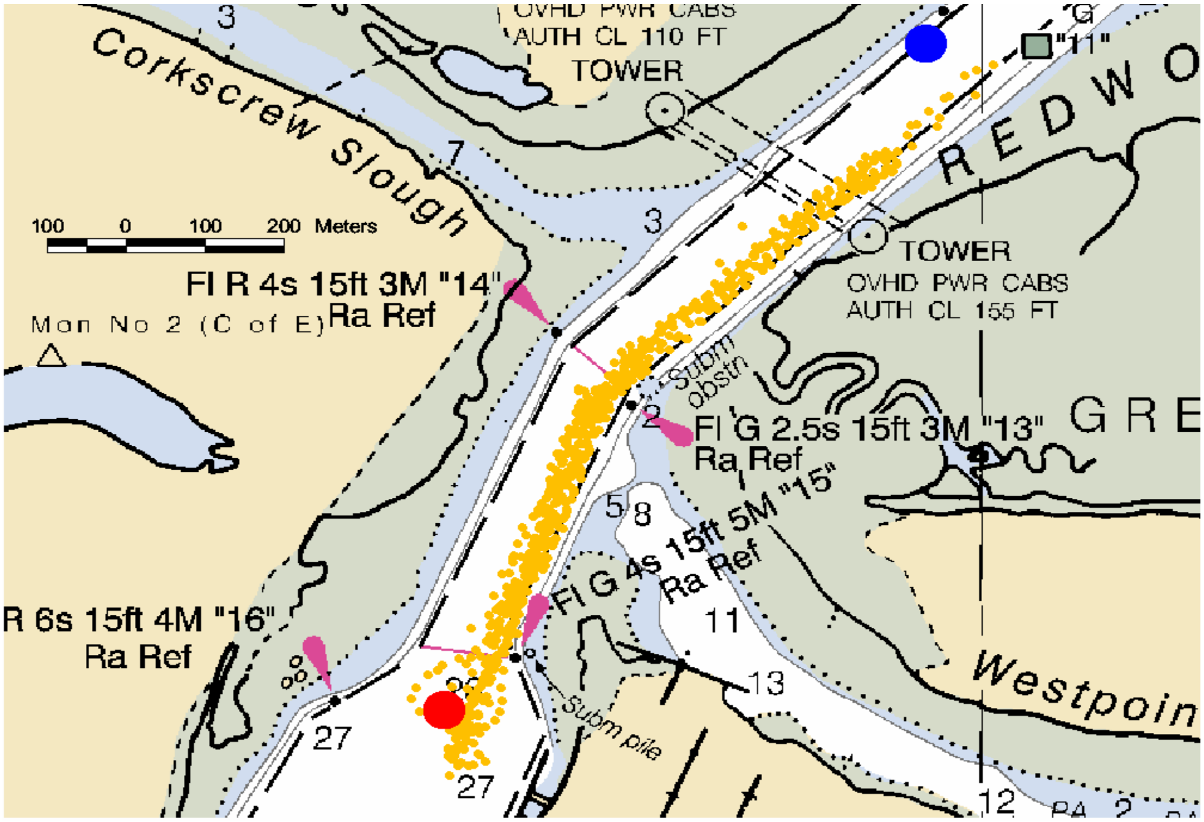

Figure 19. Locations of the northern (solid blue circle) and southern (solid red circle) moored OBS buoys and the knockdown barge tracks (orange circles) on 26 October.

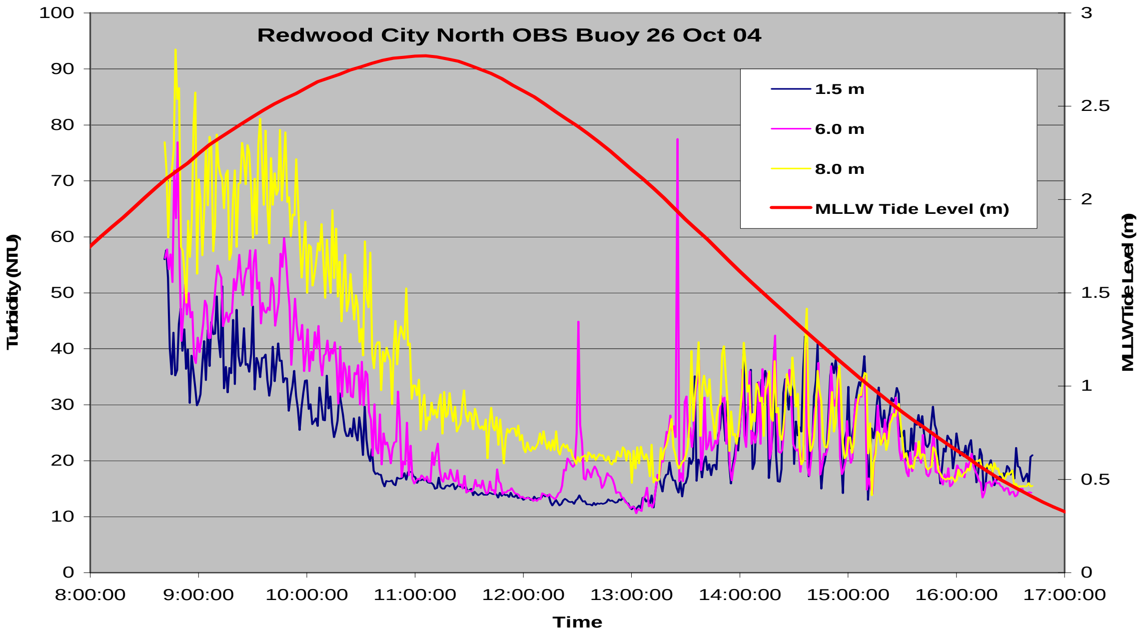

Figure 20. Time series record of turbidity at the northern moored buoy during knockdown operations on 26 October.

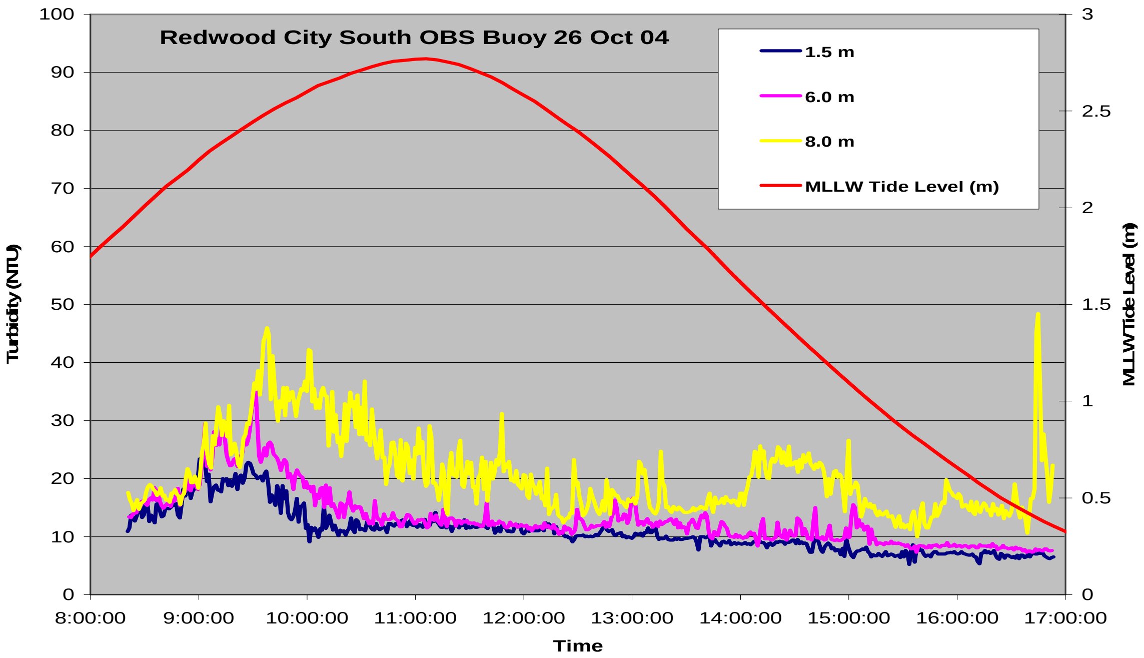

Figure 21. Time series record of turbidity at the southern moored buoy during knockdown operations on 26 October.

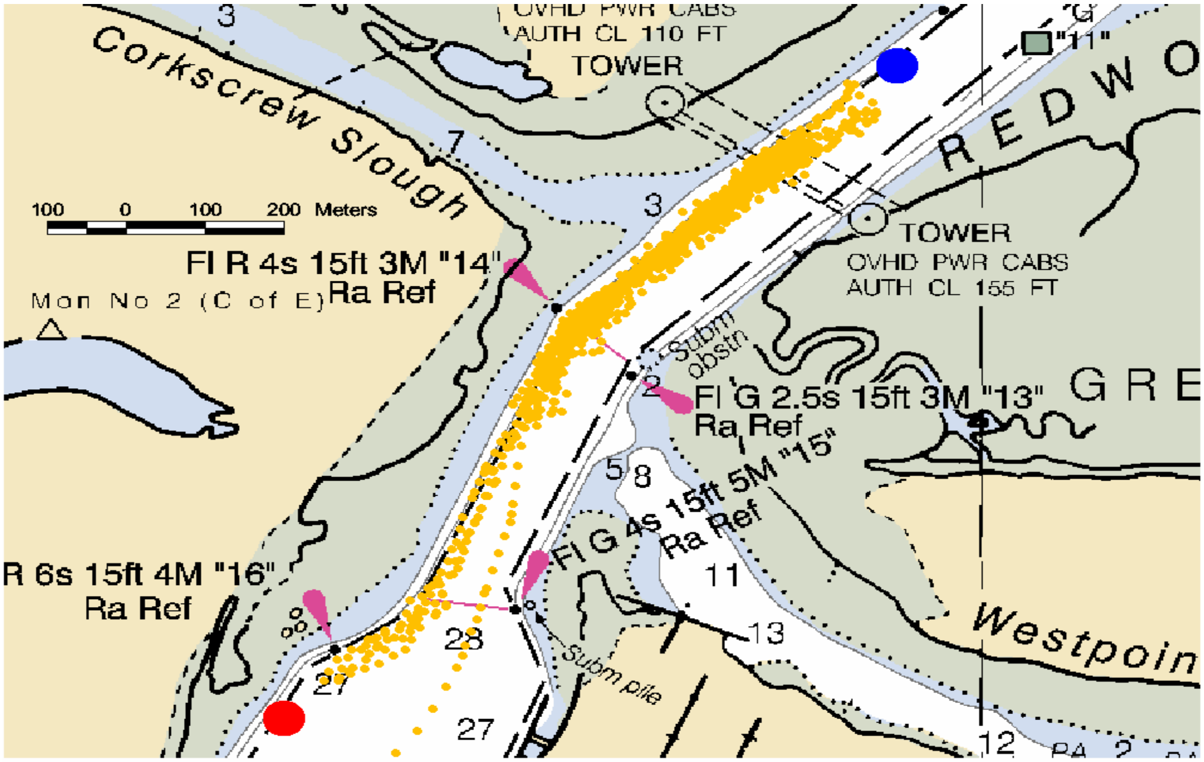

Figure 22. Locations of the northern (solid blue circle) and southern (solid red circle) moored OBS buoys and the knockdown barge tracks (orange circles) on 27 October.

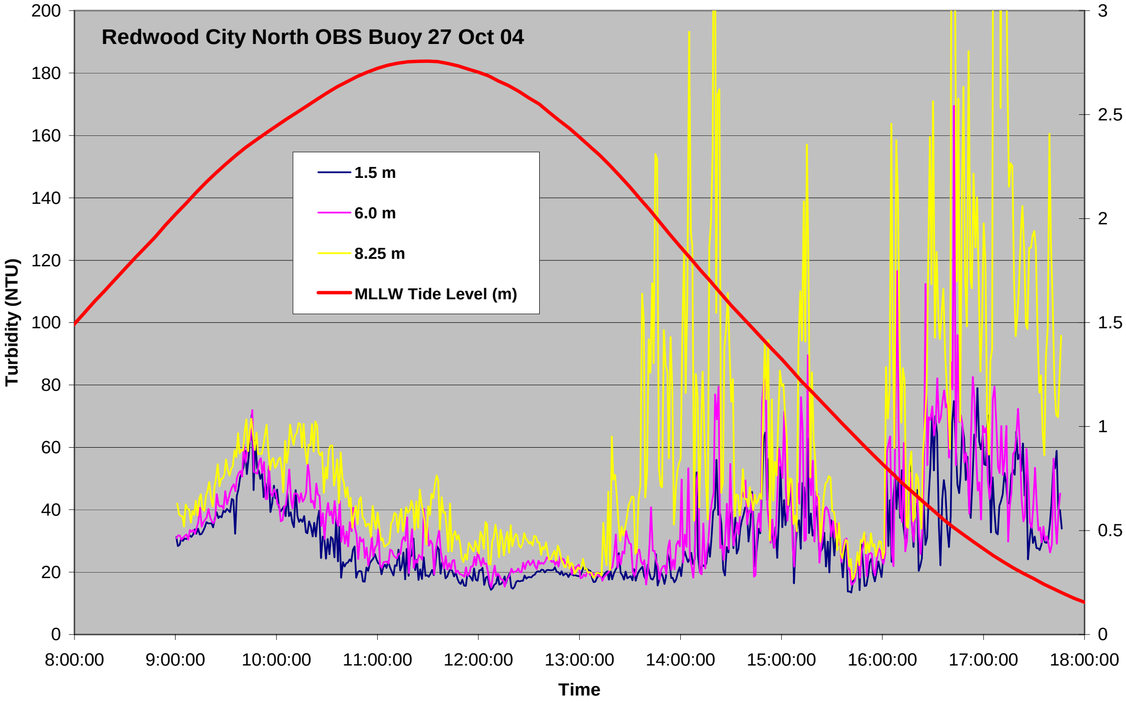

Figure 23. Time series record of turbidity at the northern moored buoy during knockdown operations on 27 October.

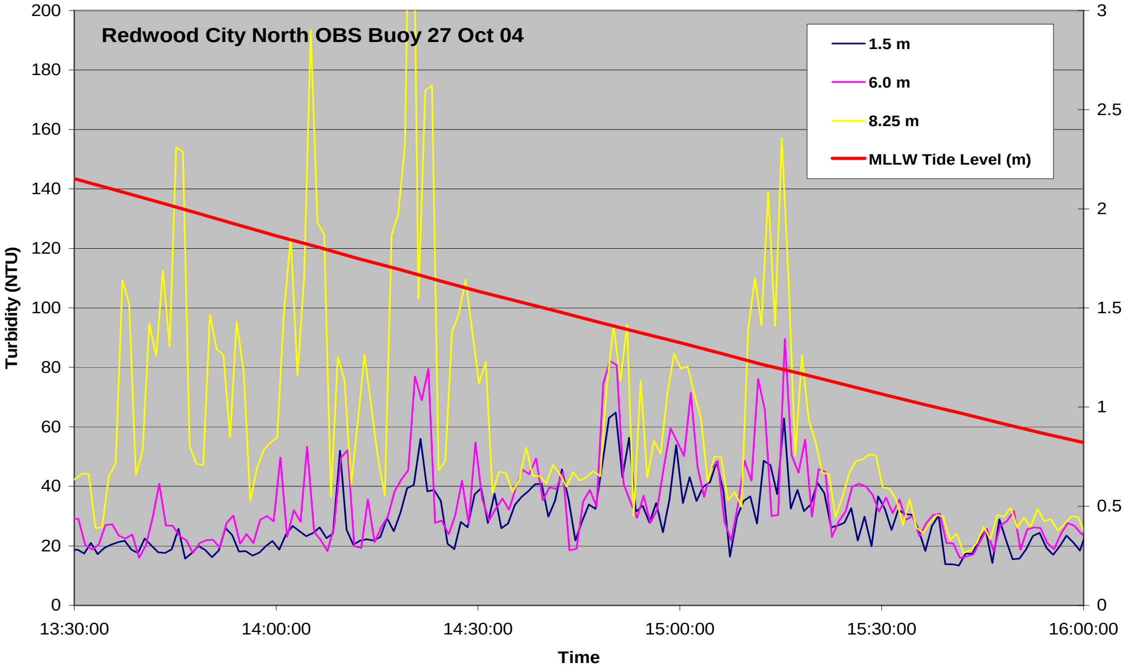

Figure 24. Expanded view of the knockdown plume turbidity signature during an ebbing tide on 27 October.

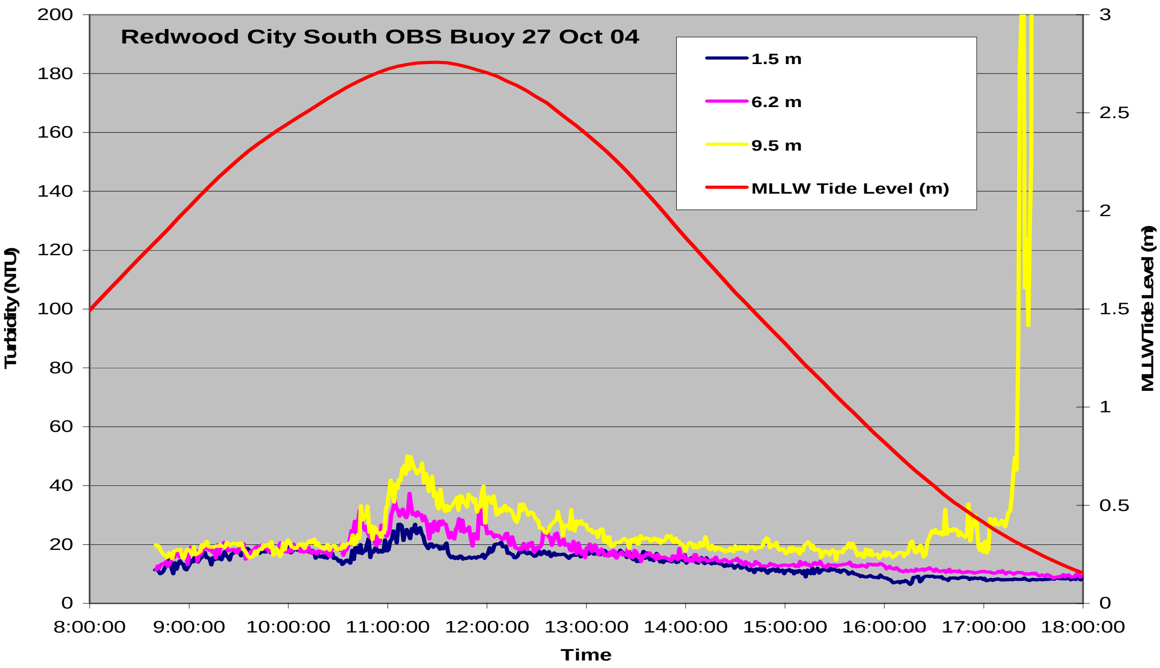

Figure 25. Time series record of turbidity at the southern moored buoy during knockdown operations on 27 October.

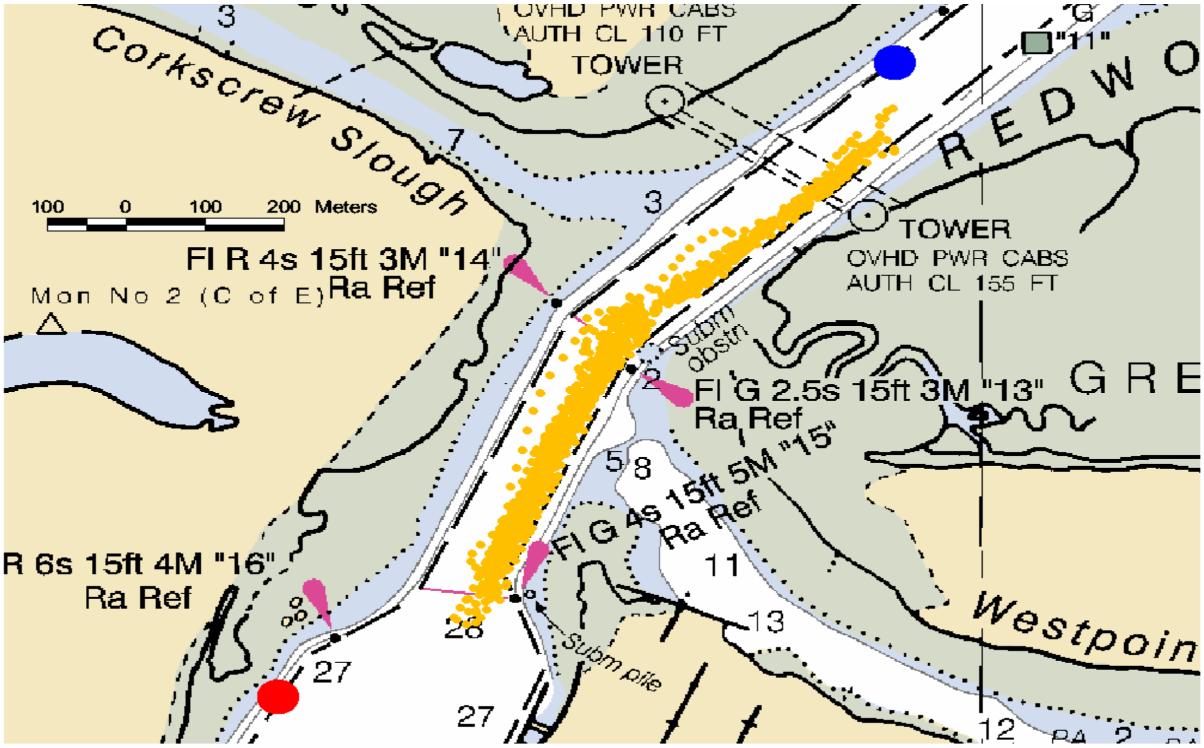

Figure 26. Locations of the northern (solid blue circle) and southern (solid red circle) moored OBS buoys and the knockdown barge tracks (orange circles) on 28 October.

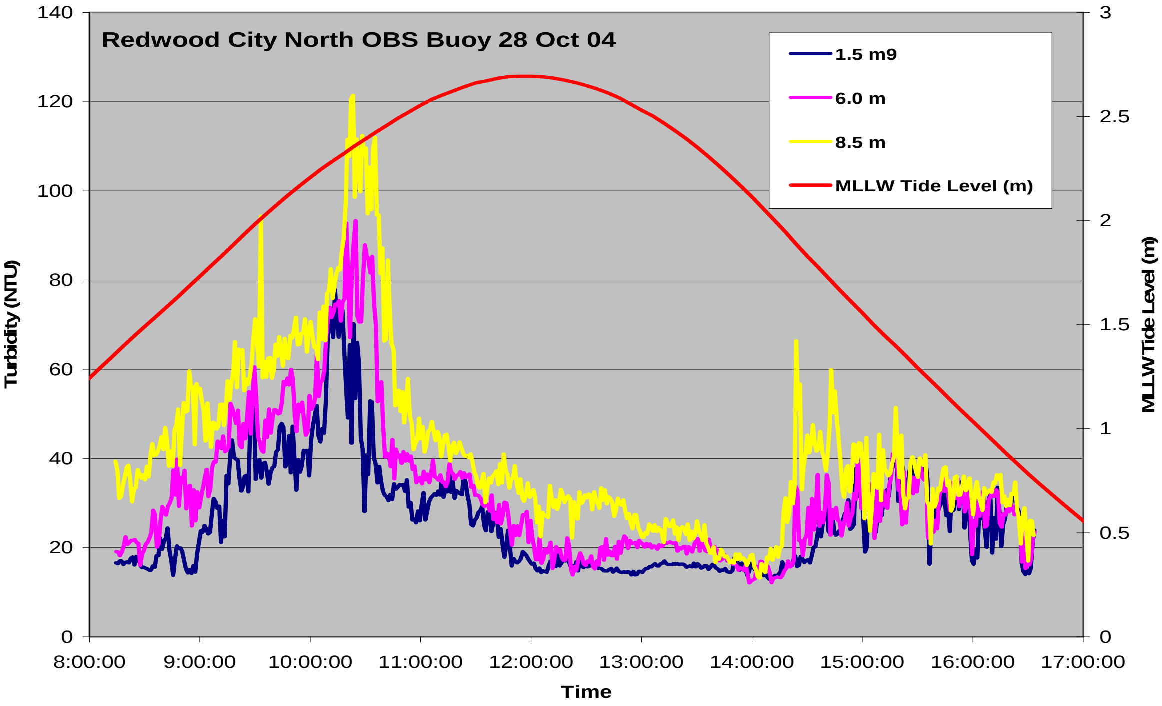

Figure 27. Time series record of turbidity at the northern moored buoy during knockdown operations on 28 October.

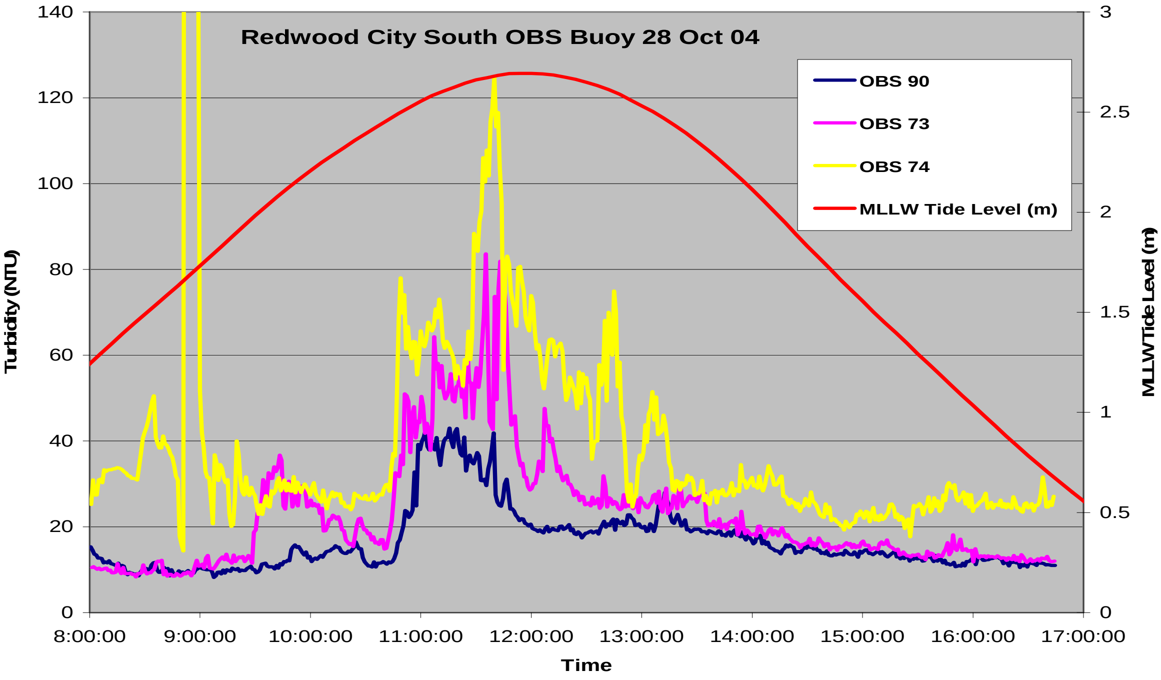

Figure 28. Time series record of turbidity at the southern moored buoy during knockdown operations on 28 October.

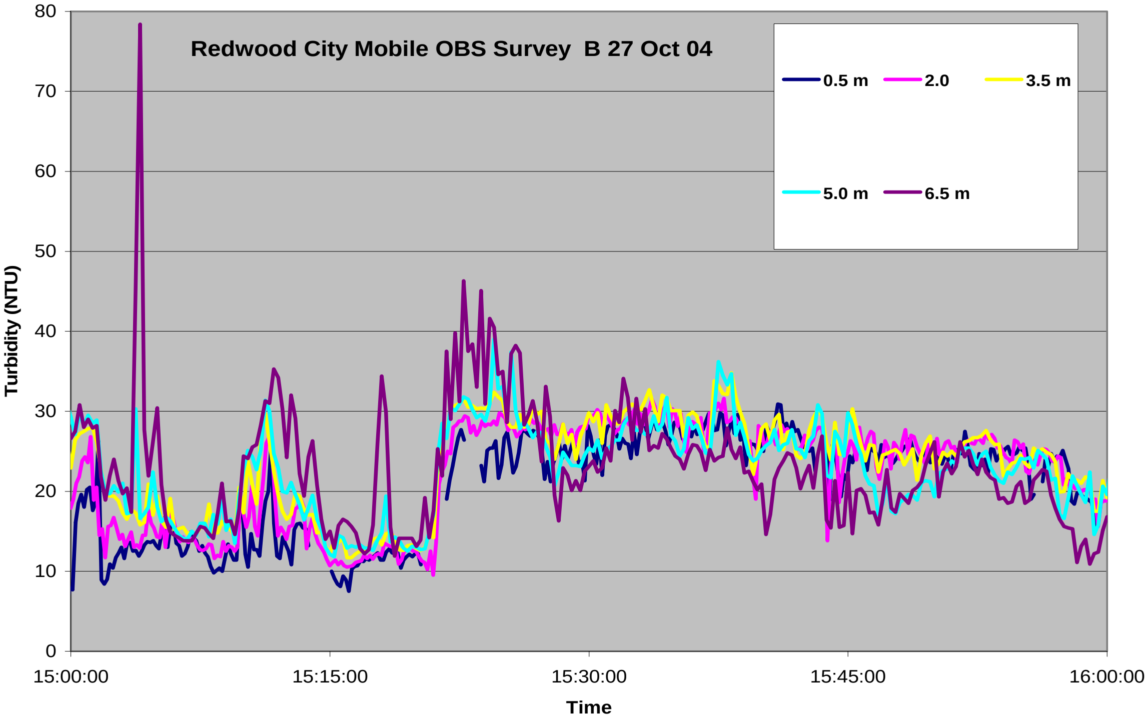

Figure 29. Time series record of turbidities as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge.

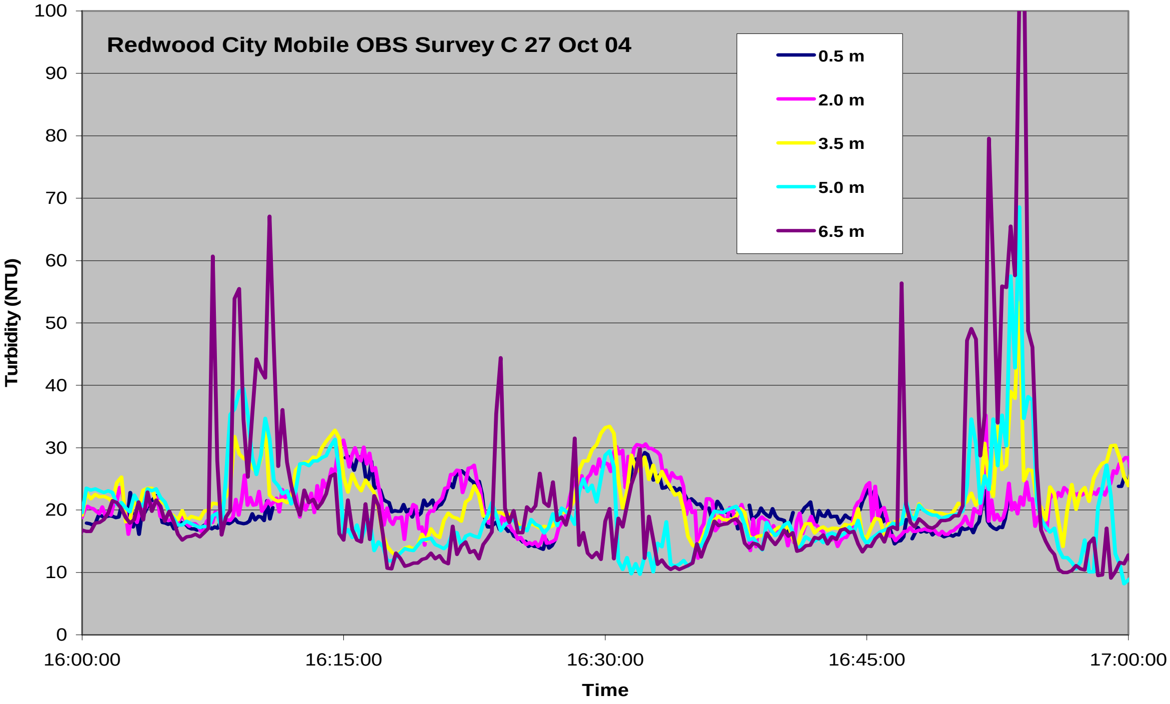

Figure 30. Continued time series record of turbidities as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge.

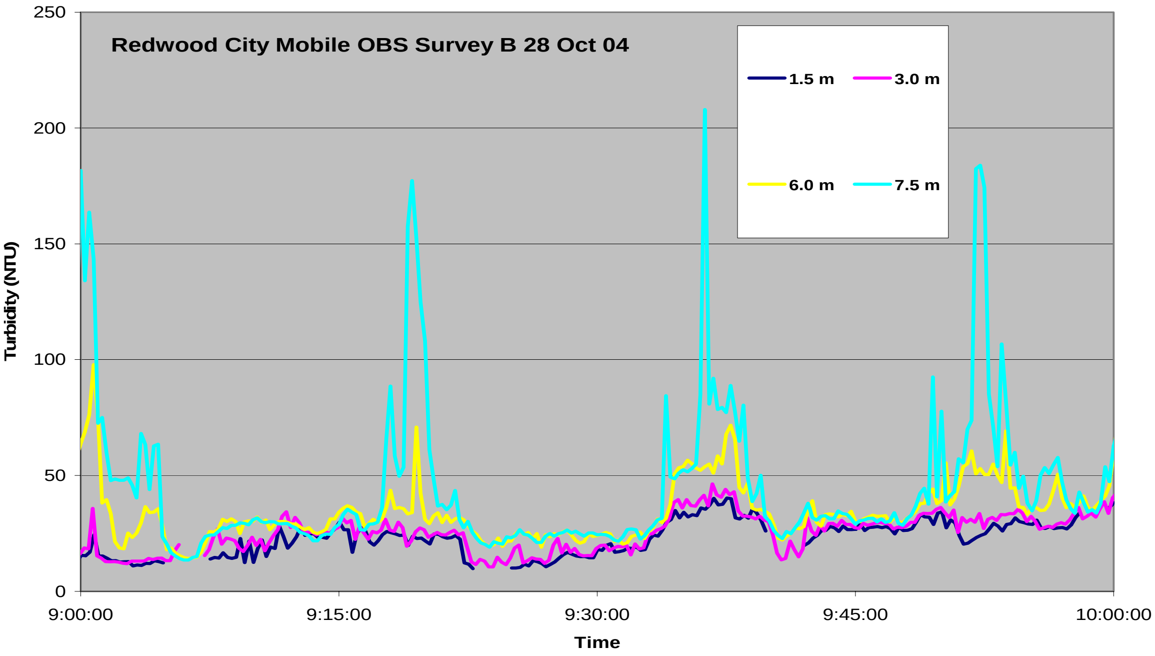

Figure 31. Time series record of turbidities as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge.

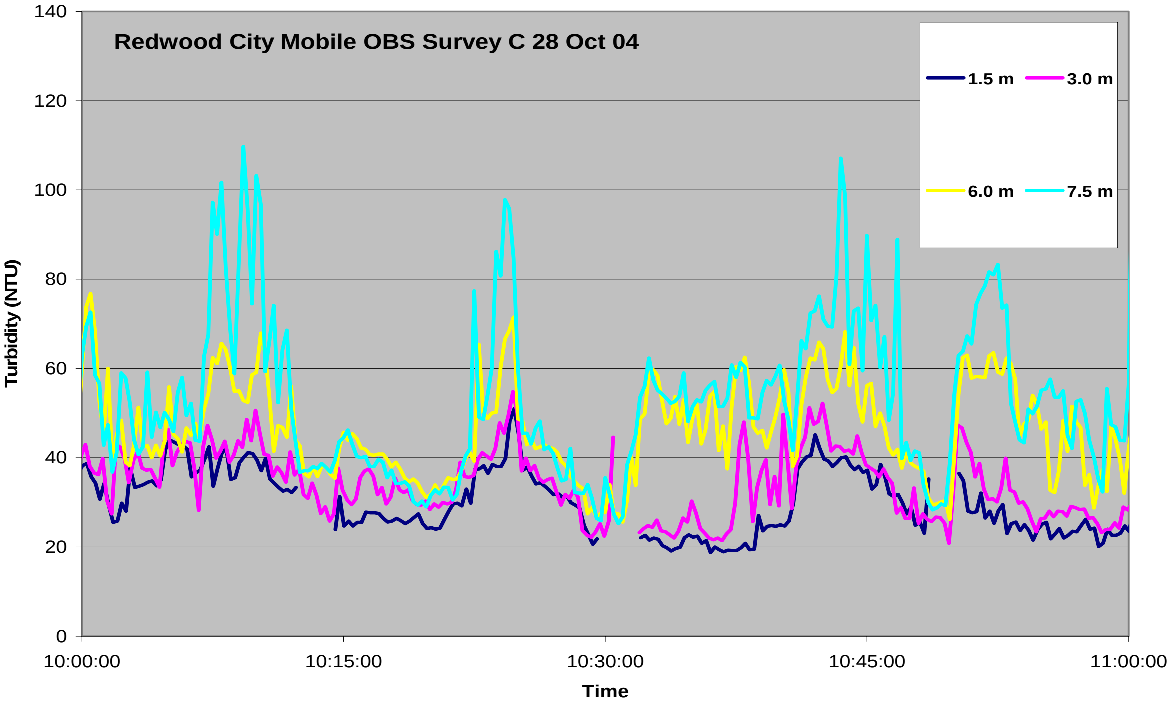

Figure 32. Time series record of turbidities as the survey vessel passed repeatedly through the knockdown plumes at a consistent distance behind the barge.

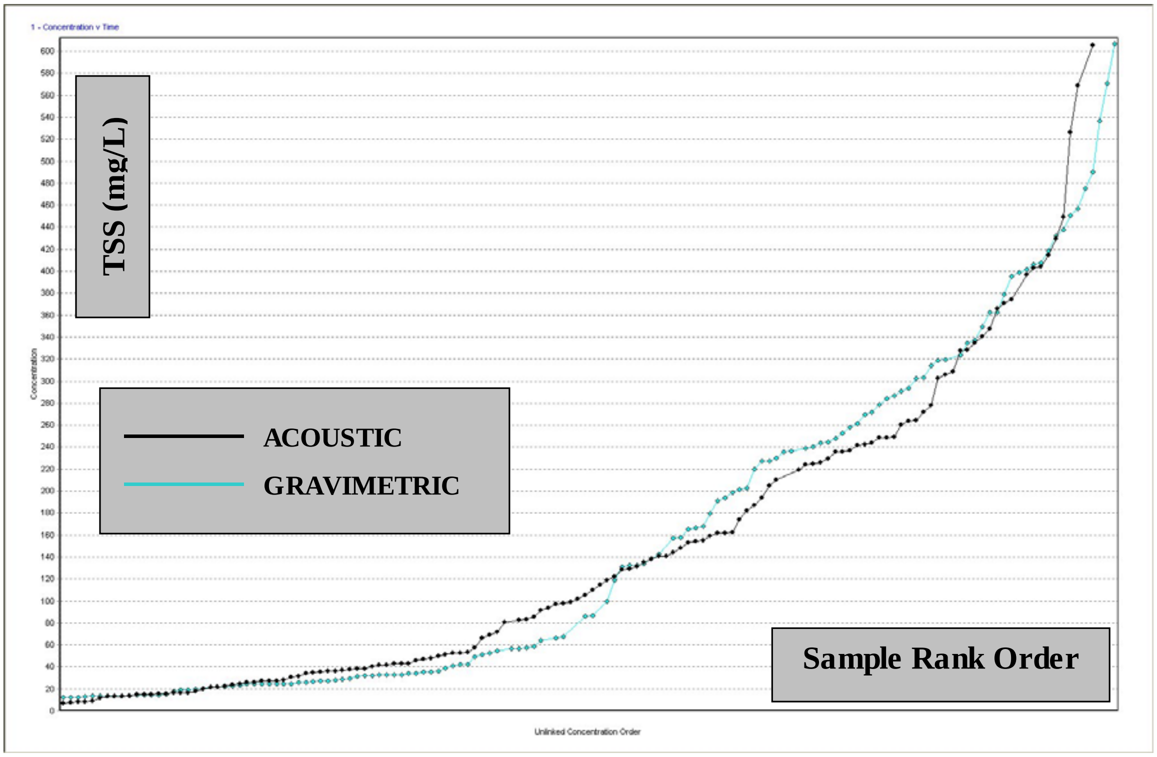

Figure 33. Comparison of gravimetric and acoustic estimates of TSS concentration for the entire population of samples taken in Redwood Creek in rank order.

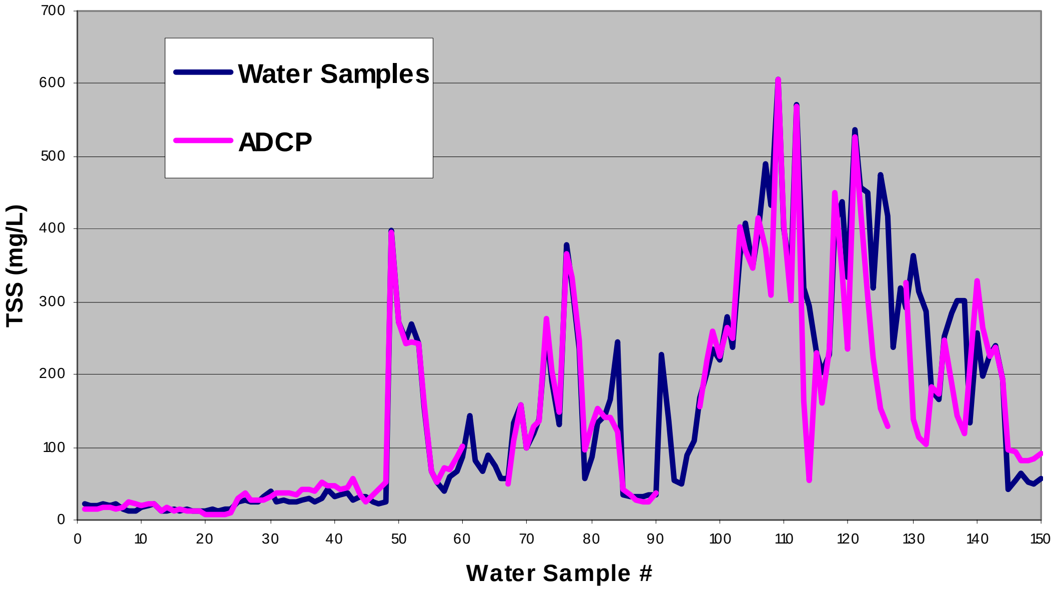

Figure 34. Correspondence between acoustic and gravimetric measures of TSS for matched data pairs.

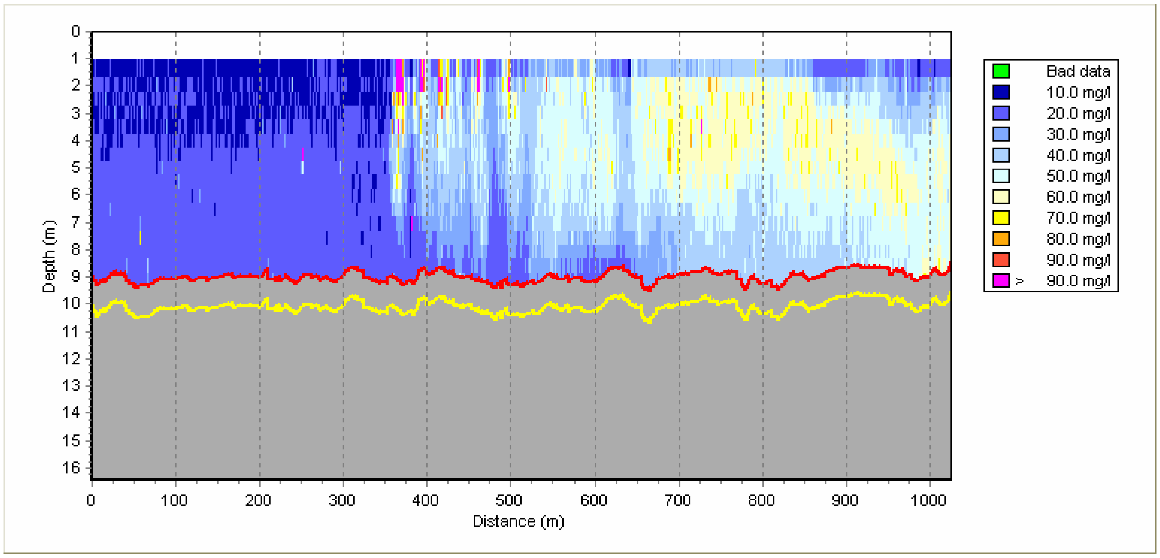

Figure 35. Vertical profile of ambient TSS concentrations across Redwood Creek during an ebbing tide.

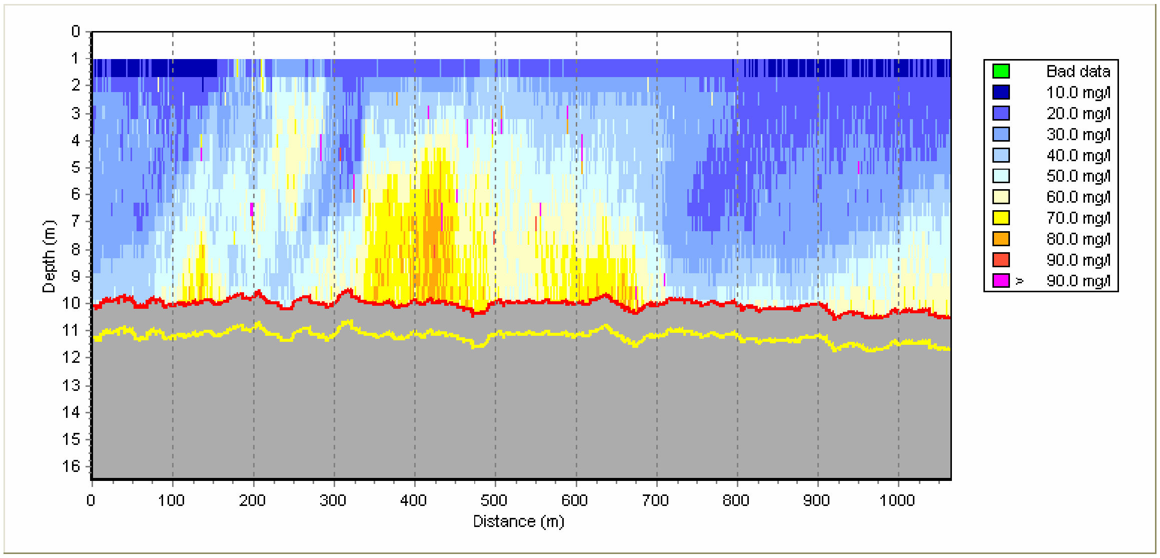

Figure 36. Vertical profile of ambient TSS concentrations across Redwood Creek during a flooding tide.

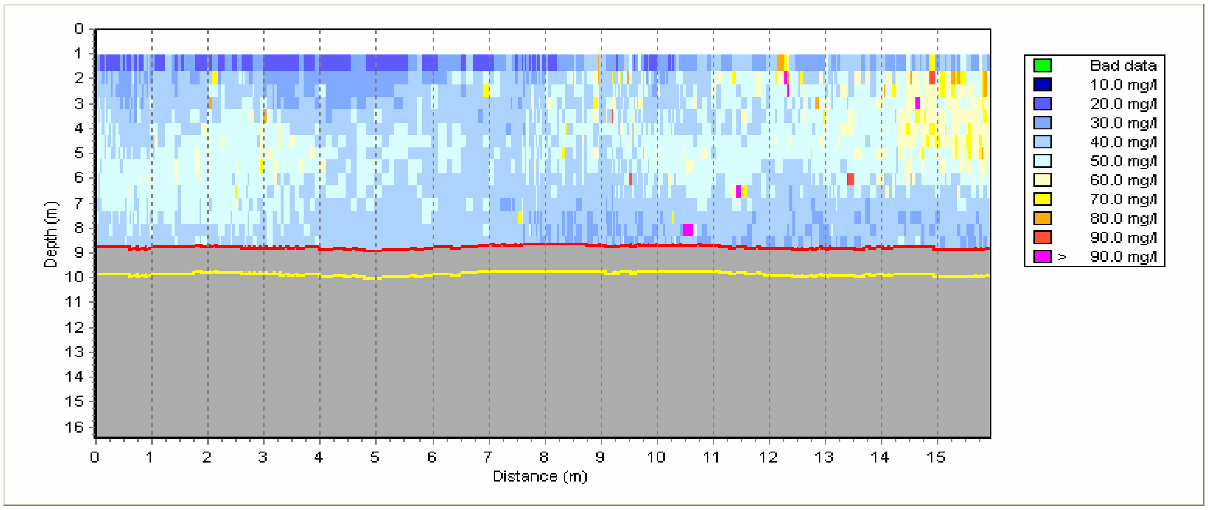

Figure 37. (RCWS05) Ambient, ebb tide, drifting during water sample collection.

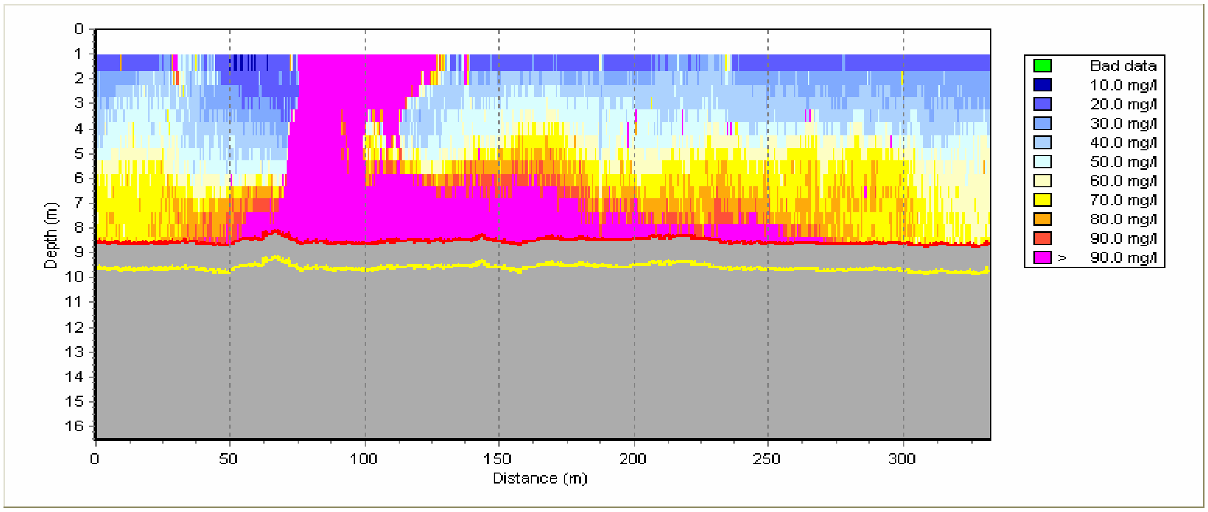

Figure 38. (RCWS17) Flood tide, drifting during water sample collection in plume.

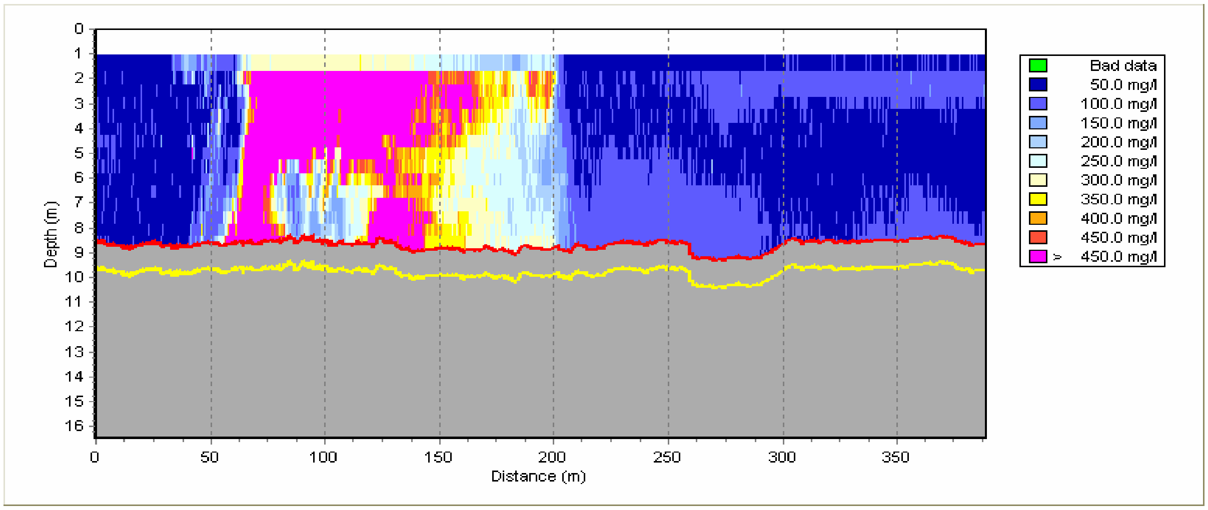

Figure 39. (RCWS12) Ebb tide, drifting during water sample collection in plume.

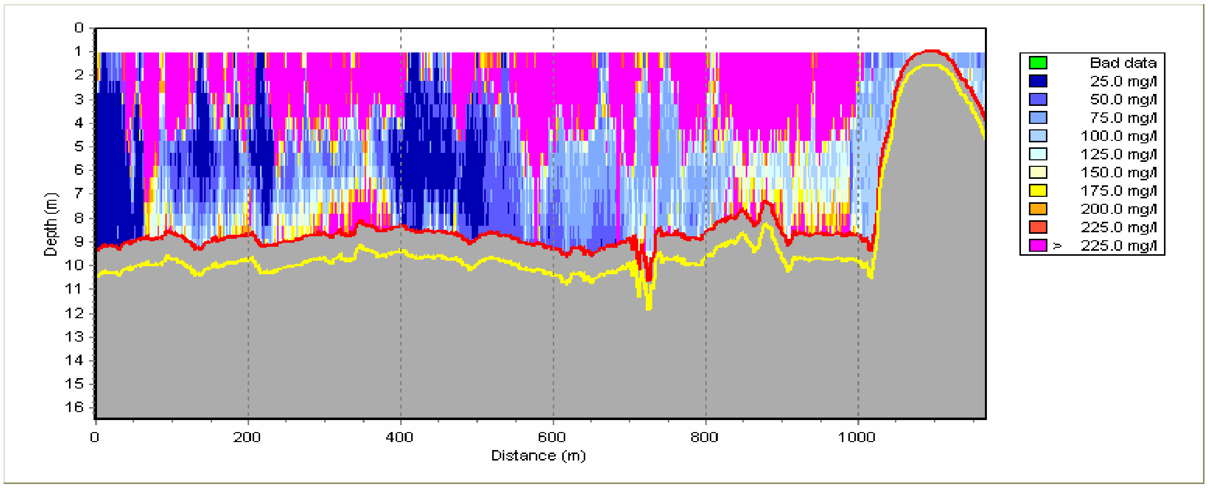

Figure 40. (RKEA32) Parallel course, 60 m directly behind barge.

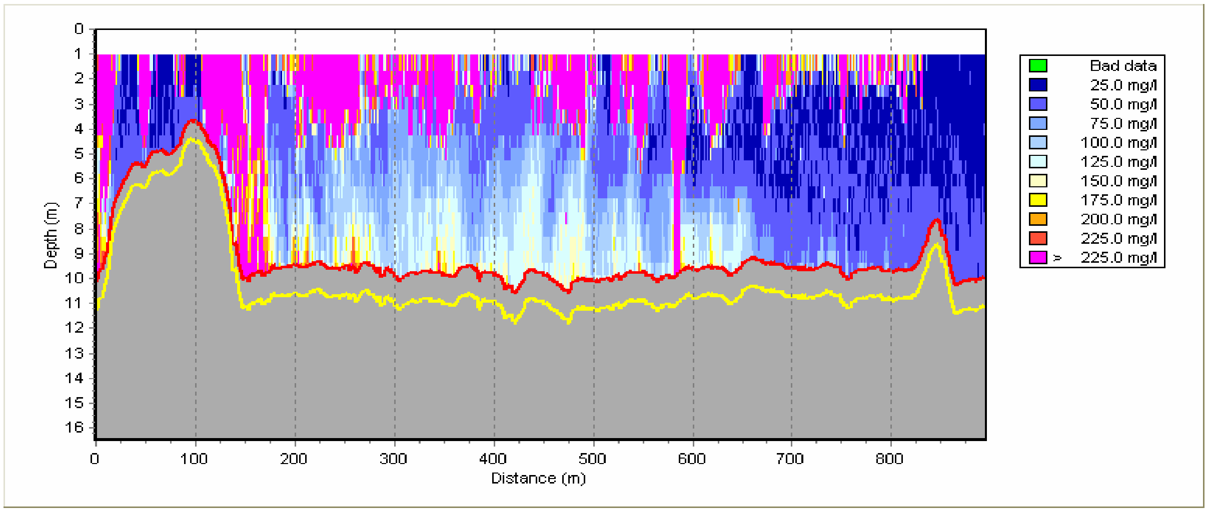

Figure 41. (RKEA01) Parallel course, 70 m directly behind barge.

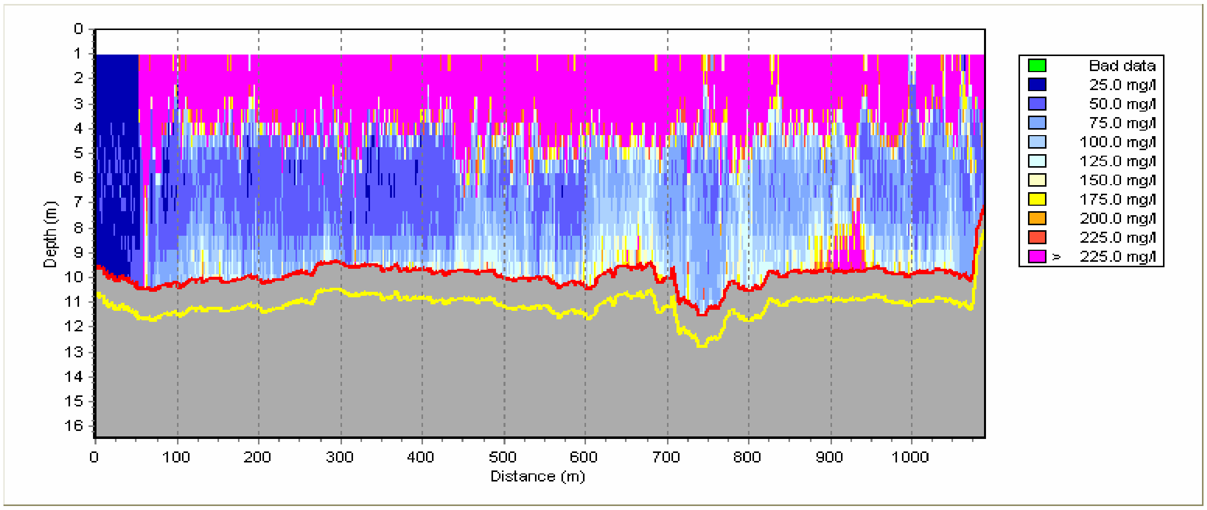

Figure 42. (RKEA02) Parallel course, 70 m directly behind barge.

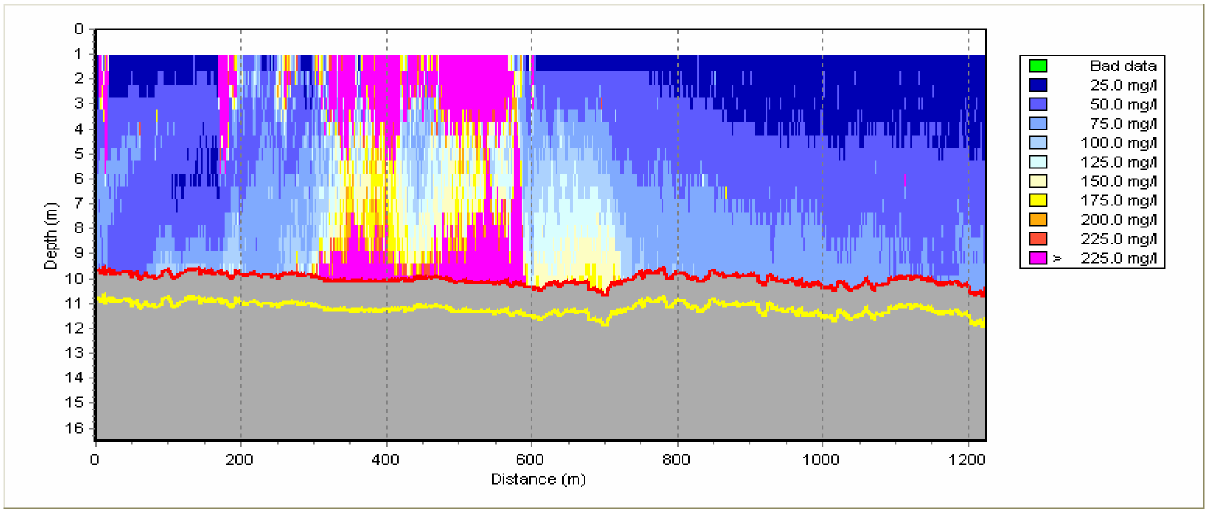

Figure 43. (RKEC01) Parallel course, 50 m directly behind the barge at slack water.

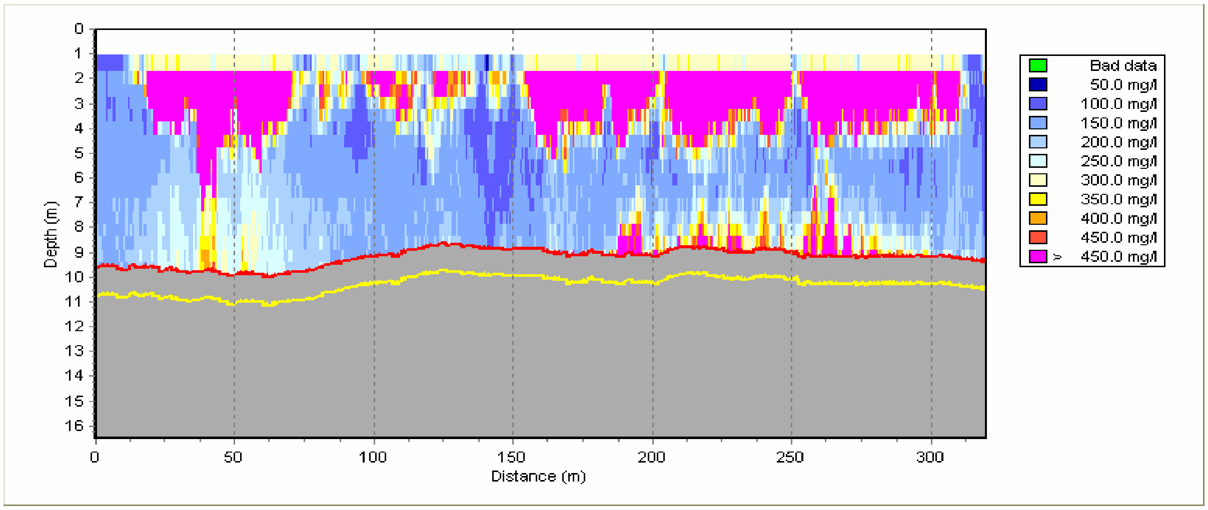

Figure 44. (RKFB09) Parallel course, 55 m directly behind the barge.

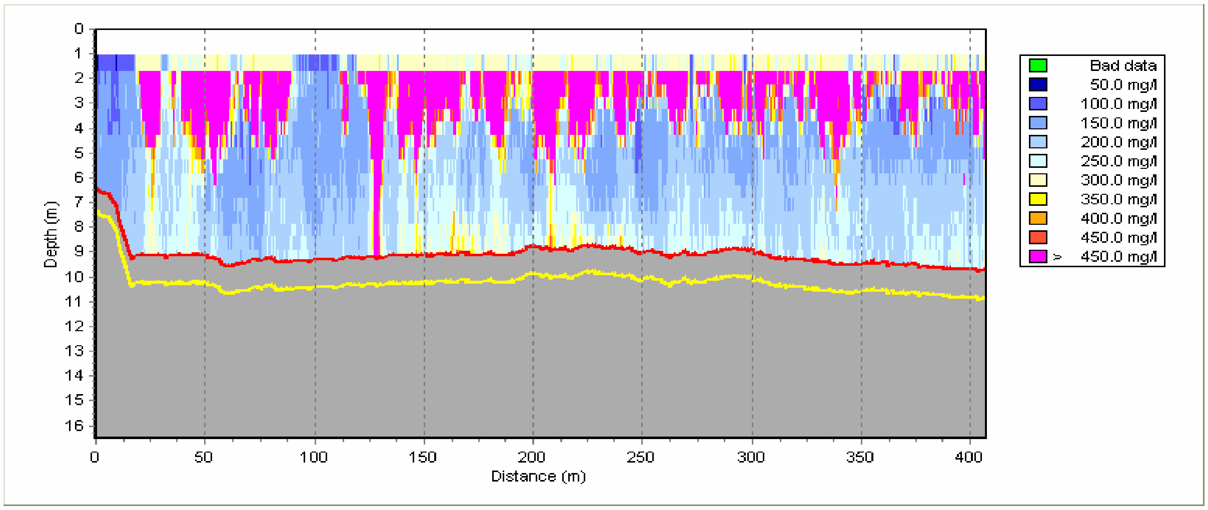

Figure 45. (RKFB08) Parallel course, 80 m directly behind the barge.

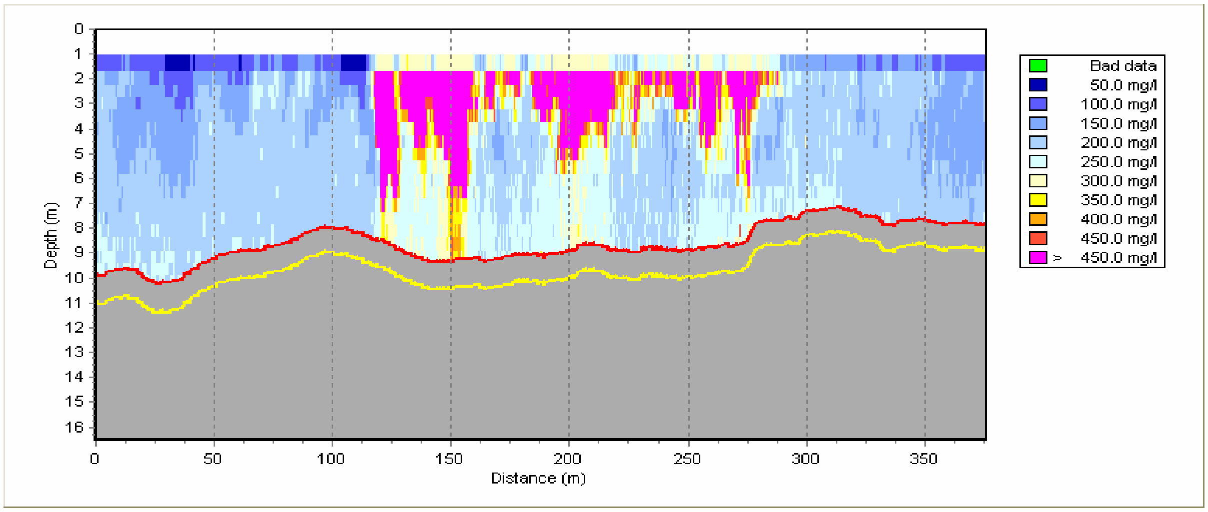

Figure 46. (RKFB07) Parallel course, 130 m directly behind the barge.

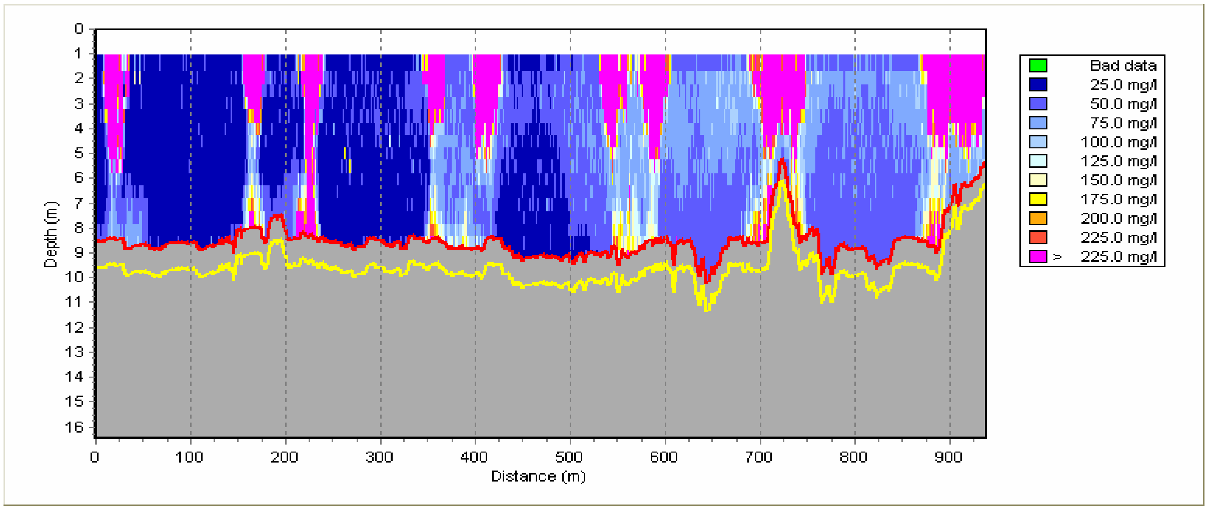

Figure 47. (RKEA34) Zigzag course, 60 m behind barge.

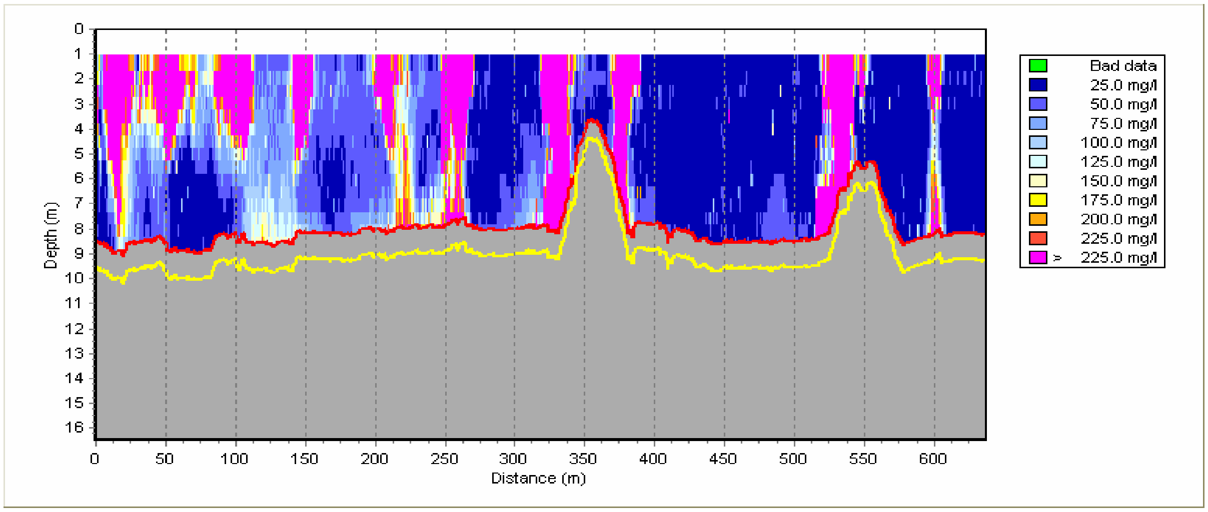

Figure 48. (RKEA37) Zigzag course, 70 m behind barge.

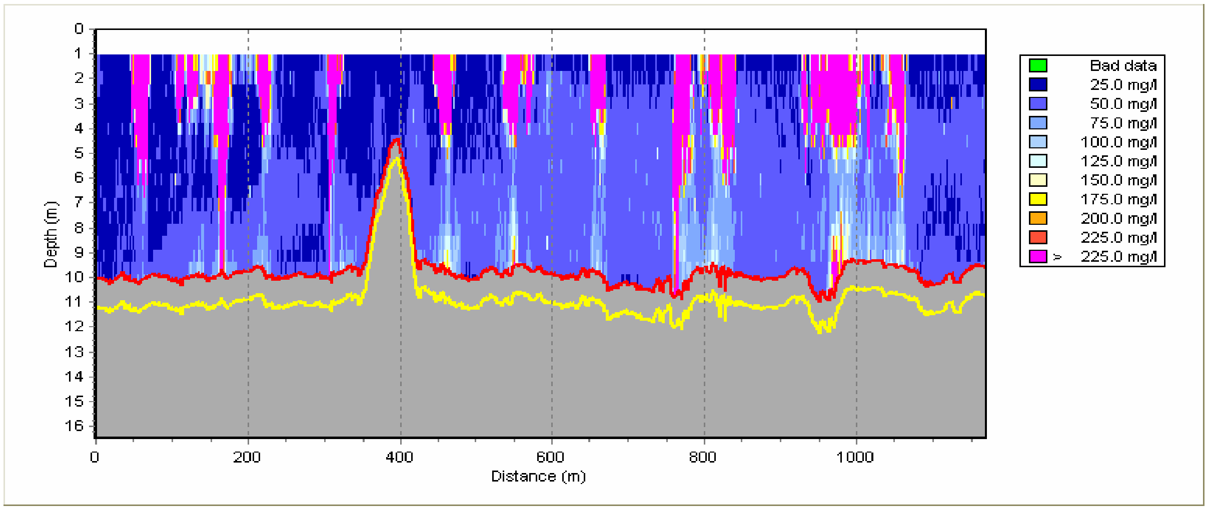

Figure 49. (RKEA04) Zigzag course, 90 m behind barge.

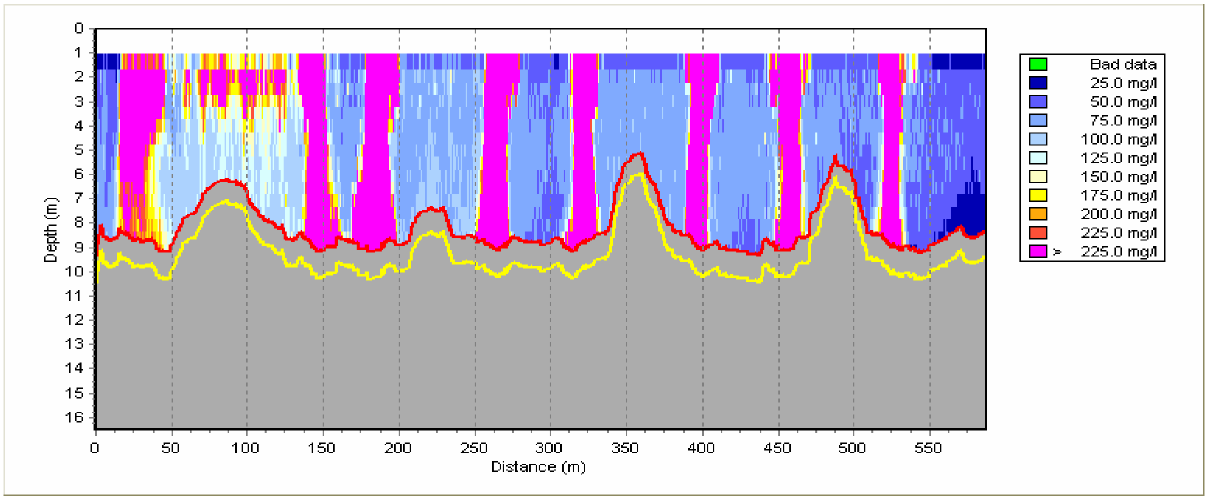

Figure 50. (RKEC29) Zigzag course, 75 m behind the barge.

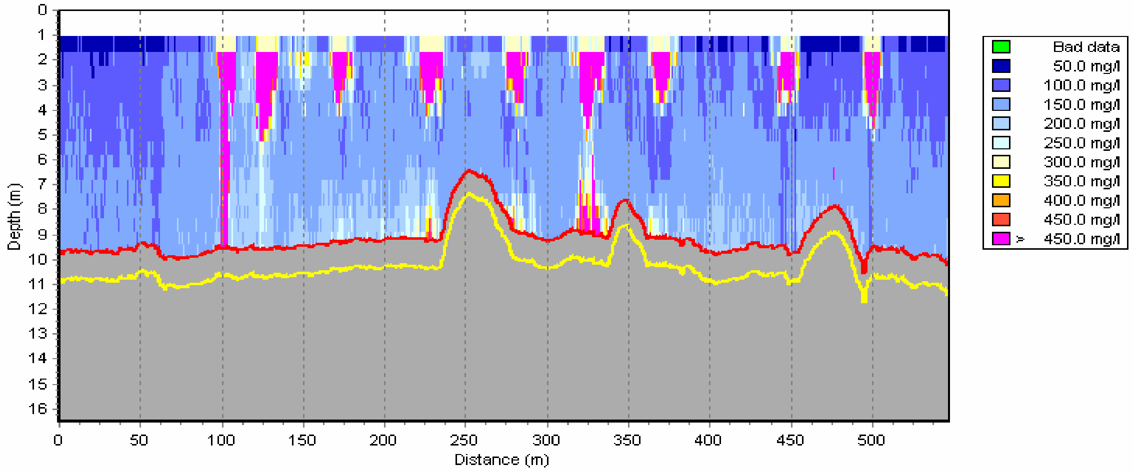

Figure 51. (RKFB10) Zigzag course, 45 m behind the barge.

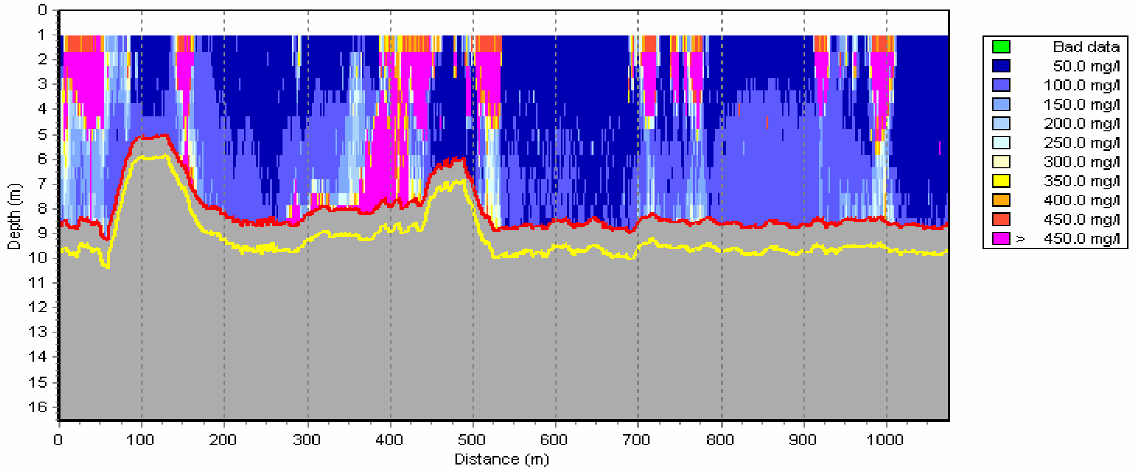

Figure 52. (RKFB01) Zigzag course, 65 m behind the barge.

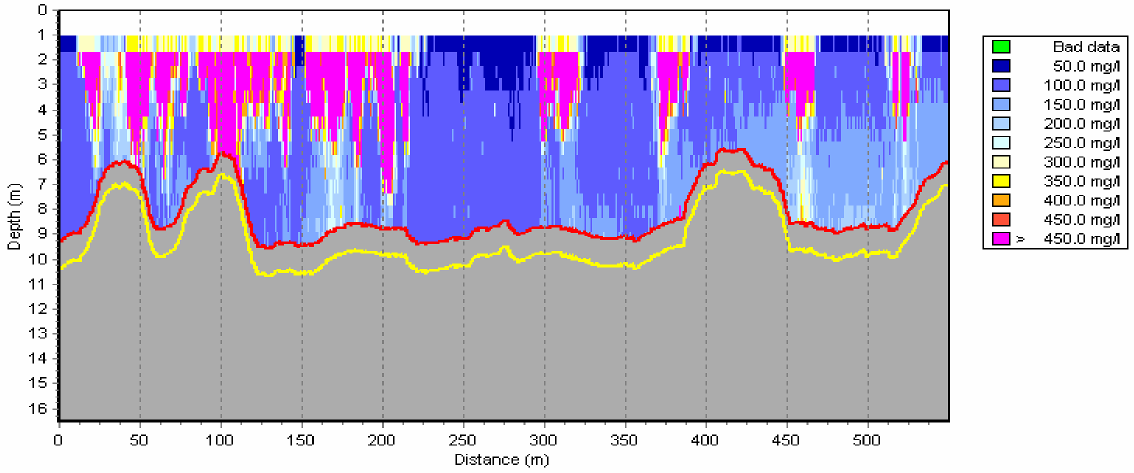

Figure 53. (RKFB04) Zigzag course, 100 m behind the barge.

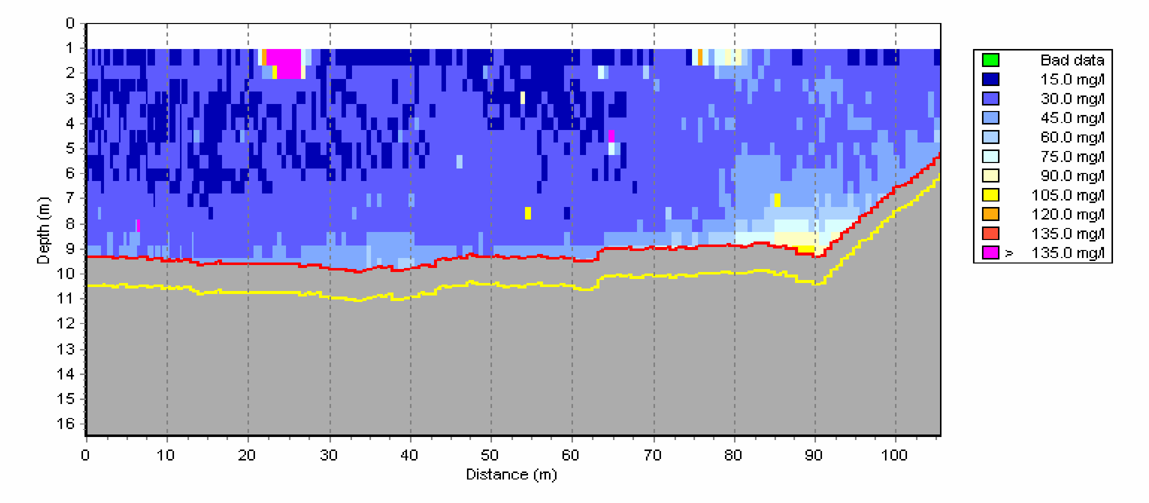

Figure 54. (RKEA010) Perpendicular course, barge approaching transect location.

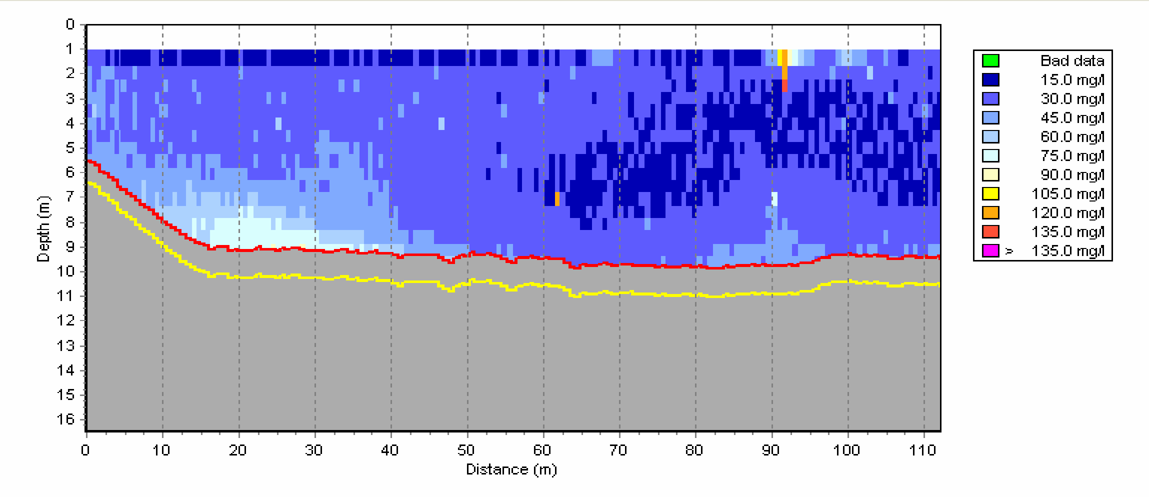

Figure 55. (RKEA0110) Perpendicular course, barge approaching transect location.

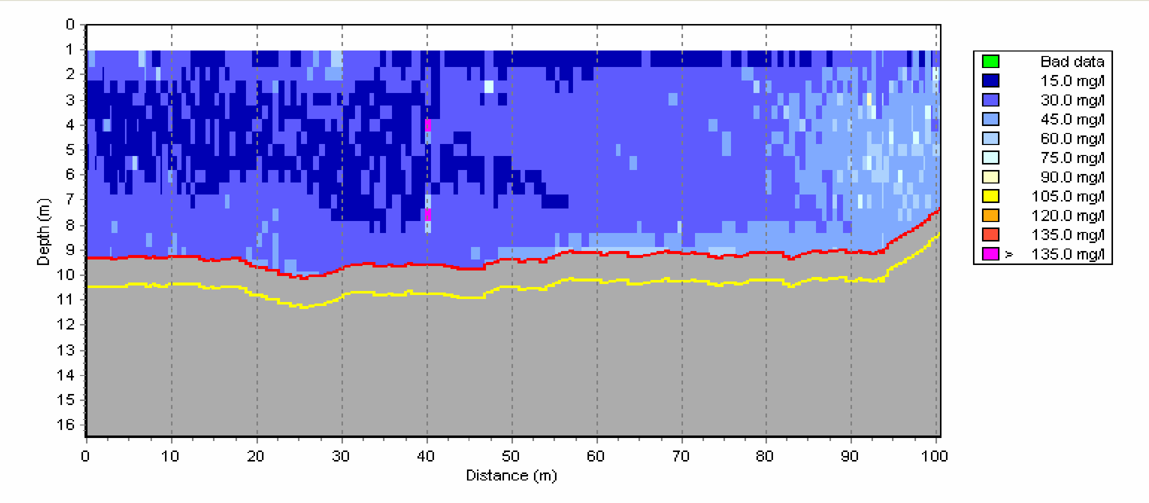

Figure 56. (RKEA012) Perpendicular course, barge approaching transect location.

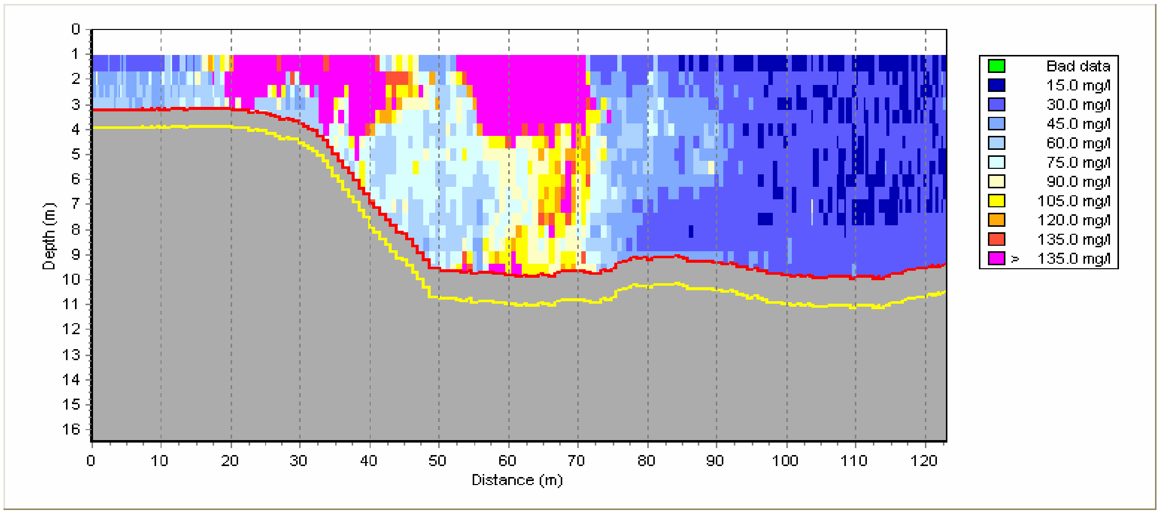

Figure 57. (RKEA013) Perpendicular course, barge passes 40 m beyond transect. Time reference = zero.

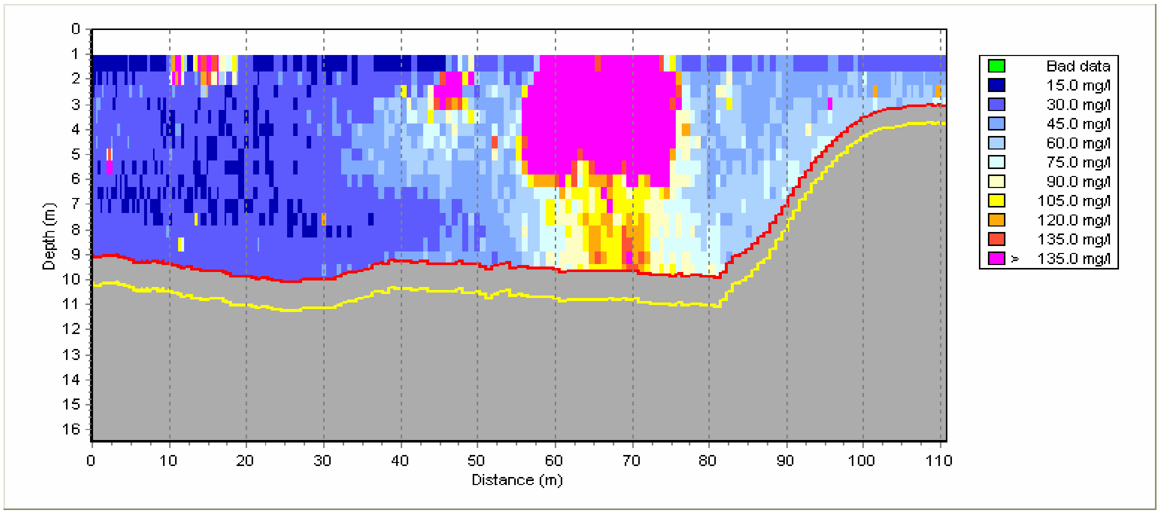

Figure 58. (RKEA014) Perpendicular course, barge now 225 m from transect. Time reference = 3 minutes.

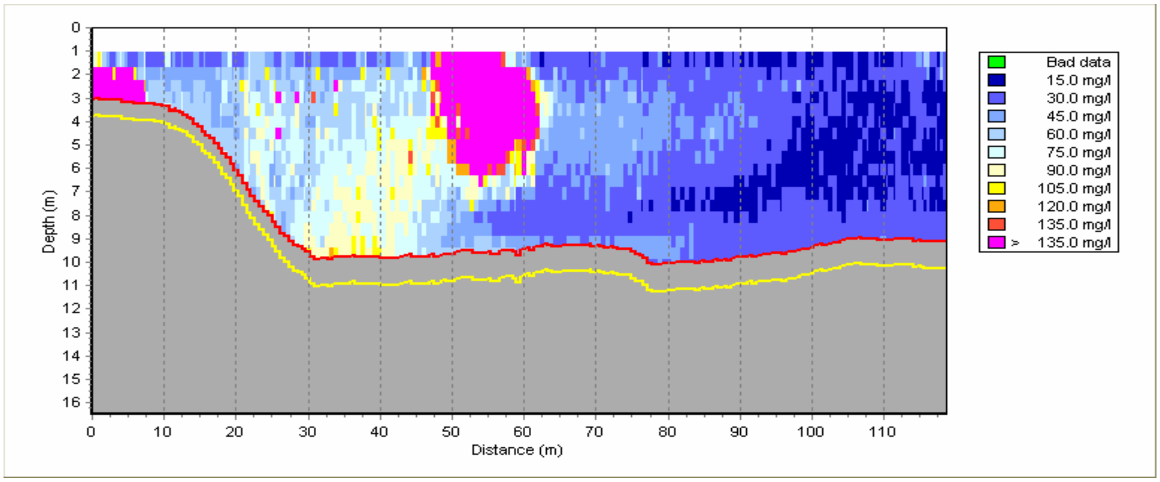

Figure 59. (RKEA015) Perpendicular course, barge now 365 m from transect. Time reference = 5 minutes.

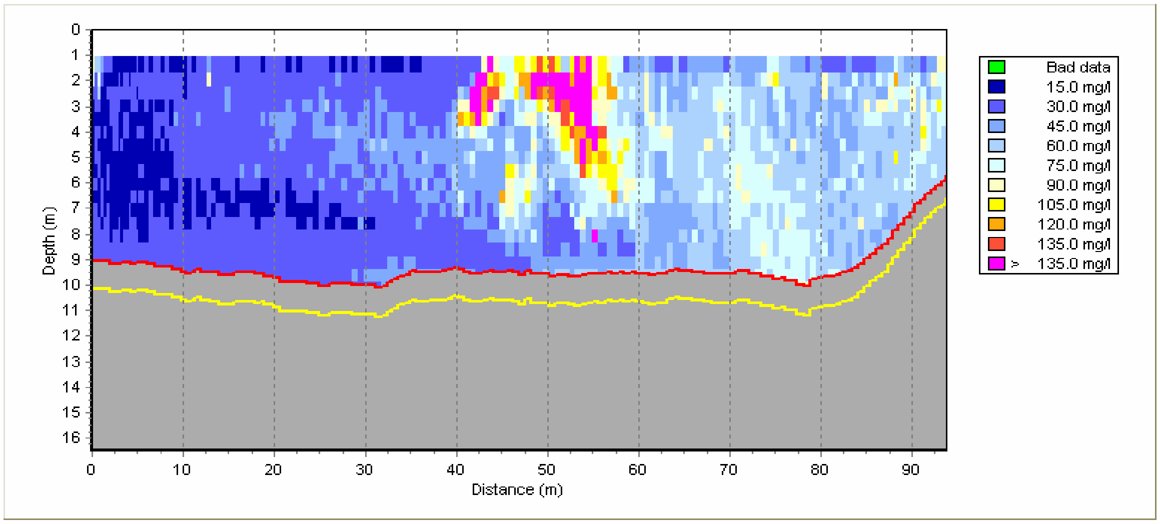

Figure 60. (RKEA016) Perpendicular course, barge now 490 m from transect and turning. Time reference = 7 minutes.

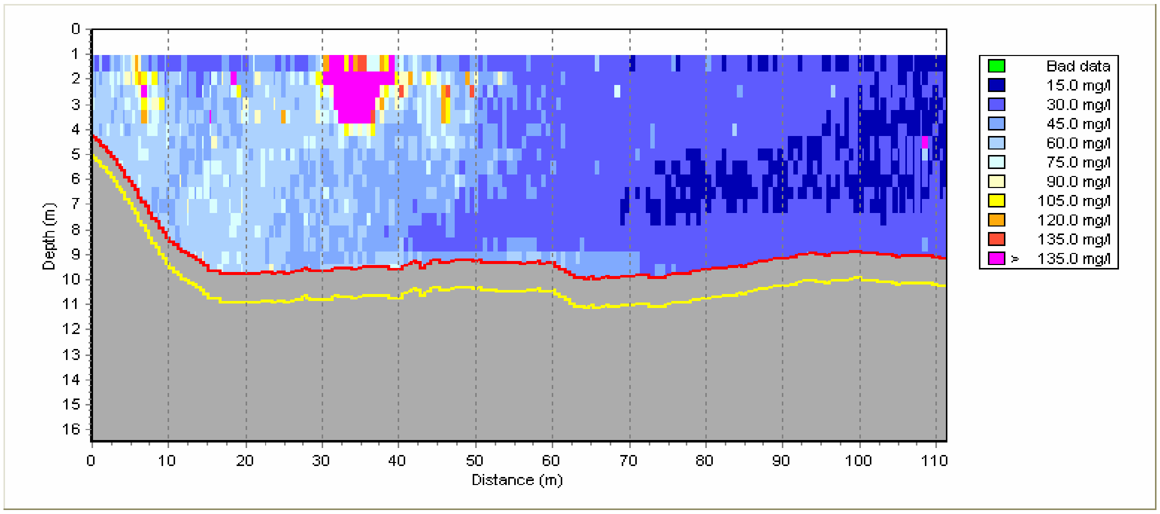

Figure 61 (RKEA017) Perpendicular course, barge approaching at 365 m. Time reference = 9 minutes.

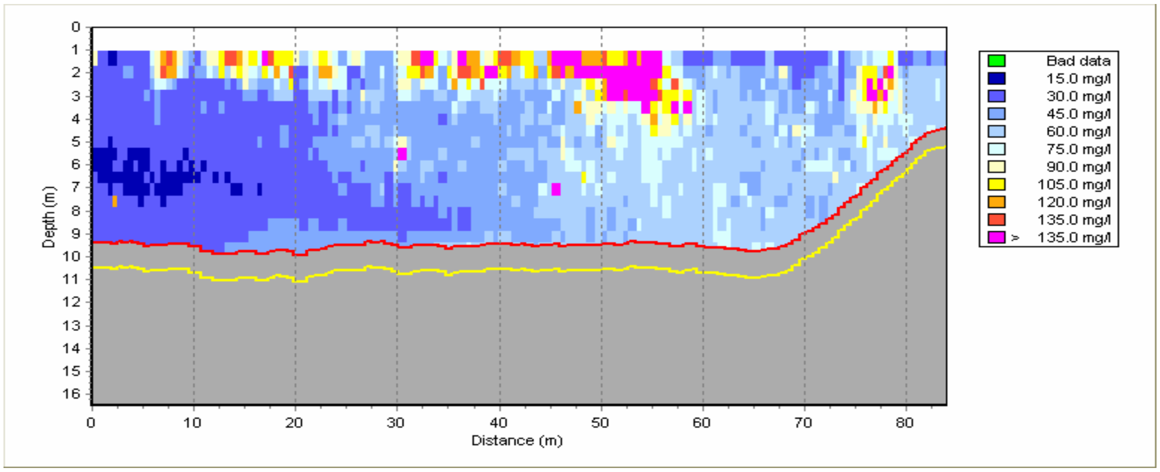

Figure 62. (RKEA018) Perpendicular course, barge approaching at 210 m. Time reference = 13 minutes.

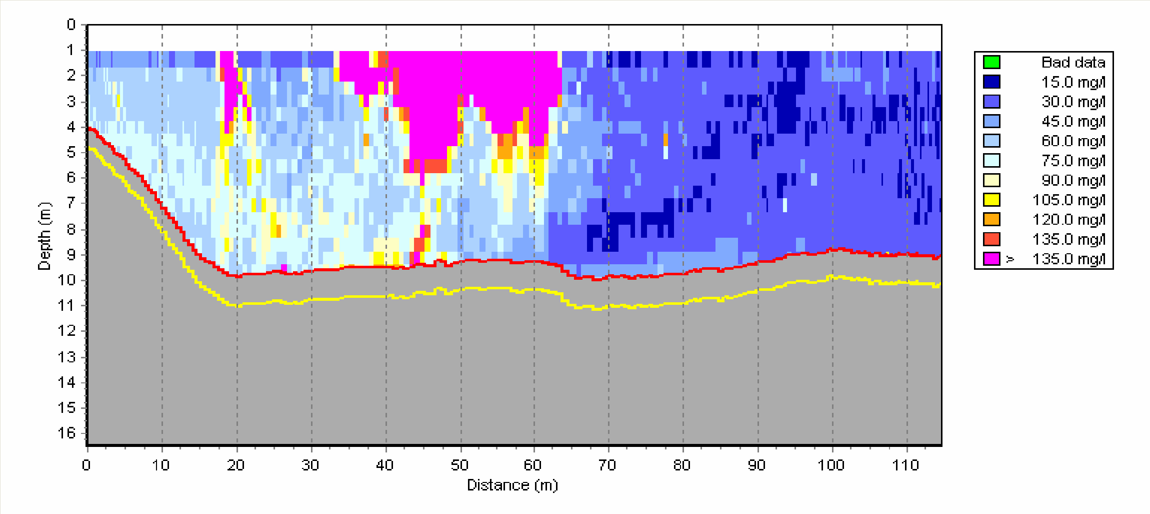

Figure 63. (RKEA019) Perpendicular course, barge passes 30 m beyond transect. Time reference = zero.

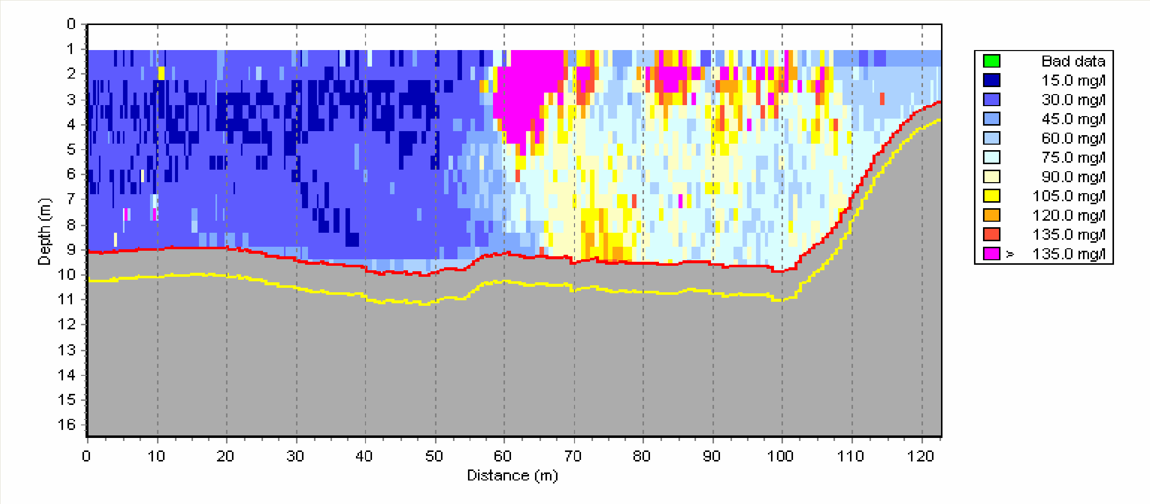

Figure 64. (RKEA020) Perpendicular course, barge now 240 m from transect. Time reference = 2 minutes.

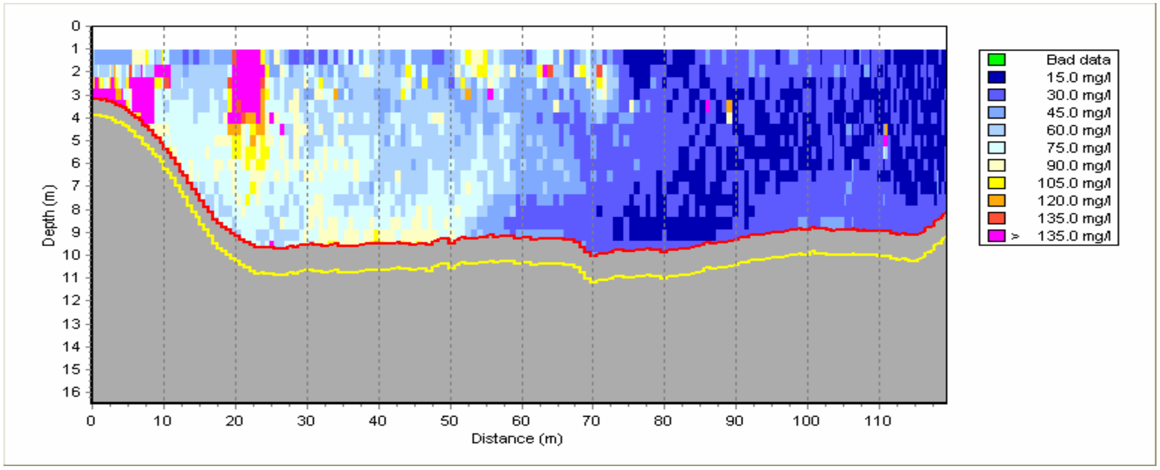

Figure 65. (RKEA021) Perpendicular course, barge now 445 m from transect. Time reference = 5 minutes.

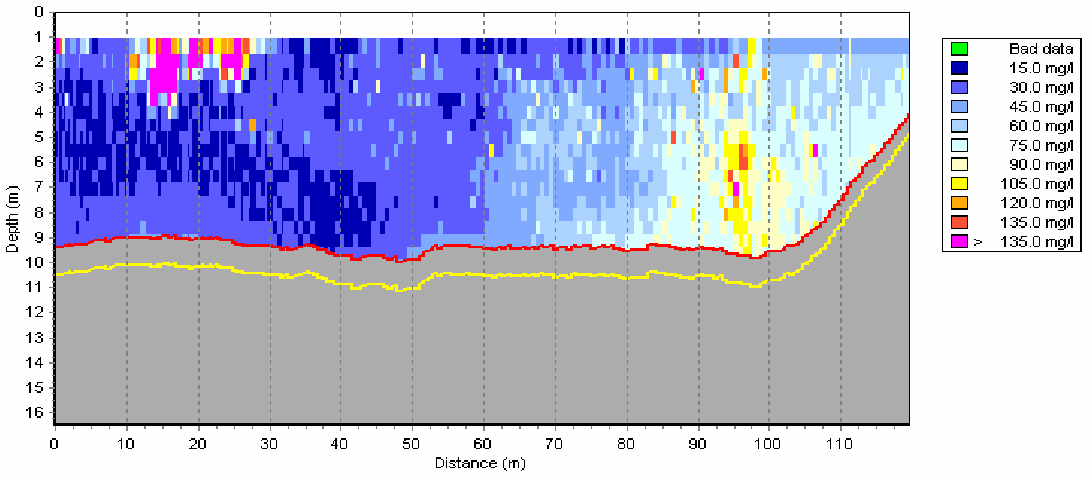

Figure 66. (RKEA022) Perpendicular course, barge now 415 m from transect and turning. Time reference = 7 minutes.

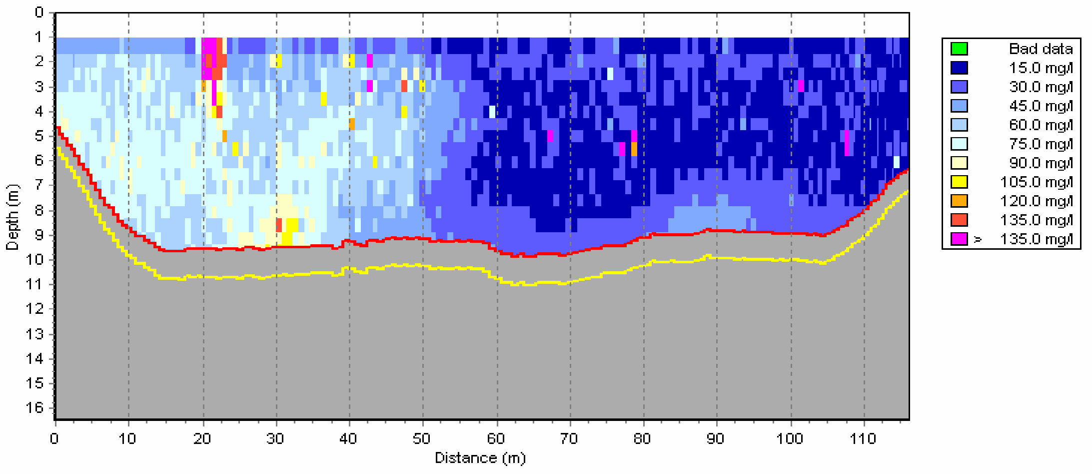

Figure 67. (RKEA023) Perpendicular course, barge now approaching transect at 345 m. Time reference = 9 minutes.

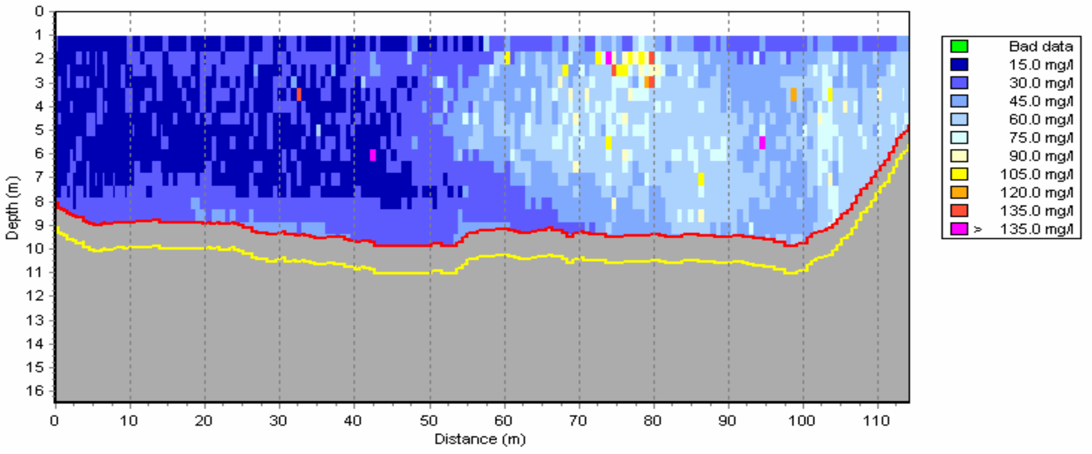

Figure 68. (RKEA024) Perpendicular course, barge approaching transect at 215 m. Time reference = 11 minutes.

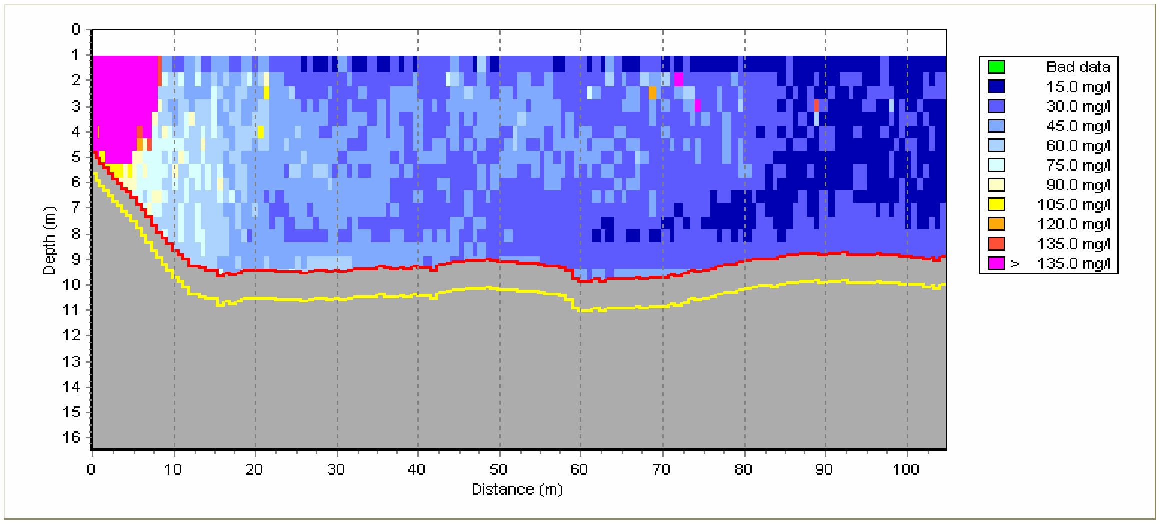

Figure 69. (RKEA025) Perpendicular course, barge approaching transect at 85 m. Time reference = 14 minutes.

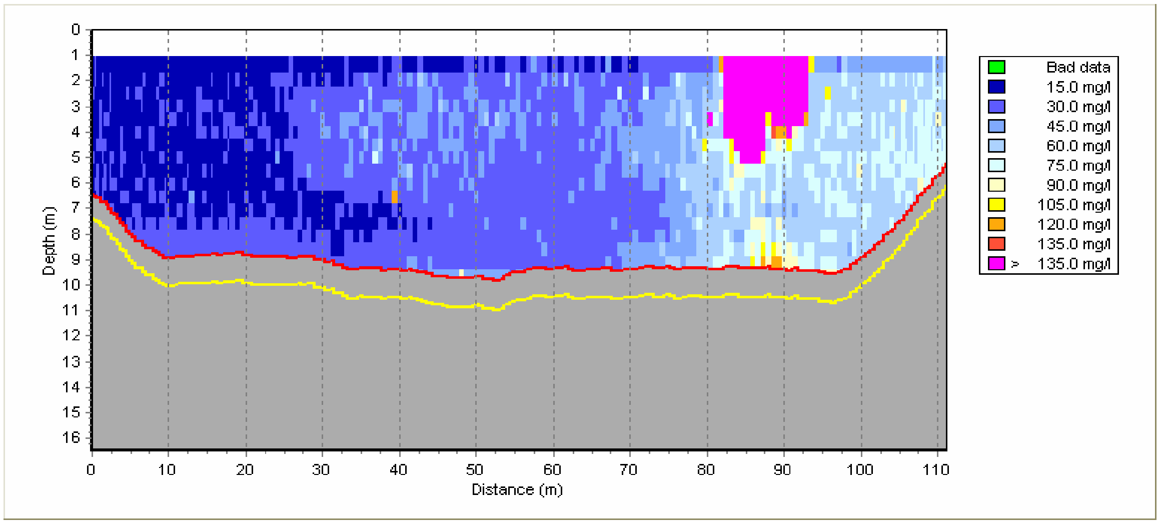

Figure 70. (RKEA026) Perpendicular course, barge passes 40 m beyond transect. Time reference = zero.

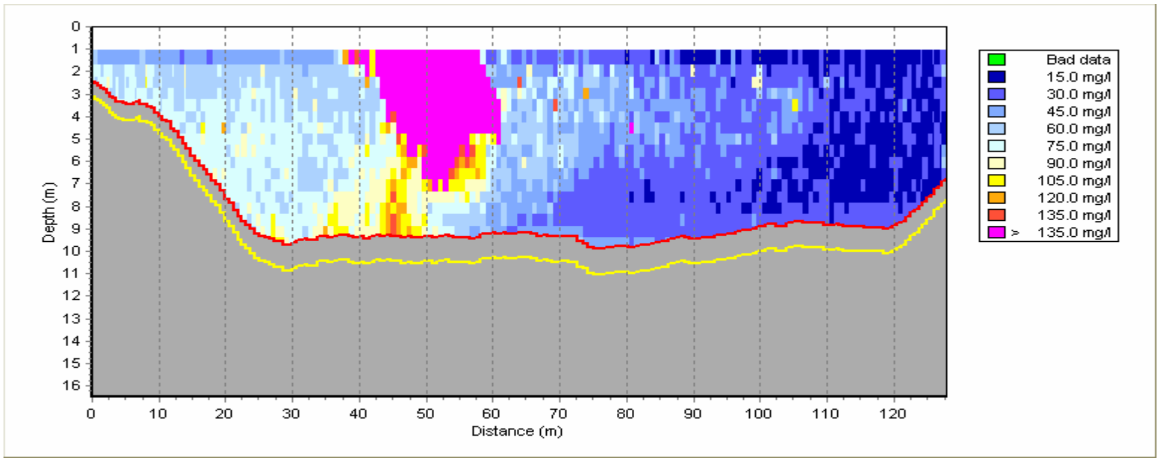

Figure 71. (RKEA027) Perpendicular course, barge now 90m from transect. Time reference = 1 minute.

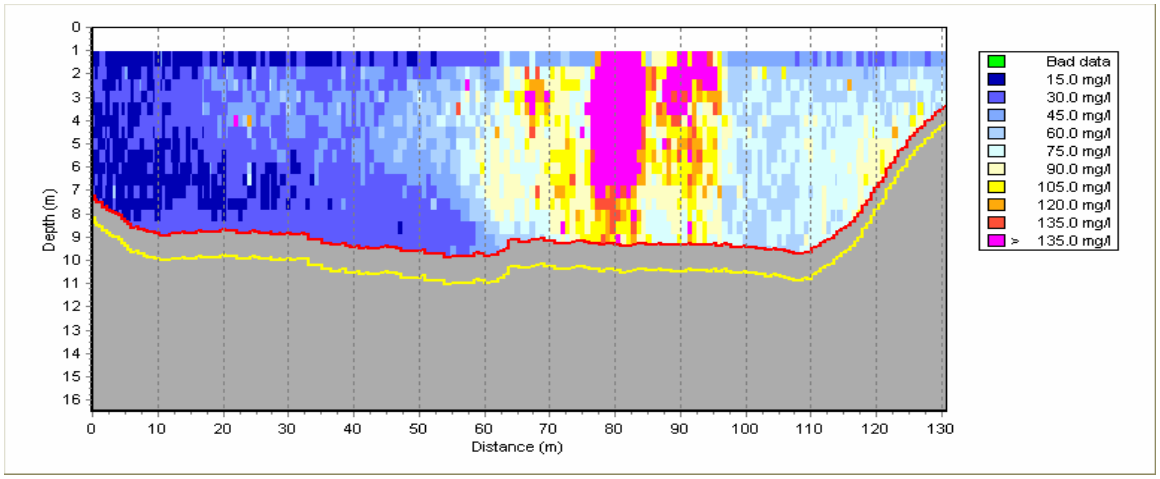

Figure 72. (RKEA028) Perpendicular course, barge now 275 m from transect. Time reference = 4 minutes.

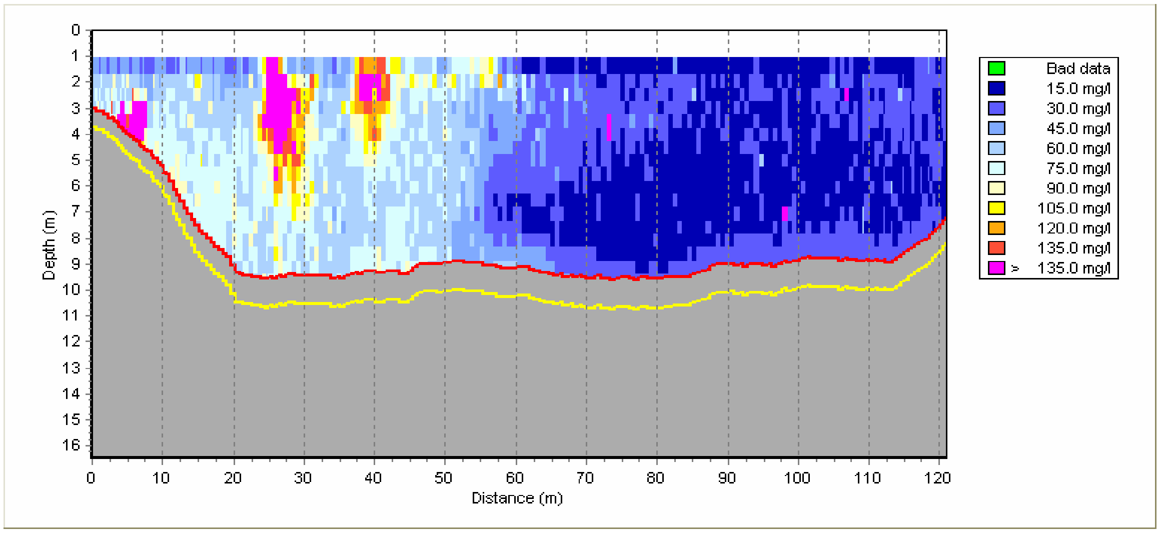

Figure 73. (RKEA029) Perpendicular course, barge now 360 m from transect. Time reference = 6 minutes.

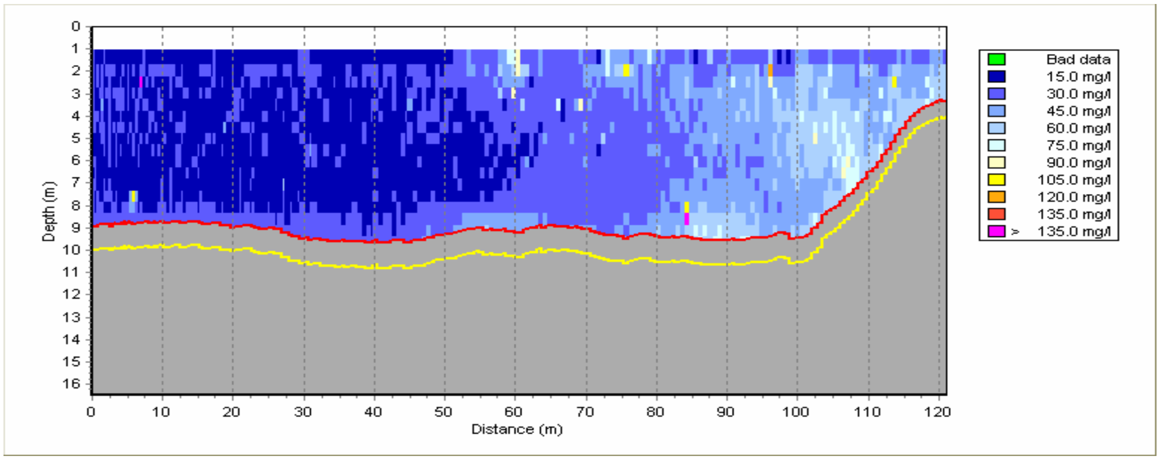

Figure 74. (RKEA030) Perpendicular course, barge now 500 m from transect and turning. Time reference = 8 minutes.

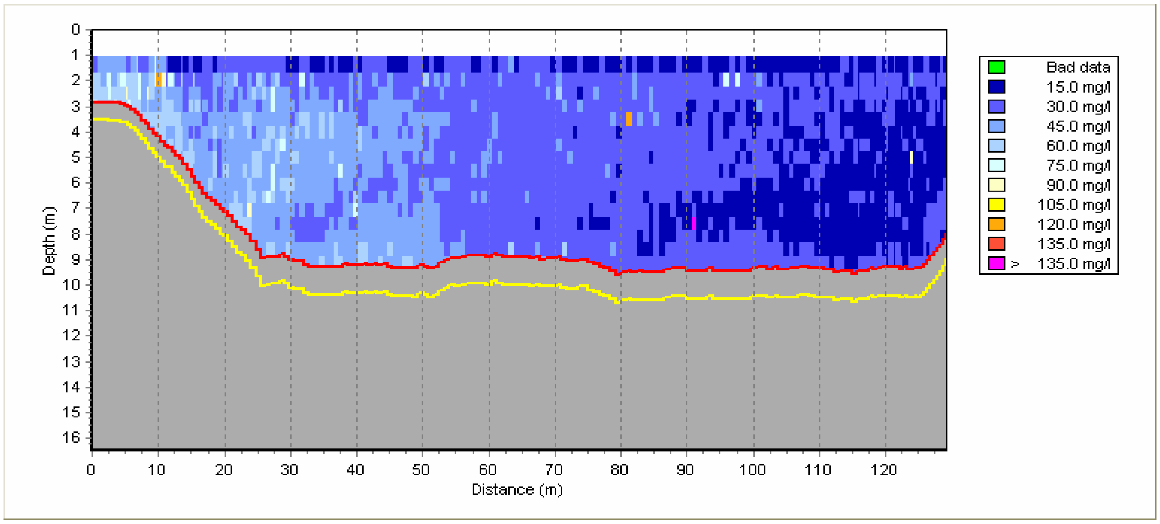

Figure 75. (RKEA031) Perpendicular course, barge approaching transect at 335 m. Time reference = 11 minutes.

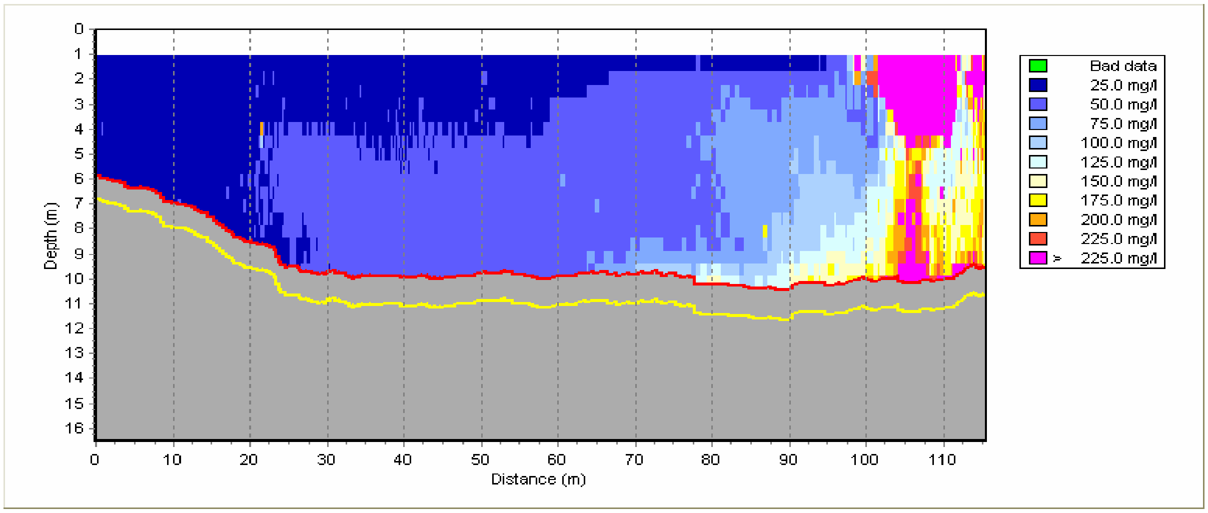

Figure 76. (RKEC005) Perpendicular course, barge passes 50 m beyond transect. Time reference = zero.

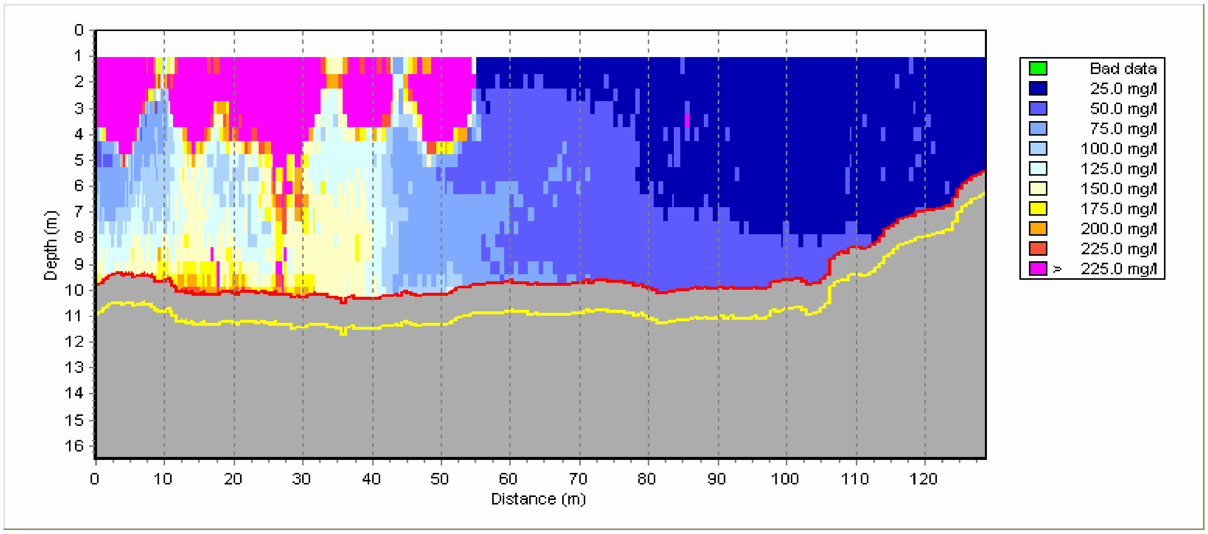

Figure 77. (RKEC006) Perpendicular course, barge now 120 m from transect. Time reference = 3 minutes.

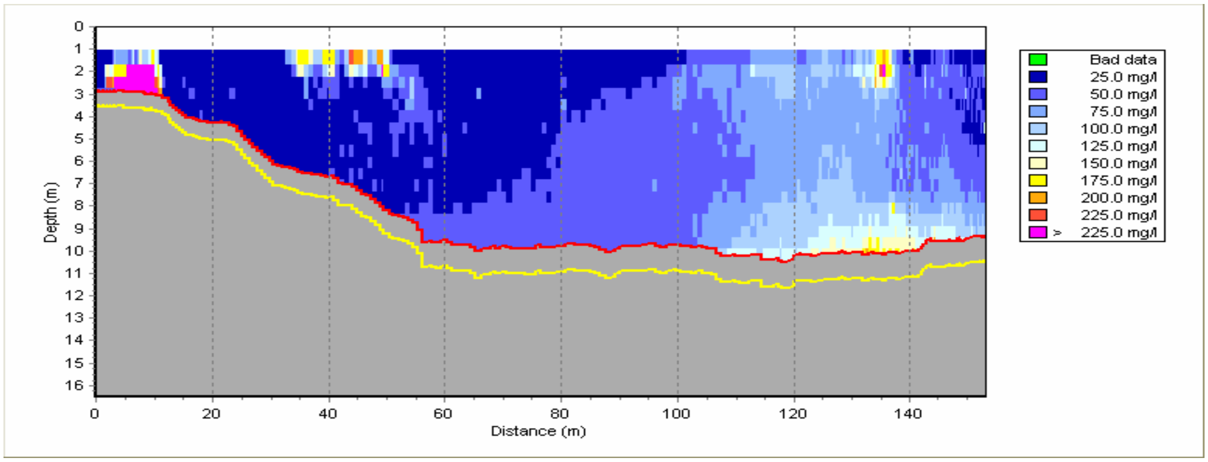

Figure 78. (RKEC007) Perpendicular course, barge now 245 m from transect and turning. Time reference = 6 minutes.

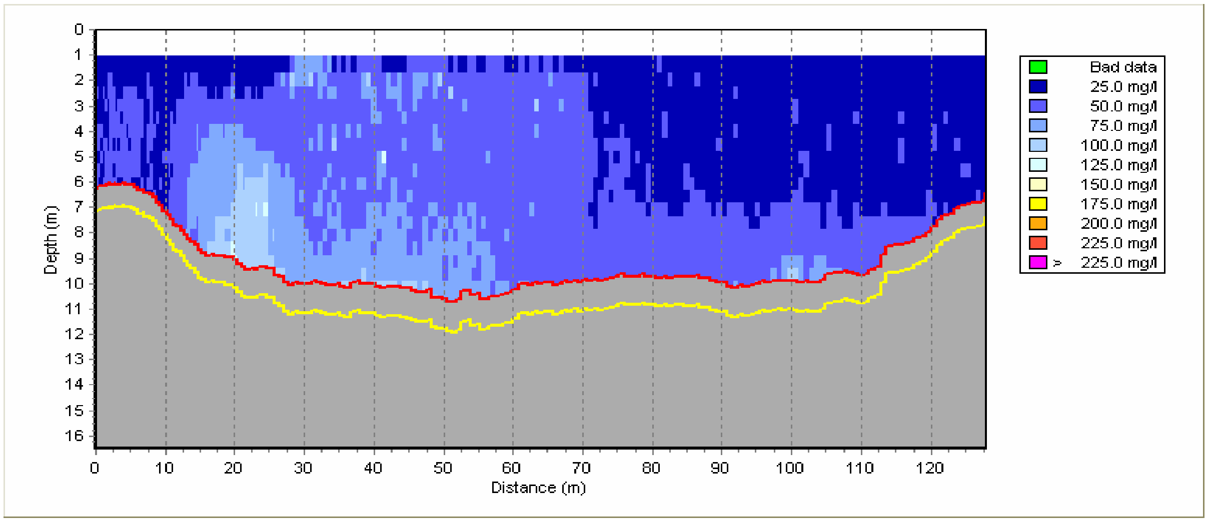

Figure 79. (RKEC008) Perpendicular course, barge approaching transect at 220 m. Time reference = 8 minutes.

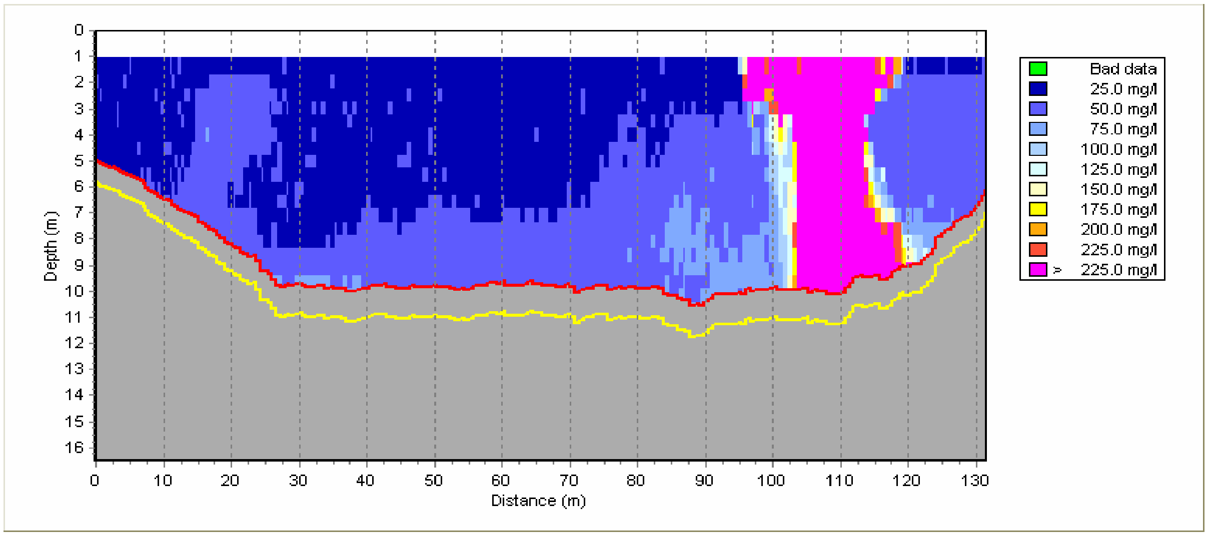

Figure 80. (RKEC009) Perpendicular course, barge passes 75 m beyond transect. Time reference = zero.

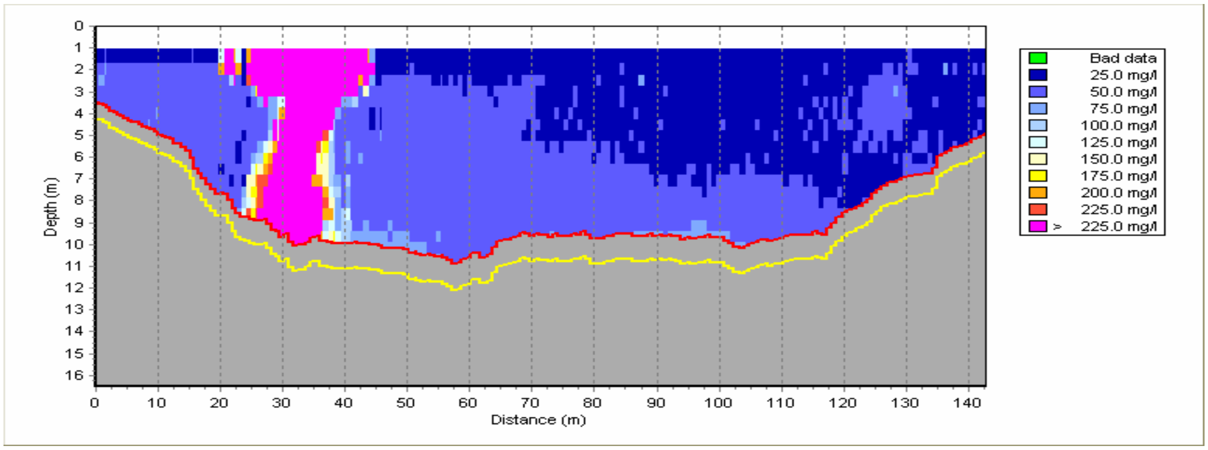

Figure 81. (RKEC010) Perpendicular course, barge now 120 m from transect. Time reference = 2 minutes.

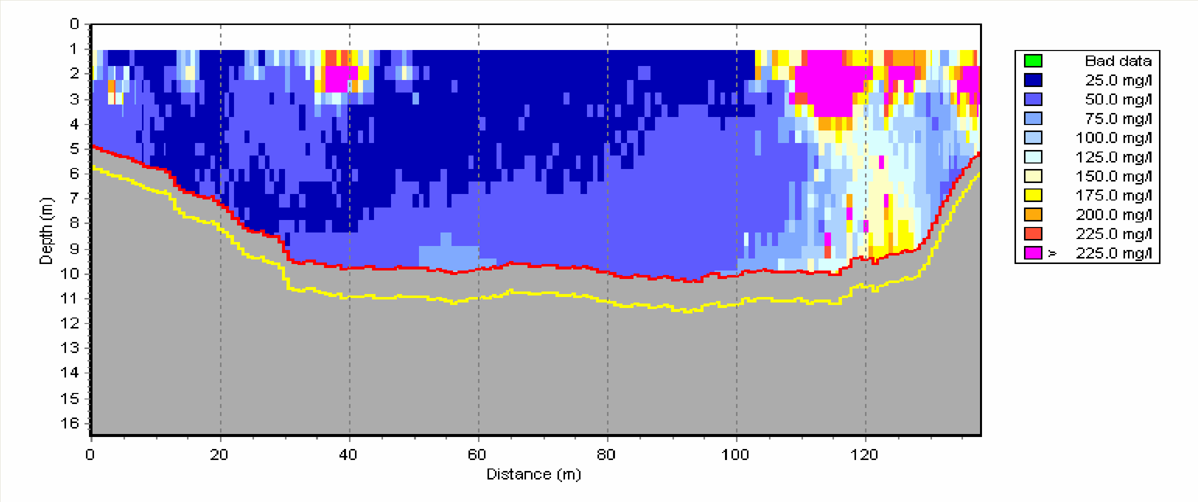

Figure 82. (RKEC011) Perpendicular course, barge now 200 m from transect and turning. Time reference = 5 minutes.

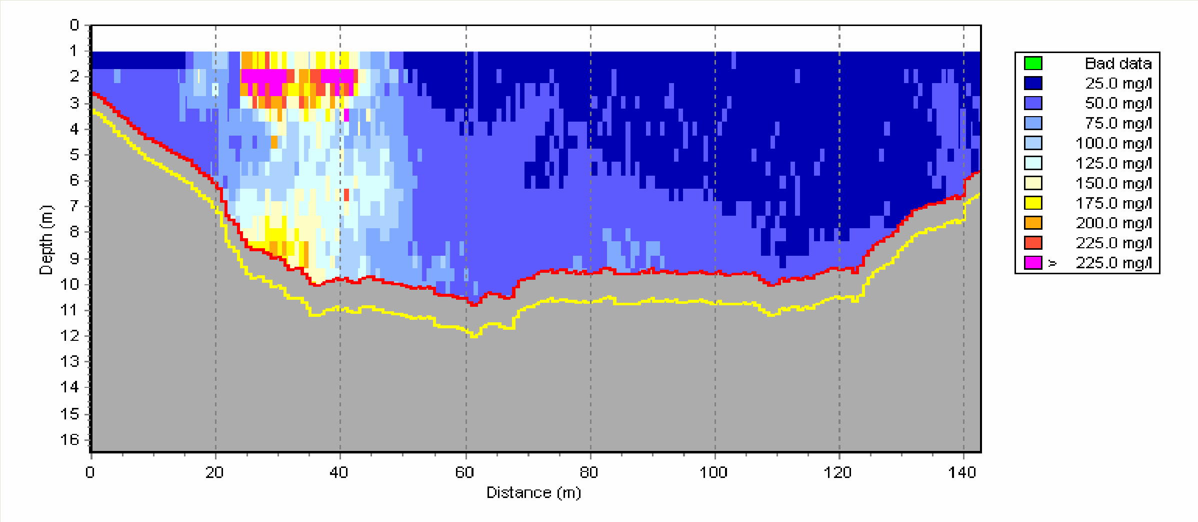

Figure 83. (RKEC012) Perpendicular course, barge approaching transect at 183 m. Time reference = 7 minutes.

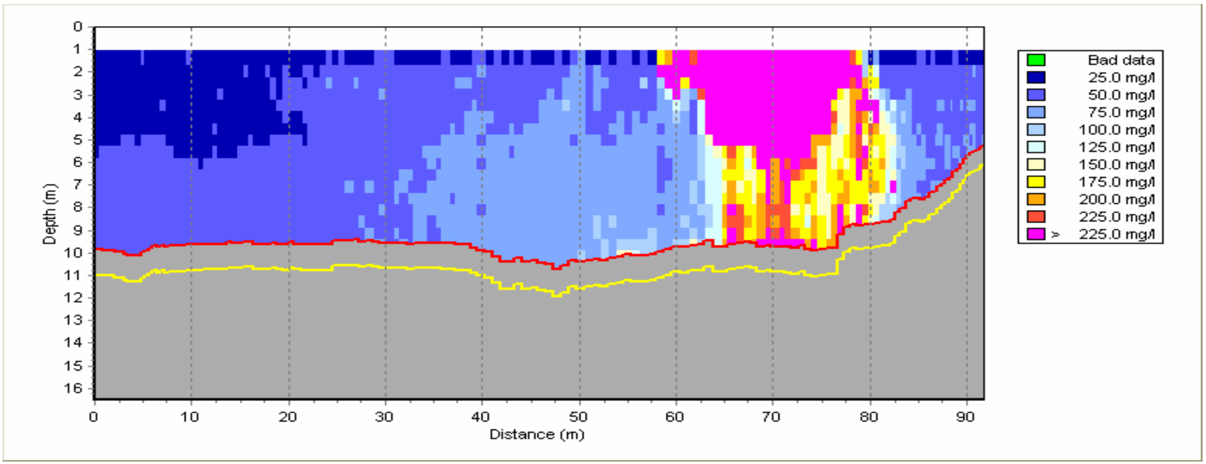

Figure 84. (RKEC013) Perpendicular course, barge passes 60 m beyond transect. Time reference = zero.

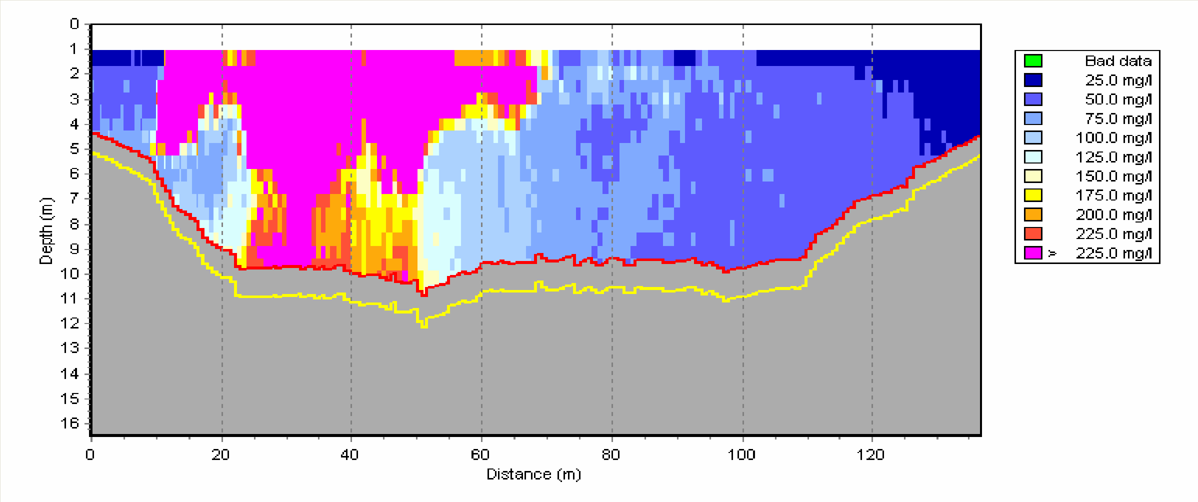

Figure 85. (RKEC014) Perpendicular course, barge now 200 m from transect. Time reference = 2 minutes.

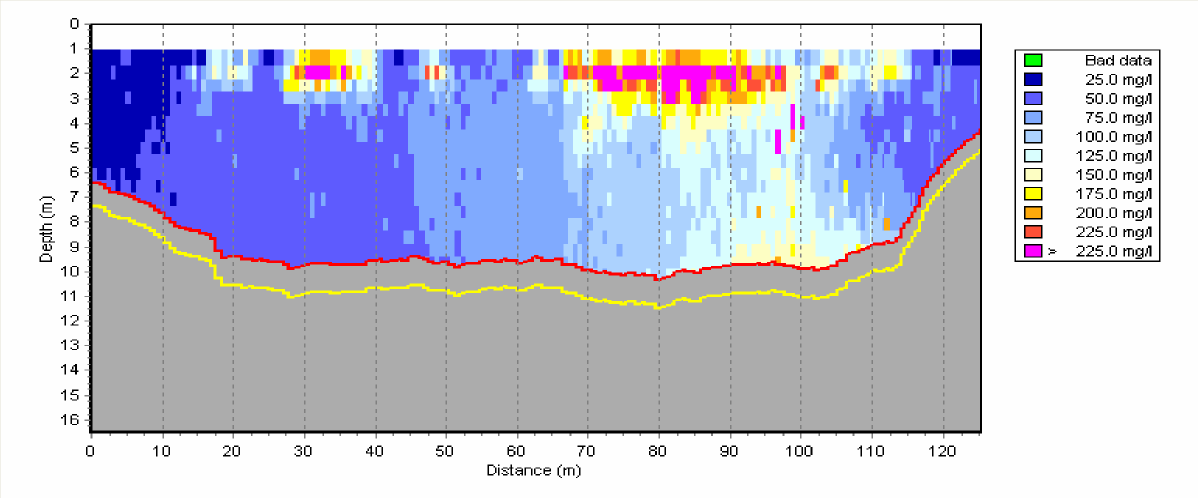

Figure 86. (RKEC015) Perpendicular course, barge now 235 m from transect. Time reference = 5 minutes.

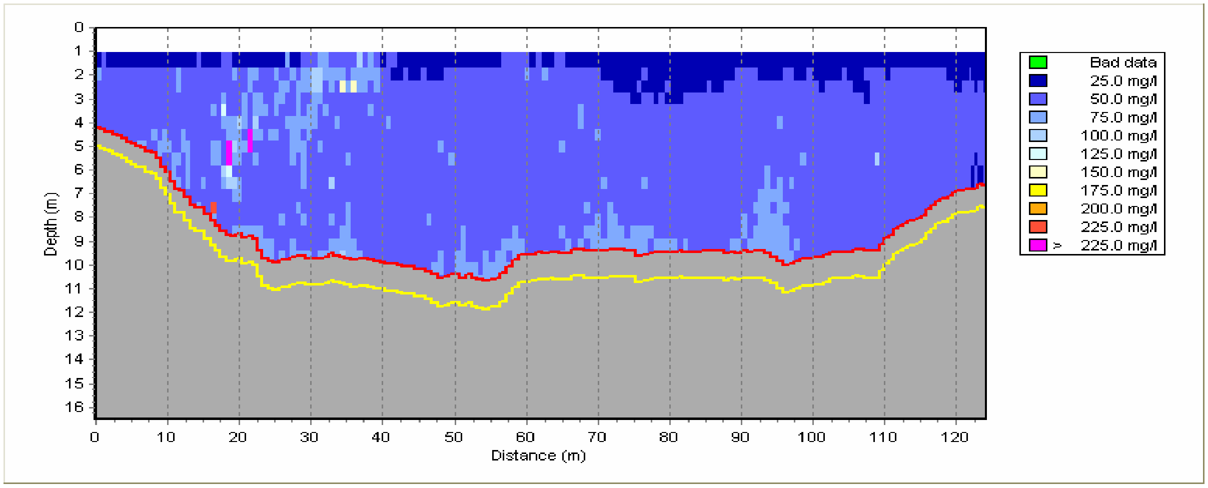

Figure 87. (RKEC016) Perpendicular course, barge now 300 m from transect and turning. Time reference = 7 minutes.

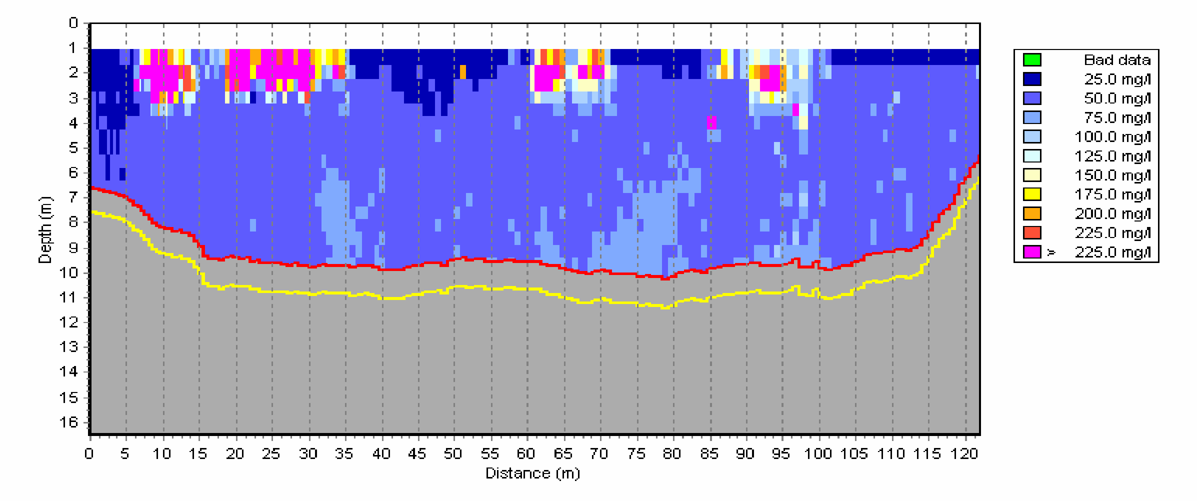

Figure 88. (RKEC017) Perpendicular course, barge approaching transect at 235 m. Time reference = 9 minutes.

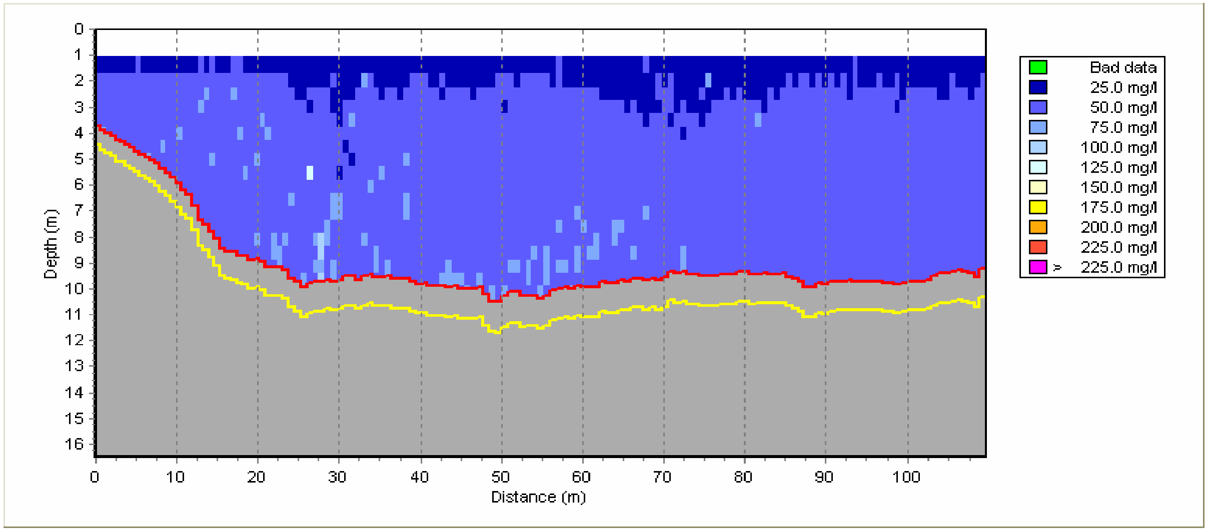

Figure 89. (RKEC018) Perpendicular course, barge approaching transect at 210 m. Time reference = 11 minutes.

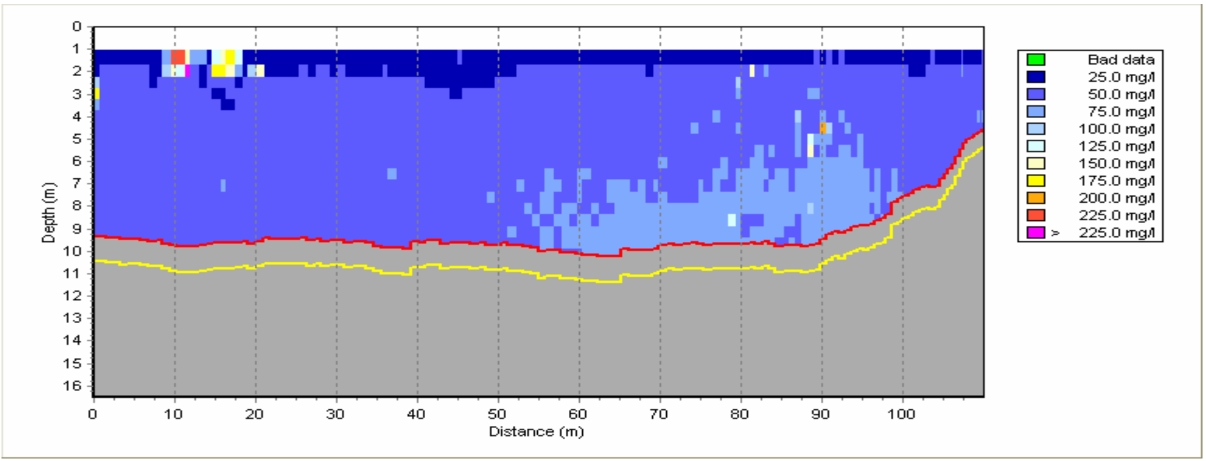

Figure 90. (RKEC019) Perpendicular course, barge approaching transect at 130 m. Time reference = 13 minutes.

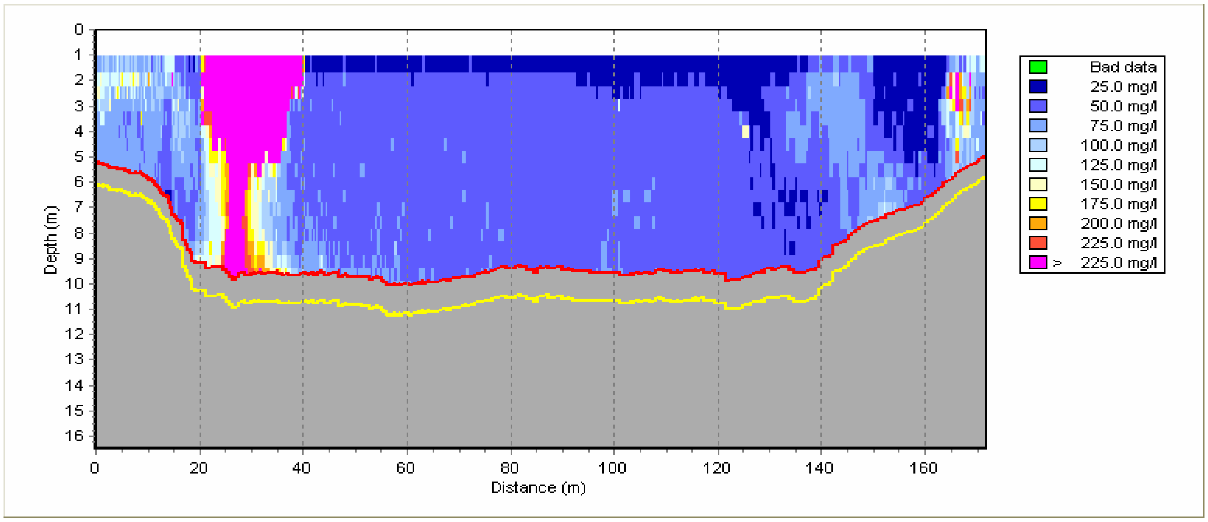

Figure 91. (RKEC020) Perpendicular course, barge passes 40 m beyond transect. Time reference = zero.

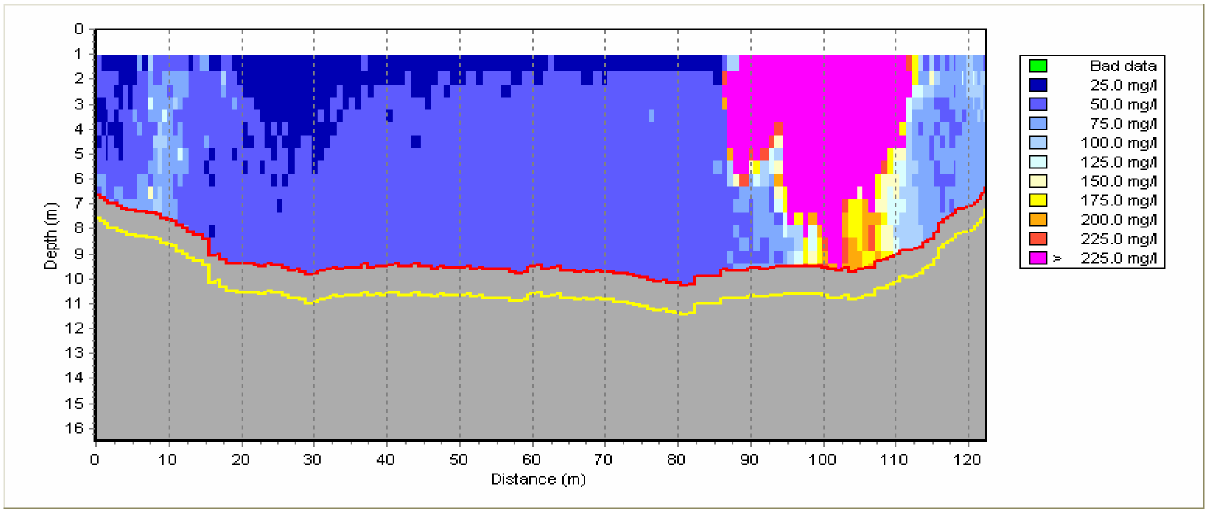

Figure 92. (RKEC021) Perpendicular course, barge now 135 m from transect. Time reference = 4 minutes.

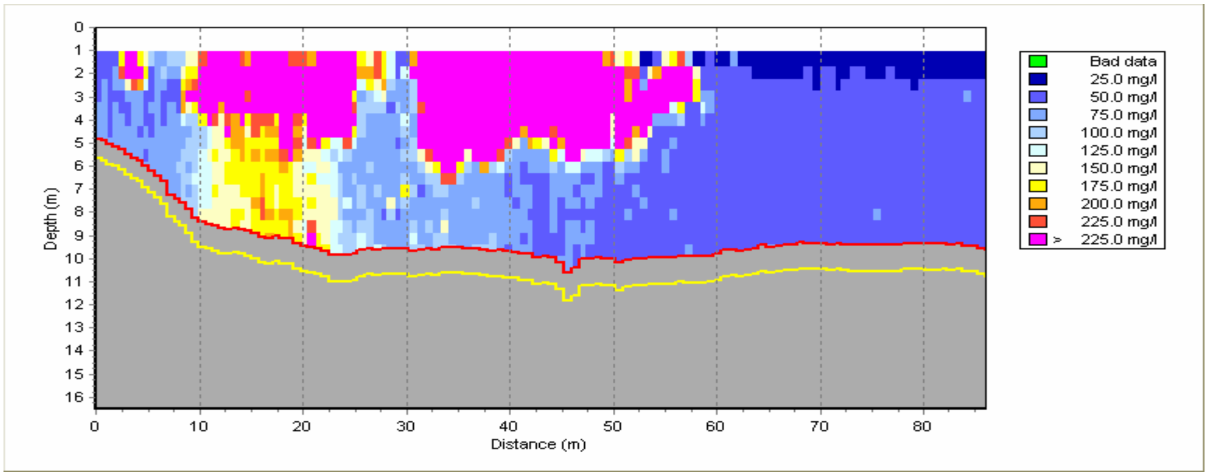

Figure 93. (RKEC022) Perpendicular course, barge now 122 m from transect. Time reference = 6 minutes.

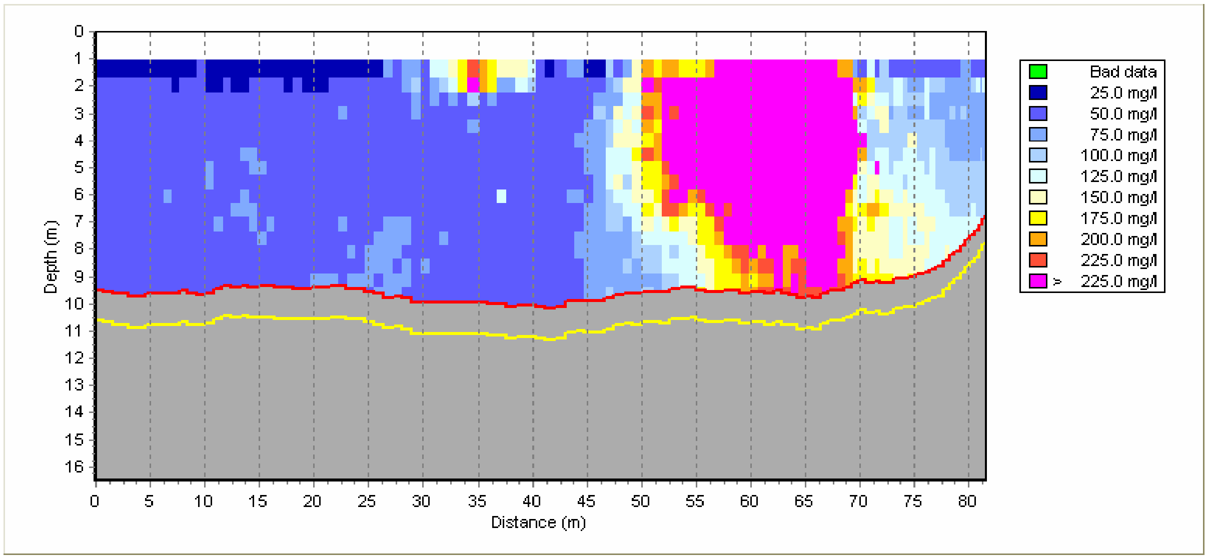

Figure 94. (RKEC023) Perpendicular course, barge now 105 m from transect and turning. Time reference = 8 minutes.

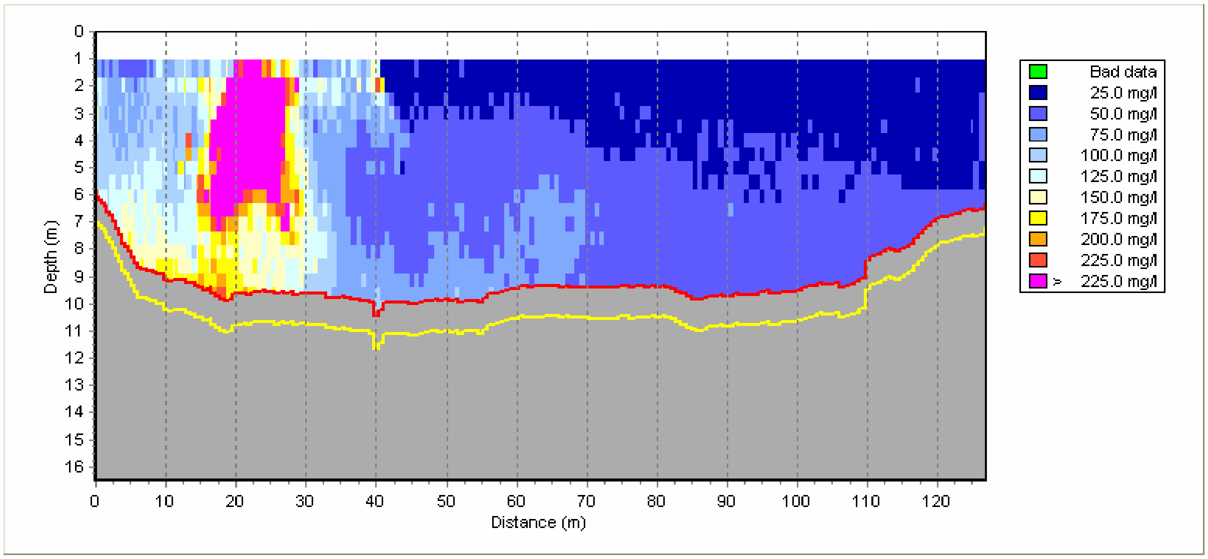

Figure 95. (RKEC024) Perpendicular course, barge approaching transect at 70 m. Time reference = 9 minutes.