APPENDIX 3

ASSESSMENT OF SUSPENDED SEDIMENT PLUMES ASSOCIATED WITH NAVIGATION DREDGING IN THE ARTHUR KILL WATERWAY, NEW JERSEY

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1 PURPOSE

The purpose of the total suspended sediment (TSS) sampling was to understand and quantify to the fullest extent possible the sediment resuspension associated with fine-grained sediment dredging operations within the Newark Bay Study Area (NBSA). The objectives of this study focus on determining the amount of sediment that is in the water column under normal (ambient) conditions and comparing it to the amount produced by dredging. Sediment added to the water column from dredging generally takes the form of a “plume” with higher concentrations near the dredge and decreasing concentrations as distance from the dredge increases, depending on tidal and weather conditions as well as sediment characteristics.

The objectives of this study were to determine:

1) Ambient turbidity and Total Suspended Solids (TSS) concentrations within the selected study area.

2) Spatial structure and temporal dynamics (extent and duration) of suspended sediment plumes associated with dredging activities in areas with fine-grained sediment.

3) Relationships between gravimetric, optical, and acoustic measurements of turbidity and TSS within the selected study area.

4) An estimate of the amount of sediment released into the water column for use in modeling applications.

This study was conducted as part of the U.S. Army Corps of Engineers – New York District’s (USACE-NYD) Harbor Deepening environmental program within the New York/New Jersey Harbor. TSS data collected from this study was used to calibrate and validate the modeling effort (EA Appendix 1) for the current NBSA environmental assessment (EA).

1.1 Background

For more than two centuries, the United States Army Corps of Engineers (USACE) has played a major role in the development and ongoing maintenance of NY/NJ Harbor as one of the nation’s largest and most viable commercial ports. To remain competitive in a rapidly changing and now global marketplace, however, ports nationwide must be able to accommodate the newest generation of deep-draft container ships. Recognizing this need for continued improvement of the Harbor's navigational channels, the Port Authority of New York/New Jersey (PANY/NJ) and the USACE – New York District (USACE-NYD), in coordination with a variety of state and federal agencies, have begun a comprehensive dredging program known collectively as the NY/NJ Harbor Deepening Project (HDP). A key component of the HDP as initially defined in the Final Environmental Impact Statement (FEIS) for the NY/NJ Harbor Navigation Study (December 1999) involves the deepening of the main navigational channels of NY/NJ Harbor to a depth of 50 feet.

During dredging operations, some sediment is typically resuspended into the water column. In many cases, this suspended sediment is evident as visible turbidity plumes within the vicinity of the dredge operation. Potential impacts of sediment resuspension and subsequent deposition on aquatic organisms and their habitats have been a persistent concern of environmental resource agencies. To address aspects of these concerns, an understanding of dispersion of resuspended sediment from dredging sources is required.

Because suspended sediment plumes are dynamic rather than static phenomena and because they vary over large areas in short periods of time, particularly when driven by tidal forces, characterizing plumes can present a difficult challenge. Data collected at arbitrary determined points in time at fixed locations are inadequate to assess dredge plume structure. However, advanced acoustic technologies offer advantages in capturing data at appropriate spatial and temporal scales to allow more accurate interpretation of plume dynamics.

1.2 Study Area

This study was performed by the USACE-NYD in June 2006 to determine the spatial dimensions, concentration gradient structures, and temporal dynamics of suspended sediment plumes during flood and ebb tidal phases during dredging associated with harbor deepening in the Arthur Kill navigation channel north of Shooters Island (Arthur Kill 2/3 contract), west of the Bayonne Bridge and east of Howland Hook in New Jersey waters (Figure 1).

The North of Shooters Island Reach navigation channel is approximately 1,000 feet wide and is a heavy vessel traffic area frequented by tugs and barges as well as large deep draft vessels including container ships and car carriers. Typical water depths within the main channel range between 35 and 45 feet. North of the channel water depths quickly drop off to less than five feet in extensive shallows that stretch to the Elizabeth, New Jersey shoreline. Immediately south of the navigation channel lies the shoreline of Shooters Island, which is lined with abandoned and partially submerged pier pilings and rip-rap. Currents of the North of Shooters Island Reach are influenced by the tidal fluctuations at the confluence of the Arthur Kill and Kill Van Kull waterways and Newark Bay.

1.3 Dredge Plant

Equipment and operational measures significantly affect sediment resuspension. The dredge contractor, Donjon Marine Company, Inc., used the mechanical dredge *Michigan*, configured with an 18-cubic-yard capacity environmental cable arm bucket (Figures 2 and 3). The cable arm bucket is a version of a "closed" environmental clamshell bucket designed specifically to minimize release of sediment to the water column while allowing the operator precise positional control of the bucket. In contrast to conventional "grab" buckets, the cable arm can produce a relatively level cut when removing bottom sediment, thereby enhancing vertical as well as horizontal control. For harbor deepening navigation dredging, the cable arm is being used to remove surface layers of maintenance overburden to a "depth of refusal".

In addition to the use of a closed environmental clamshell bucket, operational measures to reduce overall sediment resuspension are included in the best management practices followed for the project. Measures ensuring full bucket closure and controlled penetration of the bucket into the substrate are collectively used as "best management practices" (BMP) to achieve minimal resuspension.

2 METHODS

2.1 Overall Survey Design

Sediment plumes were characterized by tandem deployments of moored turbidity sensors and mobile acoustic Doppler current profiler (ADCP) surveys. An RD Instruments 600-kHz Mariner Workhorse Series ADCP was used to collect current velocity, current direction, and acoustic backscatter data. RD Instruments WinRiver software was used for real time display of plume acoustic signatures and data recording. Data were recorded in horizontal and vertical bins of predetermined sizes (30 0.5-meter vertical bins) to optimize plume resolution. Depth, water temperatures and navigation data were collected concurrently and integrated during post-processing.

In addition to measuring current velocities and vectors, the ADCP records relative acoustic backscatter from sediment particles and other reflectors in suspension. The backscatter data were collected during ebb and flood tidal phases from 19 through 23 June 2006. Survey transects were oriented in a north-south direction, perpendicular to the channel, and extended down-current until plume acoustic signatures could not be detected against background conditions. Additional survey lines were conducted, when feasible given the configuration of the dredging plant, parallel to the port and starboard sides of the dredge and barge in an east-west direction.

Individual transect length was generally determined by bathymetry at the site, but always with the objective of extending beyond the detectable boundaries of the plume. Numbers, and consequently spacing, of cross-plume transects were maximized within the designated tidal phase. Composite surveys provided complete spatial coverage of the detectable plumes and optimal resolution of internal plume structure.

2.2 Current Regime Survey

ADCP data provided characterization of prevailing water circulation in the North of Shooters Island Reach. Raw data for all ambient and plume transects were processed and examined for evidence of stratified flows, tidal eddies, and other patterns that could influence plume dispersion.

2.3 Plume Surveys

2.3.1 Ambient

Ambient data was collected to establish background conditions within the study area. This data is used as a basis of comparison of turbidity and suspended solids concentrations within the dredge plume. Ambient suspended sediment concentrations were characterized by conducting transects well outside of the area influenced by plumes and during times of prolonged shutdowns by the dredge plant. Ambient data were collected during survey events on 19, 21, and 22 June 2006. Because dredging activities began prior to the arrival of the field survey crew, no pre-dredging ambient data were collected.

- On 19 June, six (6) north-south transects were conducted up-current from the dredging operation during the early portion of a flooding tide. This survey was repeated during the later stage of the tidal cycle and completed one hour prior to maximum flood conditions.

- On 21 June, two (2) down-current and four (4) up-current, east-west transects were conducted during a flooding tide while the dredge was inactive. The dredge was inactive for approximately five hours before ambient data was collected.

- On 22 June, two (2) east-west transects, each running the length of the study area, were conducted during an ebbing tide. These data were collected before dredging activities resumed at approximately 0935 hours. The dredge had shut down for maintenance and repairs the previous evening at approximately1735 hours.

2.3.2 Ebb

Two (2) plume characterization surveys were completed during the first half (1500-1800 hours) of an ebbing tide (peak ebb at 2230 hours) on 19 June. The first survey (designated Survey NJEA) consisted of 24 transects (Figure 4). The downstream extent of the survey was based on the observed decay of the plume to relative ambient conditions. Six (6) transects were conducted on the up-current side of the dredging operation, from approximately two meters astern of the dredge out to approximately 150 meters west of the dredge, terminating near Channel Marker 16A.

Eleven (11) transects were conducted down-current from the dredge in the direction of plume movement. The first of these was located approximately 25 meters from the point of insertion of the bucket into the water. Ensuing transects were conducted east of this position, towards Channel Markers 16 and 17 at progressive increments of approximately 25 to 30 meters. Orientation of both up- and down-current transects were perpendicular to the channel axis and the dredge plant and ran in a general north-south direction. Seven (7) transects, four (4) along the starboard side of the dredge and three (3) along the port side, were run in an east-west direction parallel to both the channel and dredge plant. Transect length ranged from approximately 110 to 248 meters (mean = 188 meters).

A second survey (designated Survey NJEB) was completed on 19 June. A total of 12 transects were necessary to cover the full extent of the plume (Figure 4). One (1) up-current transect was conducted at a distance of approximately 10 meters from the dredge plant to confirm that no sediment was moving west of the dredge's position. Two (2) transects consisted of circles around the derrick and barge at distances of approximately 5 and 10 meters from the dredge and barge. Nine (9) down-current transects were conducted in an easterly direction terminating at Channel Markers 16 and 17.

2.3.3 Flood

A plume characterization survey (designated NJFD) was completed during the early portion (1050-1230 hours) of a flooding tide (peak flood = 1638 hours) on 20 June. Twenty-eight transects were needed to adequately cover the full extent of the plume (Figure 5). Transect orientation followed a pattern similar to that used during the ebb tide surveys. Four (4) cross-channel transects beginning at Channel Markers 16 and 17, running perpendicular to the dredging operation and navigation channel were conducted up-current from the dredge to assess ambient conditions. Nineteen (19) cross-channel transects were conducted down-current from the dredging operation in the direction of plume movement. The remaining five (5) transects: three (3) along the starboard side of the dredge and two (2) along the port side were run parallel to the dredge plant in an east-west direction. Transects extended from approximately 120 m east to approximately 620 meters west of the point of excavation. Distances between transects generally averaged 25 meters. Transect length ranged from approximately 101 to 316 meters (mean = 200 meters).

A second plume characterization survey (designated NJAB) was completed during the early portion (1430-1500 hours) of a flooding tide (peak flood = 1833 hours) on 22 June (Figure 5). Two (2) transects encircled the dredge at distances of approximately five and 20 meters. After completion of the two (2) initial transects, the dredge advanced east to just beyond Channel Marker 16A to begin a new cut. Three (3) additional transects were then run encircling the dredge at a distance of under 10 meters. The first transect was conducted as close to the dredge plant as was safely possible. Five (5) cross-channel transects were conducted down-current from the dredge, the first located approximately three meters from the point of excavation. Ensuing transects were conducted out to a distance of approximately 163 meters from the point source.

2.4 Fixed Buoy Turbidity Survey

D&A Instrument Company optical backscatter sensors (Model OBS-3A), capable of measuring turbidities in the 0-1,000 Nephelometric Turbidity Unit (NTU) range, were used in this study. OBS units project a beam of light into a known volume of water and measure the amount of light scattered out of the beam.

Ten (10) OBS units were deployed during each monitoring event to capture both ambient and plume data. In general, three (3) monitoring stations: one (1) up-current and two (2) down-current (Figure 6) were conducted at the dredge site. At each station, three-four OBS units were deployed at varying depths from the surface to the bottom. Whenever possible, OBS units were tethered to a taut line buoy and anchored at predetermined locations. When this technique was impractical (i.e. during periods of frequent commercial vessel passage) OBS units were hung from the survey boat and data were collected for a minimum of 15 minutes. Data collection times varied depending on the method of deployment as well as other dredging associated activities (e.g., advances of the dredge along a cut or movements of empty or full barges by the dredge's tug).

During the flood tide survey (20 June), the ambient station was located approximately 150 meters up-current from the dredging operation and was isolated from the influence of the dredge plume. The station consisted of three (3) sensors located at depths of 4, 7.4 and 9.5 meters below the surface.

Ambient turbidity data were collected on two (2) occasions during ebbing tides at approximately 350 meters (22 June) and approximately 540 meters (23 June) up-current from the dredging operation. Three (3) sensors were deployed on 22 June at depths of approximately 1.9, 4.7 and 7.5 meters, whereas four sensors were deployed on 23 June at depths of approximately 0.5, 2, 5, and 8 meters.

Two (2) OBS arrays were located within the plume. The near-field array consisted of either three (3) (20 and 22 June) or four (4) sensors (23 June) at a distance of approximately 60 meters from the dredging operation. Although a down-current station distance of approximately 30 meters was targeted, this was not possible in two (2) of the data collection events due to orientation of the dredge and barge and direction of current flow. Sensor depth ranged from approximately 0.3 to 9.5 meters for near-field plume measurements. The far-field array used a similar deployment strategy to that of the inner array, but at a distance of approximately 150 meters down-current.

2.5 Water Samples

For calibration of the raw ADCP acoustic backscatter data conversion to Total Suspended Solids (TSS) concentration, a total of 100 water samples were collected using a Niskin-type water bottle deployed in a horizontal orientation. The water sampler had a capacity of 2.2 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 computer aboard the survey vessel, thereby providing real time NTU measurements during the water sampling. The water sampler was manually triggered to close when the observed backscatter signal from the ADCP and turbidity measurements from the OBS units were within a targeted range. All water samples were transferred to Severn Trent Laboratories, Inc., in Newburgh, New York for processing.

Of the 100 water samples taken, 24 were collected during an ebbing tide on 23 June to assess ambient conditions. The remaining 76 samples were collected during dredging operations, of which 21 were collected during a flooding tide and 55 were collected during an ebbing tide on 21 and 22 June. Samples were taken by lowering the water sampler to a specified depth. The water sampler was triggered manually when real-time ADCP data indicated the sampler was in the plume. The OBS NTU reading and ADCP ensemble number were recorded at the instant of trigger for each individual water sample.

2.6 Data Analysis

2.6.1 Suspended Sediment Plume Acoustic Signature Detection

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 TSS concentration. This process requires collecting a calibration data set consisting of discrete water samples analyzed gravimetrically. The sample population represents the concentration gradient at the study site and is used to “ground truth” the acoustic data. The calibration samples were collected at known locations within the water column, so that individual gravimetric samples can be directly compared with acoustic estimates of TSS concentration for a “bin” of water as close to the water sample as possible.

Because air is injected into the water column as the bucket breaks the air-water interface, and air bubbles are acoustic reflectors, care must be exercised in converting acoustic data derived very close to the operating bucket. Bubbles dissipate by rising to the surface with time. The distance down-current of bubble interference of the signal is therefore influenced by current velocities. During the present study, current flows were relatively slow to moderate, consistent with flows observed in the Providence River where a closed bucket was monitored during maintenance dredging operations (Reine et al. 2006). Experiments during the Providence River monitoring, in which the bucket was intentionally plunged through the air-water interface without removing sediment from the bottom, determined that the “bubble signature” pattern dissipated within approximately 50 meters of the source. Beyond 50 meters estimates of TSS concentration for the calibrated ADCP should be accurate.

2.6.2 TSS Water Sample Lab Analysis

Water samples were processed gravimetrically for TSS [milligrams per liter (mg/l)] and optically for turbidity (NTU) using standard laboratory procedures established for water and wastes, EPA-600/4-79-020, March 1983 and subsequent revisions. A single sediment grab was collected from the dredge scow during the monitoring effort for grain size analysis to assist in the calibration. This sample was processed according to procedures established by Plumb (1981).

2.6.3 Sediment Grain Size Analysis

During the monitoring effort, one sediment sample was collected from material placed in the dredge scow. This sample was analyzed for sediment grain size distribution to characterize the type of sediment being dredged during the survey period. The sediment sample was analyzed for grain size distribution by Severn Trent Laboratories using the ASTM D422 method. This test method covers the quantitative determination of the distribution of particle sizes in soils. The distribution of particle sizes larger than 75 µ (retained on the No. 200 sieve) is determined by sieving, while the distribution of particle sizes smaller than 75 µ is determined by a sedimentation process, using a hydrometer.

3 RESULTS

3.1 Weather Conditions

Local climatological data for Newark Liberty International Airport was obtained from the National Climatic Data Center operated by the National Oceanic & Atmospheric Administration. During the survey period from June 19, 2006 to June 23, 2006, no ground precipitation was reported except for a trace amount on June 22 and .22-inches on June 23. During the survey times between 0700 and 1900, dry bulb temperatures ranged between a low of 73° F at 0700 on June 21 to a high of 91°F at 1600 on June 22. Relative humidity ranged between 37% at 1300 on June 21 to 79% at 0700 on June 20. Winds were pretty much out of the south and west during the entire survey with speeds varying between 5 and 20 mph. June 19 was generally the windiest day with speeds consistently at or above 10 mph. Sunrise and sunset did not vary more than one minute during the week with sunrise occurring at 0425 on June 21 with sunset at 1931.

3.2 Dredging Operations

3.2.1 Bucket Cycles

To examine the bucket cycle sequence as applied in the Arthur Kill project, a video record was obtained of 20 complete cycles. The video record was then analyzed for time increments for each component of the cycle (Figure 7). The average total elapsed time per cycle was 92.0 seconds. A certain degree of variability in cycle component elapsed times can be seen across the 20 cycles in Figure 7. The shortest cycle was 82 seconds, whereas the longest was 102 seconds.

3.2.2 Production Rates

Daily dredging inspection logs submitted by the contractor for the Dredge *Michigan* were used to estimate production rates (Table 1). Production rates were calculated simply as the total cubic yards excavated divided by the total hours of active dredging on a given day. Therefore, these production rates represent an integration of a very large number of bucket cycles. However, these rates do not reflect the highly punctuated activity that was observed to characterize the dredging operation over hourly intervals. For example, periods of high productivity while the dredge was digging in “new” sections of the cut or where the dredge encountered thicker overburdens were interspersed with periods of a series of bucket cycles in which little sediment was actually removed. The latter probably typified dredging as the bucket approached the depth of where the unconsolidated overburden layer was thin.

Daily production rates changed substantially during the course of the dredging project. At the start of monitoring on 19 June, when both ebb tide surveys (NJEA and NJEB) were conducted, the production rate was 114.8 cubic yards per hour. Production rates increased on 20 June to 257.7 cubic yards per hour, during which time the flood survey (NJFD) was completed. This latter production rate was closer to the average production rate for the entire project. The remaining survey (NJAB) was conducted during a period when the dredge removed only 59.5 cubic yards per hour.

3.3 Current Regime Results

Depth-averaged current vectors indicated a generally uniform vertical flow pattern during flood tide surveys as compared to comparable data obtained during an ebbing tide. Vector headings indicated flows predominantly to the west into the Arthur Kill during the flooding tide, with current velocities ranging from approximately 0.32 to 0.40 meters per second (m/sec). During the ebb tidal phase, flows were vertically mixed. On the northern terminus of each transect, current flows were typically to the west (0.34 m/sec) with the exception of the upper one to two meters of the water column. On the southern end of each transect, flows (0.28-0.30 m/sec) were generally to the east. Representative examples of current direction and velocity profiles from the flood and ebb tide plume surveys are illustrated in Figures 8 and 9.

3.4 Acoustic Estimates of Sediment Plumes

The results in this section for the ADCP plume transects are presented graphically in three (3) different ways:

- Three-dimensional (3-D) depiction – TSS concentrations are plotted in X and Y coordinates with an exaggerated Z (depth) axis.

- Plan view – TSS concentrations are presented as composite horizontal “slices” through the plume signature at 2 m depth increments.

- Vertical Profiles – Composite from the 3-D and plan view. Vertical cross-sections can be examined in detail for internal TSS concentration gradient structure of the plume at known distances from the source of resuspension. In all vertical cross-sectional profiles the northern shoal is depicted on the left side.

3.4.1 Ambient Conditions

Ambient suspended sediment concentrations were characterized daily when the dredge was inactive and or by surveying areas outside the influence of plumes. Ambient conditions were consistently below 10 mg/l during each of the sampling efforts. The only departure from this occurred in the lowest one meter of the water column, just above the channel bottom where readings up to 15 mg/l were observed, although this condition was infrequent. Two (2) examples of representative vertical profiles of ambient conditions surveyed on 19 and 22 June are illustrated in Figure 10. Note that for the purpose of presentation of plume acoustic signatures in cross-sectional profiles, concentrations <10 mg/l will be considered ambient conditions. All acoustically estimated TSS concentrations >10 mg/l are herein considered to be above background and attributable to the presence of the dredging-induced plume unless otherwise stated, e.g., as when ship passage generated a plume signature clearly distinct from that of the dredge.

3.4.2 Ebb Tide

<u>NJEA Transect Results – 19 June 2006</u>

A three-dimensional depiction of the plume detected during Survey NJEA is presented in Figure 11. Plan view layouts of ADCP transects with acoustic estimates of suspended sediments at selected depths are given in Figures 12 through 17. To examine plume structure in as complete detail as possible, a series of vertical profiles (Figures 18 a-z) were also generated at increasing distances down- current of the dredging operation.

Seven (7) Survey NJEA transects (Figures 18 a-g) were conducted on the up-current side of the dredging operation. As with the ambient survey, bottom water TSS concentrations fluctuated between 10 and 15 mg/l.

Four (4) Survey NJEA transects were conducted on both the north (port) (Figures 18 h-k) and south (starboard) (Figures 18 l-o) sides of the dredging operation to assess lateral spreading of the sediment plume. Transects conducted close to the dredging operations (Figures 18 h and i) had higher TSS concentrations (70 mg/l) than transects conducted 70 meters away (Figure 18 k) from the excavation site, which exhibited TSS concentrations of 30 mg/l. Lateral spreading of the plume at the point of excavation was confined to the lower half of the water column (>7 m). This is evident in Figure 11 which shows ambient conditions in the upper water column (represented by blue shading) and plume in the lower water column, expanding in spatial coverage and corresponding increasing TSS concentrations with depth (also see Figures 12 through 17). TSS concentrations up to 20 mg/l above background extended outward to 70 meters north (port), but were confined to the bottom three meters of the water column, as shown in Figure 18 k. A passing ship earlier in the survey on this side of the dredge plant is likely to have contributed some portion of the suspended sediment evident on this transect.

Detection of plume-derived suspended sediment south of the dredge was not possible until the plume emerged from under the barge. Resuspended sediment was detected in the lower half of the water column, six meters from the barge. TSS concentrations here were less than 50 mg/l. By 12 meters south (starboard side of dredge), TSS estimates (50-60mg/l) above background were confined to the bottom meter of the water column (Figures 18 i and m). Detection of a distinct plume signature against background levels was not made beyond this distance.

The remaining 11 Survey NJEA transects were conducted down-current of the dredging operation in the direction of plume movement. The plume present on the down-current transects was largely confined to the lower water column within the navigation channel basin. A surface plume (i.e., at a depth of two meters) was not evident beyond 100 meters from the point of excavation (Figure 12), and the detectable plume was not more than 30 meters wide and averaged 20 mg/l. There was no evidence of the plume leaving the boundaries of the navigation channel (Figures 12-17). Figures 18 “p” and “q” profiles were conducted at distances of 25 and 65 meters down-current and show the concentration gradient structure at the plume’s most prominent point. TSS concentrations in the lower portion of the water column reached 70 mg/l in a small central core of the plume. Note that air entrained in the upper part of the water column on both vertical profiles is highlighted in red.

NJEB Transect Results – 19 June 2006

Halfway through this survey, the dredge stopped removing material and did not resume dredging until after the survey was completed. Figure 19 shows a three-dimensional representation of the plume during Survey NJEB with the most intense segment of the plume highlighted in red. Similar to the previous ebbing tide survey, some lateral spreading of the plume to the north (port) side of the dredge was observed. A small area of relatively intense acoustic signature is present in the lower water column at the stern of the dredge and is most likely associated with the somewhat mixed flows and overall weak current pattern.

Figures 20 through 25 show the plume's spatial distribution and TSS concentrations at selected water depths. The main body of the plume apparently resided under the dredge plant and barge. The majority of the surface plume was confined to the area immediately abreast of the dredge, although a narrow band approximately 50 meters wide did travel down-current as far as 100 meters. Beyond 50 meters, TSS concentrations exceeded ambient concentrations by less than 20 mg/l in surface waters. Movement of the plume was in a west to east direction and stayed within the boundaries of the navigation channel proper. The largest down-current "footprint" of the plume was found at a water depth of 8 meters (Figure 23). Higher TSS concentrations were found along the north side of the dredge and up-current from the dredge at a depth of 12 meters as a result of a reversed current flow along the channel bottom (Figure 25).

Plume structure can be studied in significantly greater detail in the series of vertical cross-sectional profiles for transects at increasing distances from the dredging operation (Figures 26a-l). Maximum TSS concentrations of 130 mg/l were found in the bottom depth stratum (>11 meters) on a transect encircling the dredge plant and barge at a distance of five meters. A small area of intense plume signature located on the port side of the dredge was not present on an ensuing transect occupied at a distance of 20 meters. On this transect only, the main body of the down-current plume was detected.

Overall, the plume observed during this survey can be characterized as a narrow band of increased TSS initially extending throughout the water column within a swath less than 50 meters wide with maximum TSS concentrations of 60 mg/l (Figure 26 c). Movement of the plume was generally to the east. Very little lateral spreading of the plume was observed in the down-current direction. By 88 meters (Figure 26 e), TSS concentrations fell to less than 40 mg/l and were confined to depths deeper than seven meters. At 142 meters (Figure 26 g), current flow along the bottom of the channel reversed direction opposite to the flow in the upper part of the water column and consequently, the bottom portion (>9 meters) of the plume was lost. By 210 meters down-current from the source (Figure 26 k), only a faint plume signature remained with concentration estimates exceeding background by less than 10 mg/l. At 270 meters (Figure 26 l), distinct plume signatures were not detected against background conditions.

For both ebb plume surveys, maximum TSS concentrations were considerably lower than those detected during the flooding tide survey (see Section 3.4.3, Flood Tide). During the ebbing tide surveys, currents were not as strong or as unidirectional as observed during the flooding tide. Additionally, the dredge had moved to a more central position within the channel reach with less material to remove as indicated by a reduction in production rates to 114.8 cubic meters per hour. Rapid settling of the plume occurred and by 100 meters down-current, only a faint plume signature remained with acoustic estimates exceeding background by only 10 mg/l, although the diffuse plume still occupied most of the water column. The plume continued to settle lower in the water column over the next 100 meters, and by 200 meters down-current, occupied a swath less than 60 meters wide that remained confined to the lower two meters of the water column. A return to ambient conditions occurred at a distance of 270 meters down-current from the source.

3.4.3 Flood Tide

<u>NJFD Transect Results – 20 June 2006</u>

Prior to the start of this survey, the dredge had been in full production mode for several hours, but stopped removing sediment for about 30 minutes (0946-1015 hours) to change barges. The down-current portion of the survey began at 1120 hours. Dredging production rates on that day averaged 258 cubic yards per hour, the highest rate during any of the plume tracking surveys.

Overall plume movement was in a northwesterly direction until it reached the channel dogleg at Channel Marker 16A, then turned further to the west. The plume remained in the southern half of the navigation channel and remained completely within the confines of the channel proper. Some lateral spreading was observed as the plume broadened from approximately 65 meters near the source to a maximum of 100 meters approximately 225 meters down-current from the dredging operation. No evidence of plume migration over the adjacent shoals was seen. The general direction of movement and maximum spatial extent of the plume is clearly shown in Figure 32.

Figure 27 provides a three-dimensional depiction of plume TSS concentrations for Survey NJFD. Plan views of ADCP transect and TSS concentrations for selected water depth strata for this survey can be found in Figures 28-33. The first four (4) transects were conducted on the up-current of the dredging operation. Along the northern extent of these transects, TSS concentrations exceeding ambient concentrations were found from mid-water to the channel bottom. This plume resulted from the passage of a deep draft vessel traveling from west to east through the study area. TSS concentrations as high as 40 mg/l occurred in the lower three meters of the water column (Figures 34 a-d). Background levels were exceeded by 10 to 20 mg/l for almost the entire width of the navigation channel. Because the exact time of ship passage was not recorded, the state of decay of the ship-induced plume cannot be estimated.

Three (3) transects were conducted on the starboard side of the dredge as part of the plume mapping survey. The first two (2) transects were parallel to the dredge plant at distances of two and 10 meters (Figures 34 e and f). TSS concentrations ranged as high as 350 mg/l, although concentrations estimated this close to the source likely included bubble contamination. Lower in the water column, where air entrainment is less likely to be present, the maximum observed TSS concentration did not exceed 250 mg/l. Figures 34 e and f show TSS concentrations in this range at water depths of eight to 10 meters. At 30 meters starboard of the dredge plant (Figure 34 g), plume signatures above 10 mg/l were not detected. No detection of plume signature against background was made on either of the two (2) transects along the port side of the dredge (Figures 34 h and i).

The remaining transects (Figure 34 j through bb) were conducted down-current from the dredging operation. Figure 34 j depicts a well-defined suspended sediment plume extending from surface to bottom 100 meters from the dredging operation. TSS concentrations ranged from 20 mg/l along the outer periphery of the plume to greater than 120 mg/l within the plume’s central core. Some air entrainment in the upper portion of the plume is evident as the area shaded in red in Figure 34 k. Note the change in concentration scale between Figures 34 j and k, which represent a spatial shift of only 15 meters. Over this short distance, decay of the plume is apparent as maximum TSS concentrations fell from 120 mg/l to 90 mg/l and were present in the lowest one meter of the water column. Over the next 40 meters, TSS concentrations continued to decline to 50 mg/l, or approximately 40 mg/l above background. The surface portion of the plume shows rapid decay and was undetectable against background at 195 meters from the source (Figure 34 n). At 344 meters (Figure 34 t), only a faint signature of the degraded plume can be detected above background. This faint signature continued to diminish in size, but remained detectable against background as far as 621 meters from the source (Figure 34 bb).

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The dredge was located near the centerline of the navigation channel. Dredging resumed at 0935 hours after having been shut down the previous evening for maintenance and repairs. The survey started at 1335 hours, about one hour into the tidal cycle. Production rate on this date was relatively low at 59.5 cubic yards per hour. Perhaps reflecting the low sediment removal rate, the plume signature was not as prominent as that observed in the previous flooding tide survey. A three-dimensional representation of the plume is given in Figure 35. Plan views of transects and TSS concentrations for selected depth strata are provided in Figures 36 through 41. Plume movement was to the west and followed the centerline of the channel. Down-current movement of this small plume occurred mainly within the lower portion of the water column. Figure 40 illustrates the limited spatial dispersion of this plume.

As in the previous survey, the first two (2) transects encircled the dredge at distances of five and 20 meters. TSS concentrations of 70 to 80 mg/l were found in the central portion of the plume in the lower three meters of the water column at five meters distance from the source (Figure 42 a). At a depth of six meters, TSS concentrations ranged between 20 mg/l along the periphery and 40 mg/l within the plume’s core. TSS concentrations as high as 50 mg/l were found in the surface plume, but may have been influenced by air entrainment. Concentrations fell from a maximum of 80 mg/l to 50 mg/l over a span of 15 meters, although the plume signature still occupied the entire water column (Figure 42 b).

After the completion of second transect, the dredge advanced 55 meters to the east to begin a new cut. The circle transects were then repeated at five and 10 meters distances (Figures 42 c-e). Plume signatures were not well defined along either transect, even in such close proximity to the source. The down-current portion of the plume was mapped over five (5) transects, the first at three meters from the point of excavation (Figures 42 f-j). Some air entrainment was evident in the upper two to three meters of the water column. Maximum TSS concentrations were less than 60 mg/l. Plume width averaged less than 60 meters in the lower water column. At 28 meters down-current (Figure 42 g), the plume was a relatively narrow band of elevated TSS, primarily consisting of a small inner core at depths below 10 meters, with TSS concentrations up to 40 mg/l, a slightly larger outer core in mid-water at 30 mg/l, and an outer periphery extending from near the surface to the bottom at 20 mg/l. At 78 meters from the source (Figure 42 h), the plume had settled to the lower half of the water column and was not detectable against background down to a depth of approximately seven meters. The overall appearance of the plume changed little over the next 60 meters with continued settling in the water column (Figure 42 i). At 163 meters down-current (Figure 42 j), only a faint trace of the plume signature could be detected against background.

3.5 Turbidity

Because optical measures of turbidity are influenced by the properties of the sediments in suspension, direct comparison of turbidity and TSS concentration cannot be made without synoptic samples obtained from the same sampled water volume. As depicted in Figure 43, TSS (mg/l) values determined from laboratory gravimetric analyses and synoptic NTU values measured by the OBS-3A unit affixed to the water sampler display a relatively high degree of correspondence (R^2 = 0.8846). Some scatter is present and 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 resuspension, are very heterogeneous with large changes in concentration occurring on very small spatial scales. Turbidity measurements taken at five to 15-second intervals by moored sensors at ambient, near-field, and far-field stations during sampling efforts on 20, 22 and 23 June are summarized in Tables 2 through 4.

3.5.1 Ambient

Representative time series of ambient turbidities are given in Figures 44 through 46. Ambient readings ranged from 1.3 to 13.8 NTU throughout the water column. During the flooding tide, ambient readings were generally uniform throughout the water column with each sensor reporting a mean turbidity of approximately 7 NTU. In both ebbing tide time series, ambient turbidities were highest in the upper portion of the water column (< 2 meters), averaging 8.7 NTU on 23 June. The lowest average readings occurred on the same date at 2.2 NTU for the sensor deployed at a depth of 8 meters.

Readings above 10 NTU occurred only once on 20 June when a tug passed close to the moored OBS unit producing a short-lived spike in NTU values, especially at the two lower sensors (7.4 and 9.5 meters) (Figure 46). This "spike" was not a true indication of natural background turbidity because of the obvious linkage to the passage of the tug near the moored OBS array. If this single event is excluded, turbidity values less than 10 NTU can be assumed to represent ambient turbidity conditions throughout the study. Examination of data collected during dredging can reveal characteristics of ambient conditions as well. Consistent measurements between pulses or spikes of plume-associated turbidity values can be used to identify prevailing ambient conditions and trends across tidal phases.

3.5.2 Near–Field

OBS sensors were deployed during three sampling events for durations ranging from 1.5 to 3.5 hours at a distance of 60 meters down-current from the bucket at varying depths throughout the water column. The highest turbidities occurred during a flooding tide when current flows carried the plume to the west at relatively low velocities. Current vectors during ebbing tides varied considerably from westerly (northern terminus of transect) to easterly (southern terminus) with mixed flows in the middle reach of the channel. Therefore it is possible that not all resuspended sediment moved consistently in the direction of the near- and far-field sensors.

Figure 47 shows the results for the 60 meter near-field station during a flooding tide. Waters were less turbid at the two (2) upper sensors where values ranged from 5.5 to 14.6 NTU (sensor at 2.1 meter, mean = 9.1 NTU) and 4.5 to 34.7 NTU (sensor at 3.4 meter, mean = 9.4 NTU), respectively. Turbidity values rarely exceeded ambient conditions at the uppermost sensor (2.1 meters). The highest turbidity value recorded in the near-field occurred at the lower sensor (9.1 meter) which peaked at 80.7 NTU. Turbidities at water depths of 6.5 meters (mean = 16.3 NTU) and 9.1 meters (mean = 21.8 NTU) were approximately twice those in the upper water column (mean = 9 NTU), indicating that the sediment plume occurred primarily in the lower half of the water column (Figure 47).

On 22 June, OBS units were also deployed 60 meters down-current from the dredging operation to assess near-field turbidities during an ebbing tide. Turbidity peaked at the mid-water sensor at 35.1 NTU (Figure 48). Turbidities differed only slightly between the shallow sensor at a depth of 1.8 meters (mean = 6.8 NTU) and the deep sensor at a depth of 8 meters (4.8 NTU). Using 10 NTU as an upper threshold for ambient turbidity, ambient conditions were exceeded by 10 NTU or higher during six short time intervals, each persisting no longer than several minutes.

OBS units were redeployed in the near-field at 60 meters on 23 June during an ebbing tide. In contrast to the previous day's results, movement of sediment was largely confined to the lower half of the water column, in a manner similar to that observed during the flooding tide. The two (2) sensors located at 0.3 meters (mean = 7.5 NTU) and two (2) meters (mean = 4 NTU) water depth recorded peak turbidities less than 13 NTU, indicating very little sediment movement in the upper water column (Figure 49). Mean turbidities in the mid (five meters) and lower (eight meters) segments of the water column were similar at 12.8 NTU and 13.2 NTU, respectively. Peak turbidity occurred at the deep sensor (8 meters) at 56.3 NTU.

3.5.3 Far-Field

OBS units were deployed 160 meters down-current from the dredging operation to assess far-field turbidity during a flooding tide on 20 June 2006. In comparison with the synoptic near-field data, peak turbidities fell by as much as 10 (shallow sensors) to 23 (deep sensors) NTU. More turbid waters were found in the lower water column with a peak turbidity of 57 NTU recorded at the deepest sensor (9.2 meters). A time series record of turbidities obtained during the flood monitoring event can be found in Figure 50. Mean turbidities increased with increasing water depth from 9.3 NTU at the shallow sensor (4 meters) to 13.7 NTU at the mid-water sensor (6.5 meters) and to 18 NTU at the deepest sensor (9.2 meters) (Table 3).

OBS units were deployed 150 meters down-current from the dredging operation on 22 June to assess turbidities during an ebbing tide. No data were obtained for the upper (1.8 meters) and lower (9.5 meters) OBS units due to sensor failure. Turbidities recorded during this monitoring event were low (< 7 NTU), indicating that during this sampling event, little or no sediment from the dredging operation was reaching the sensors at this distance (Figure 51).

OBS units were redeployed 145 meters from the point of excavation during an ebbing tide on 23 June. Average turbidity at the uppermost sensor was 9.2 NTU, within the range of ambient conditions at the site (Figure 52). Peak turbidity (17.9 NTU) exceeded ambient conditions at a depth of 5 meters, noting that 5 NTU was the maximum reading obtained from the up-current five-meter sensor (see Figures 46 and 52). Ambient readings were also exceeded by 13 NTU at the lower sensor (mean = 15.2 NTU).

3.6 Correlation of Water TSS Samples and Acoustic Estimates of TSS Concentration

Conversion of acoustic backscatter data to estimates of TSS concentration was accomplished by application of a robust 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 in turn dependent on the collection of adequate water samples to represent sediments in suspension at all depths in the water column and across the entire gradient of concentrations occurring in ambient as well as plume waters.

In this study, 100 water samples ranging in TSS concentration from 5.2 to 190 mg/l produced an excellent calibration, although the overall number of samples at the upper end of the concentration gradient was limited. In Figure 53 a, the entire population of gravimetric measurements and acoustic estimates are arranged in rank order. A relatively strong correspondence exists between the two (2) measures throughout the sampled range. When plotted with respect to paired samples, i.e. gravimetric and acoustic measures collected synoptically, some variation is seen for individual pairs, largely for samples representing higher

gravimetric or ADCP concentration estimates (Figure 54b). This variation is primarily due to the logistical constraint of obtaining synoptic measurements in a very small volume of water where large concentration gradients occur on very short time and distance scales. Collection of high concentration samples proved to be difficult because of the very small down-current distances at which high concentrations could be found. Safety factors prevented the survey vessel from maneuvering sufficiently close to the operating bucket to consistently obtain such samples.

3.7 Grain Size Analysis

A sediment grab sample was collected from the dredge scow on 19 June 2006 and was analyzed for grain size distribution by Severn Trent Laboratories using the ASTM D422 method. The sample was composed of both fine silt and coarse grains (i.e., sand and gravel), which may not be representative of the fine grained silt sediment dredged during most of the contract. A review of the dredge logs for the entire project showed a relatively low production rate of 114.8 cubic yards per hour on 19 June as compared to the rest of the month when daily production rates average three to four times higher (Table 1). This may indicate that the bucket on 19 June was cutting near a depth of refusal where more coarse grained sediments are likely to prevail. Nevertheless, a higher proportion of coarse grained sediments could be a factor in generating smaller suspended sediment plumes on this day.

4 DISCUSSION

Prevailing ambient turbidities and TSS concentrations during the study were relatively low, creating an almost ideal set of conditions for plume detection. Optically measured ambient turbidity varied slightly between sampling days, ranging from 2.6 to 8.7 NTU. Highest values were exclusively found in the lower one meter of the water column. Results obtained from the gravimetric analysis of ambient water samples indicated that ambient TSS concentrations fell within the 5.2 to 17 mg/l range (mean = 8.4 mg/l). Ambient ADCP data indicated that background TSS concentrations were consistently low, ranging from 3 to 10 mg/l throughout the water column. Thus all characterization methods employed in this study are consistent in support of the finding of generally low ambient turbidities and TSS concentrations.

With respect to turbidity, the data obtained from OBS deployments can collectively be used to describe general plume characteristics at near- and far-field distances within the channel, herein defined as approximately 60 meters and 150 meters respectively. The near-field plumes had turbidities that exceeded background levels by 5 to 15 NTU in the upper portion of the water column, 25 NTU above background in mid-water column, and 50 NTU above background in the lower portion of the water column. Maximum near-field turbidities occurred in short pulses that exceeded background by as much as 70 NTU at the deepest sensor. The far-field (150 meters) deployments collectively produced a characterization of plumes with maximum turbidities of 13 NTU above background in the upper water column, 39 NTU above background in mid-water, and 47 NTU above background near the bottom. These values reflect measurements during moderate production rates.

Some variation at comparable near- and far-field depths and distances from the source between sampling events was noted, possibly linked to short-term variation in production rates. Visual observations over the course of the field effort repeatedly noted the start-stop-start again nature of the dredging operation. Rather than a continuous operation, numerous intermittent breaks in the bucket cycles were the norm. Frequent pauses and stoppages were due to a variety of circumstances, including vessel passage, routine periodic maintenance, equipment repairs, and so on. Likewise, visual observations noted that series of bucket cycles alternated between buckets obviously removing full capacity sediment loads and loads that consisted almost entirely of water. Because the operation was intermittent, plumes would not be expected to attain a steady state condition, but rather be constantly dissipating and re-establishing when pulses of sediment released at the bucket were carried downstream within the channel confines.

Maximum TSS concentrations measured acoustically approached 300 mg/l within 10 meters of the source near the surface, although air entrainment likely affected these measurements to some degree. Concentrations measured in the lower third of the plume near the source ranged from 150 to 200 mg/l. TSS concentrations 100 meters down-current from the source generally did not exceed 120 mg/l. These values are consistent with the results of gravimetric analysis of water samples taken within the plume, which ranged from 100 to 190 mg/l within 60 meters from the source.

TSS concentrations decreased from approximately 300 mg/l immediately adjacent to the source to less than 50 mg/l at a distance of approximately 150 meters from the source, and to 20 mg/l at 350 meters from the source. Faint plume signatures with concentrations less than 10 mg/l above background did persist as far as 620 meters from the source during one flood tide ADCP survey.

For all plumes surveyed a general pattern of relatively rapid plume concentration gradient decay and settlement within the water column was apparent. Plumes exhibited minimal lateral diffusion with distance traveled down-current, seldom measuring more than 70 meters across at substantial concentrations. Maximum spatial extent of the plumes always occurred in the lower water column. Movements of plumes were generally confined to the basin of the navigation channel, with no evidence of excursion beyond the channel side slopes.

All results were consistent with previous studies of plumes created during mechanical dredging operations. For example, Bohlen et al. (1979) studied plumes created by a mechanical dredge equipped with an open bucket during operations in the Thames River Estuary, Connecticut. TSS concentrations of 200 to 400 mg/l were measured adjacent to the dredge and plumes dissipated to background concentrations within 700 meters downstream. These results were also presented by Bohlen (1978), who described the suspended sediment plume induced by a clamshell bucket under estuarine conditions as essentially small scale features with three distinct zones: an initial mixing zone where the dredge mixes materials throughout the water column, a secondary zone extending downstream approximately 100 meters in which gravitational settling predominates, and a final mixing zone in which plume sediments continue to settle governed primarily by turbulent diffusion. In a later study, Bohlen et al. (1996) used an acoustic echo sounder to track plumes and a fixed station instrument array that recorded bottom current velocities and optical turbidity to assess potential effects of sediment dispersion from an open clamshell bucket to winter flounder habitat. They concluded that high TSS concentrations (maximum 662 mg/l) were generally confined to within 100 meters of the source, and that the plumes rapidly settled. Dredge-induced pulses of suspended sediment at the fixed instrument array were concluded to be minor perturbations in contrast to wind and freshwater discharge-induced resuspension events, consistent with earlier findings in the Thames River Estuary (Bohlen 1980).

Randall (2001) described the advantages and disadvantages of mechanical and hydraulic dredges for consideration in removal of contaminated sediments. He reported that the major disadvantage of both open and closed buckets was low production rates (<100 cubic yard/hour), but that closed buckets had the advantage of low resuspension rates. Tradeoffs between production and resuspension are complex and necessarily must consider the volume of material to be removed. In navigation projects the volumes tend to be large. In addition, mechanical buckets can be used to remove debris more effectively than hydraulic dredges.

Recent studies by Bilimoria et al. (2006) and Thompson et al. (2006) detail the results of dredge-induced resuspension monitoring at a contaminated sediment site in the Lower Passaic River, New Jersey. In this cleanup pilot study a mechanical dredge using an 8 cubic-yard Cable Arm environmental bucket removed approximately 5,000 cubic yards of sediment with a production rate of approximately 90 to 215 cubic yard/hour and average bucket cycle times of 105 to 165 seconds. Preliminary data indicated that TSS concentrations ranged as high as 115 to 120 mg/l down-current from the dredge.

Reine et al. (2003) used survey designs and sampling approaches similar to those in this present study to characterize plumes created by mechanical dredging in an open-water navigation channel in Upper Chesapeake Bay. Plumes generated from dredging silt/clay with a 26 cubic-yard open bucket were detected as far as 1,500 meters downstream from the source. Tidal currents were relatively strong, peaking at over 130 cm/sec. OBS units measured turbidities as high as 220 NTU at a distance of 70 meters from the source, and TSS concentrations as high as

300 mg/l at that distance. Plumes expanded laterally to widths of up to 400 meters before being lost against background conditions.

Reine et al. (2003) also monitored plumes from mechanical dredging of silt/clay operations in Baltimore Inner Harbor, where currents were much slower, generally less than 20 cm/sec. Surface plumes were generally undetectable beyond 100 meters from the source and TSS concentrations remained below 40 mg/l beyond 350 meters from the source. Maximum turbidities measured by OBS units deployed near the bottom at 47 meters from the source were approximately 145 NTU.

Clarke et al. (2005) reported the results of monitoring mechanical dredge plumes at the Port of Oakland, California. Plumes generated by a 12 cubic-yard closed bucket generally decayed to background TSS concentrations within 400 meters from the source. Prevailing tidal currents were weak, mostly less than 30 cm/sec. TSS concentrations above 275 mg/l were only detected immediately adjacent to the source. The plumes were observed to settle rapidly and remain within the navigation channel boundaries.

Reine et al. (2006) monitored plumes associated with mechanical dredging of maintenance materials using a 26 cubic-yard closed bucket in the Providence River, Rhode Island. At two locations plumes were found to decay to background conditions within 1,100 meters of the source. At the time of the monitoring, it was determined that the dredge operator was aggressively digging and maintaining high production rates. TSS concentrations as high as 1,000 mg/l were measured immediately adjacent to the source, but concentration gradients declined steeply over short distances as the plumes settled into the lower portion of the water column.

In a previous study in the Kill Van Kull (SAIC 2002), the suspended sediment plumes associated with two excavator dredges were monitored. Based largely on OBS data, plumes were detected as far as 1,500 meters from the dredges, although in this case the plumes from both dredges had apparently merged. Background turbidity in the KVK at that time ranged from 7 to 13 Formazin Turbidity Units (FTU) and background TSS values ranged from 19 to 24 mg/l, slightly above values obtained in the present study. Direct comparisons of plumes monitored in the KVK and those of the present study are limited in that the dredge plants were very different, the sediments being dredged were substantially different (mixed glacial till versus primarily silts), and currents at the KVK site were considerably stronger (54 to 97 cm/sec in the KVK). However, observed peak TSS concentrations and turbidities within the KVK plumes were similar as well as the observed tendency for the KVK plumes to settle rapidly near the bottom and remain largely in the channel.

The results of the plume monitoring study in the Arthur Kill are also relevant to the issue of sediment loss as part of the dredging process, with particular reference to numerical simulation of far-field dispersion of resuspended sediment. Losses can vary considerably based on the mode of dredging (e.g., mechanical versus hydraulic, overflow practices, etc.). For accurate simulation of the dispersion of resuspended sediments an important input parameter for modeling applications is the loss or source strength term (Burt et al. 2000). However, absolute rates of sediment loss by various modes of dredging have proven to be exceedingly difficult to quantify. A true consensus among experts on the ranges of loss terms has not been achieved. Reported loss terms for bucket dredging operations span from less than one percent of the total volume dredged to greater than five percent (Bohlen et al. 1979; Hayes et al. 1984; Collins 1995, John et al. 2000).

A number of methods have been developed to improve confidence and consistency in mechanical dredging source strengths (Nakai 1978; Tavolaro 1984; Borrowman 2000, 2001, 2002; Burt et al. 2001; Hayes and Wu 2001). Nakai (1978) proposed a “Turbidity Generation Unit” approach that was widely used to estimate loss rates until limitations of the method were identified by Hayes and Wu (2001). Tavolaro (1984) used dry mass measures of dredged material volumes for various stages of a clamshell project to calculate loss estimates and determined that approximately 1.22 percent of the dredged material was lost by the bucket. Borrowman (2001) used a mass balance transport equation to describe the mechanisms of loss by a bucket, and derived sediment loading equations for operational characteristics, bucket dimensions, and sediment properties. Hayes and Wu (2001) have proposed that “resuspension factors (R)” or sediment mass loss rates can be calculated for the basic modes of dredging, taking into account dredge type and size, sediment characteristics, operational practices, and local environmental conditions.

Bohlen (1978) and Bohlen et al. (1979) described an approach based upon measured TSS concentrations within a theoretical cylinder around the vertical axis of the bucket. From the known volume of the cylinder and the increment in measured TSS concentration above ambient, they estimated that approximately 1.5 to 3.0 percent of the dredged sediment was injected into the water column. Collins (1995) refined this approach to include divisions of the source geometry reflecting fluid and suspended sediment motions during different phases of the bucket cycle. His calculations yielded resuspended sediment source strengths for three open-bucket scenarios ranging from 0.24 to 1.68 kilograms per second.

Hayes and Wu (2001) used data from five prior bucket dredging studies to compare resuspension factors for buckets ranging from 10 to 26 cubic-yard capacities and production rates from 380 to 1,530 cubic-meters per hour. Their calculated R values (percent loss) ranged from 0.16 percent for Collin's 1995 St. Johns River Estuary data to 0.88 percent for Bohlen et al.'s 1979 Thames River Estuary data.

Inferences have been made that closed or "environmental" buckets offer resuspension minimization advantages over open-buckets. However, few attempts have been made to compare open and closed bucket design performance under similar conditions. In an assessment of a harbor tunnel construction dredging project in Boston, Massachusetts Bowen and Hartman (1991) and Bowen et al. (1992) predicted that use of a closed bucket would increase sediment resuspension in bottom waters as compared to a conventional open bucket. Several years later, Hayes et al. (2000) measured turbidity and TSS concentrations systematically around a conventional open bucket, a watertight closed bucket, and a Cable Arm bucket at a site in Boston Harbor. Both the closed bucket and Cable Arm bucket consistently created lower TSS concentrations throughout the water column than the conventional open bucket. The closed bucket resulted in somewhat lower turbidities than the Cable Arm bucket, particularly in the middle portion of the water column, although the authors cautioned that production rate or operational differences could account for the observed differences.

Regardless of the methods used to estimate loss rate or source strength, both theoretical and empirical approaches rely upon collection of field data for validation. Hayes et al. (2001) alluded to the difficulties in obtaining TSS concentration or turbidity data in close proximity to operating buckets. In the present study, field measurements of turbidity and TSS concentrations were designed to primarily determine spatial and temporal dynamics of the plumes associated with Cable Arm bucket operations. Because the operations proved to be extremely intermittent with production maintained in spurts of relatively short duration, measurements of sediment flux at specific distances down-current could not be made. Consequently the plumes were not in a steady state stage of development for sufficient durations to collect flux measurements as required by acoustic methodologies (Burt et al., 2000; Land and Bray 2000) and loss estimates could not be calculated.

5 CONCLUSIONS

Ambient conditions as well as the spatial structure and temporal dynamics of suspended sediment plumes associated with fine-grained sediment dredging activities within the Newark Bay Study Area were successfully quantified using gravimetric, optical, and acoustic measurements of turbidity and TSS.

Acoustically measured TSS concentrations in the lower third of the suspended sediment plume ranged from 150 to 200 mg/l within 50 meters of a mechanical dredge configured with an 18-cubic-yard capacity environmental cable arm bucket. TSS concentrations 100 meters down-current from the source generally did not exceed 120 mg/l. These values are consistent with the results of gravimetric analysis of water samples taken within the plume, which ranged from 100 to 190 mg/l within 60 meters from the source.

With respect to the OBS turbidity data, maximum near-field (60 meters from the dredge) turbidities occurred in short pulses that exceeded background by as much as 70 NTU at the deepest sensor. The far-field (150 meters) deployments collectively produced a characterization of plumes with maximum turbidities of 13 NTU above background in the upper water column, 39 NTU above background in mid-water, and 47 NTU above background near the bottom. These values reflect measurements during moderate production rates.

The Arthur Kill plume dimensions and TSS concentration gradients observed in this study were consistent with the results of previous mechanical dredge plume monitoring efforts. For all plumes surveyed, a general pattern was apparent of relatively rapid plume concentration gradient decay and settlement within the water column. Plumes exhibited minimal lateral diffusion with distance traveled down-current, seldom measuring more than 70 meters across at substantial concentrations. Maximum spatial extent of the plumes always occurred in the lower water column. Moreover, movements of plumes were generally confined to the basin of the navigation channel, with no evidence of plume excursion beyond the channel side slopes.

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Table 1. Production rates for the Dredge *Michigan* based on daily inspection logs.

Date	Material Removed (Cu. yds)	Hours	Yards/Hour	Surveys Completed
6/1/2006	3,422	8.5	402.6	
6/2/2006	5,850	13.67	427.9	
6/3/2006	2,267	5.5	412.2	
6/5/2006	4,533	13.15	344.7	
6/6/2006	5,083	10.33	492.1	
6/7/2006	4,250	13.95	304.7	
6/8/2006	4,622	13.67	338.1	
6/9/2006	3,178	10.33	307.7	
6/15/2006	1,156	3.5	330.3	
6/16/2006	3,400	14.67	231.8	
6/17/2006	1,925	13.85	139.0	
6/19/2006	1,463	12.75	114.8	NJEA, NJEB, NJFA, NJFB
6/20/2006	5,025	19.5	257.7	NJFD
6/21/2006	1,157	12.85	90	NJFF, NJWS
6/22/2006	565	9.5	59.5	NJAA, NJAB, NJWS
6/23/2006	782	14.0	55.9	NJWS
Total	**48,678**	**189.72**	**265.6**	

Table 2. Field turbidity values (NTU) for deployments of OBS units during a flooding tide on 20 June 2006.

Station	Distance to Dredge (m)	Location of Buoys	Measurement	Depth (m)	NTU	
					Mean	Range
1	150	Up-current	Ambient	4	7.0	6.3-10.7
				7.4	7.4	5.9-13.8
				9.5	7.0	5.1-13.5
2	63	Down-current	Near-Field Plume	2.1	9.1	5.5-14.6
				3.4	9.4	4.5-34.7
				6.5	16.3	2.4-66.4
				9.1	21.8	4.7-80.7
3	160	Down-current	Far-Field Plume	4	9.3	4.1-23.4
				6.5	13.7	4.9-49.6
				9.2	18	4.5-57.0

Table 3. Field turbidity values (NTU) for deployments of OBS units during an ebbing tide on 22 June 2006.

Station	Distance to Dredge (m)	Location of Buoys	Measurement	Depth (m)	NTU	
					Mean	Range
1	350	Up-current	Ambient	1.9	5.2	4.8-5.7
				4.7	3.3	2.6-4.1
				7.5	2.6	2.3-3.7
2	60	Down-current	Near-Field Plume	1.8	6.8	2.4-26.7
				4.8	5.8	2.5-35.1
				8	4.8	1.2-32.7
				9.5	Sensor Failed	
3	150	Down-current	Far-Field Plume	1.8	Sensor Failed	
				5	3.3	2.3-7.1
				8	2.1	1.0-4.3
				9.5	Sensor Failed	

Table 4. Field turbidity values (NTU) for deployments of OBS units during an ebbing tide on 23 June 2006.

Station	Distance to Dredge (m)	Location of Buoys	Measurement	Depth (m)	NTU	
					Mean	Range
1	540	Up-current	Ambient	0.5	8.7	7.1-9.5
				2	4.4	3.7-5.8
				5	4.3	3.4-5.0
				8	2.2	1.3-3.6
2	60	Down-current	Near-Field Plume	0.3	7.5	6.6-11.0
				2	4.0	2.2-12.9
				5	12.8	1.3-38.7
				8	13.2	1.6-56.3
3	145	Down-current	Far-Field Plume	0.3	9.2	8.9-9.4
				2	4.0	3.3-5.4
				5	10.4	7.5-17.9
				8	5.4	3.5-15.2

Figure 1. Study site indicating location of Shooters Island in relation to Newark Bay. (Map courtesy of Google Earth)

Figure 2. Side view of cable arm environmental bucket in open position.

Figure 3. View of the cable arm environmental bucket showing the array of lateral flaps.

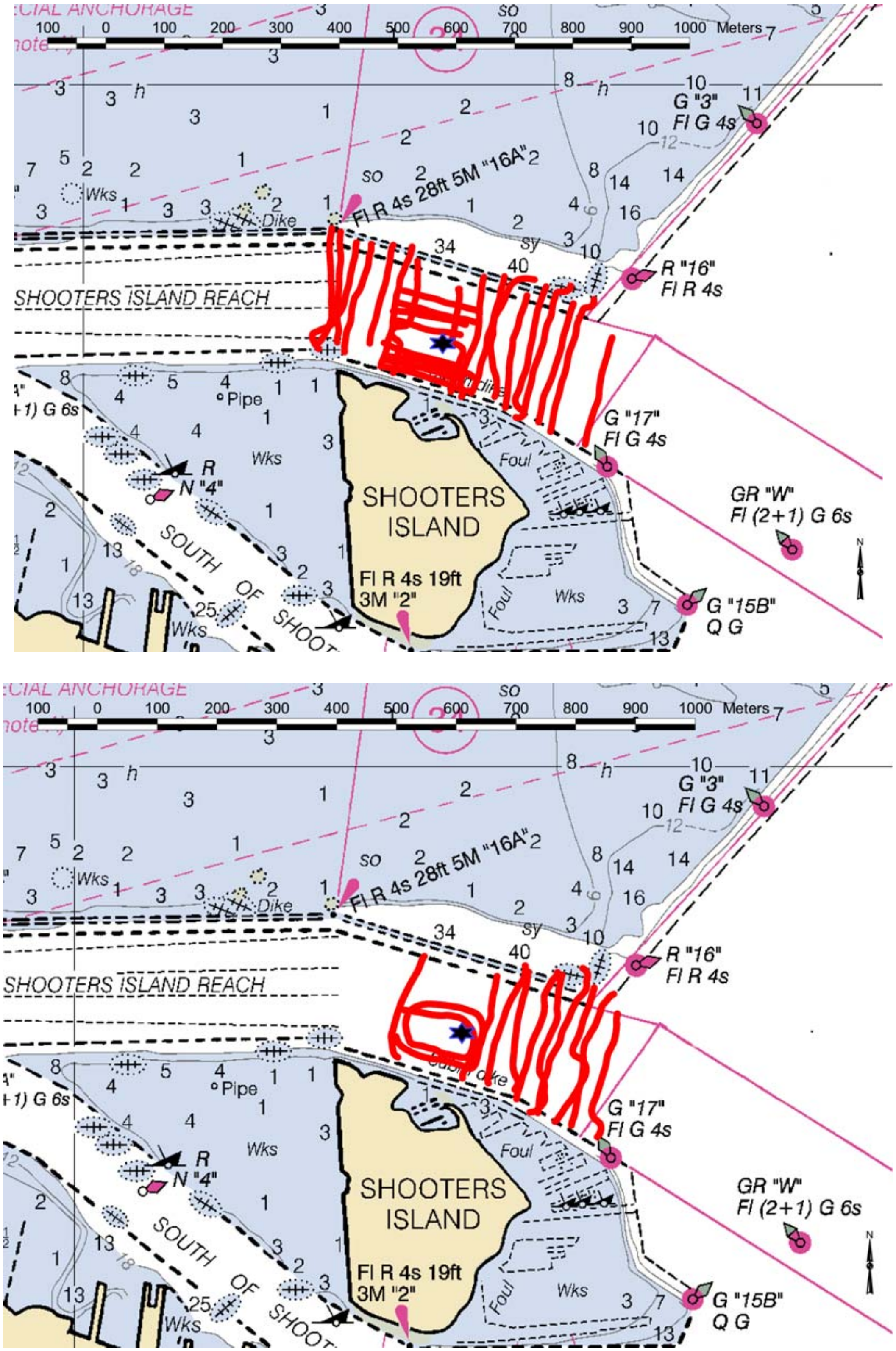


Figure 4. Layout of transects (in red) for ebb tide surveys NJEA (top) and NJEB (bottom). Approximate dredge location denoted by blue star.

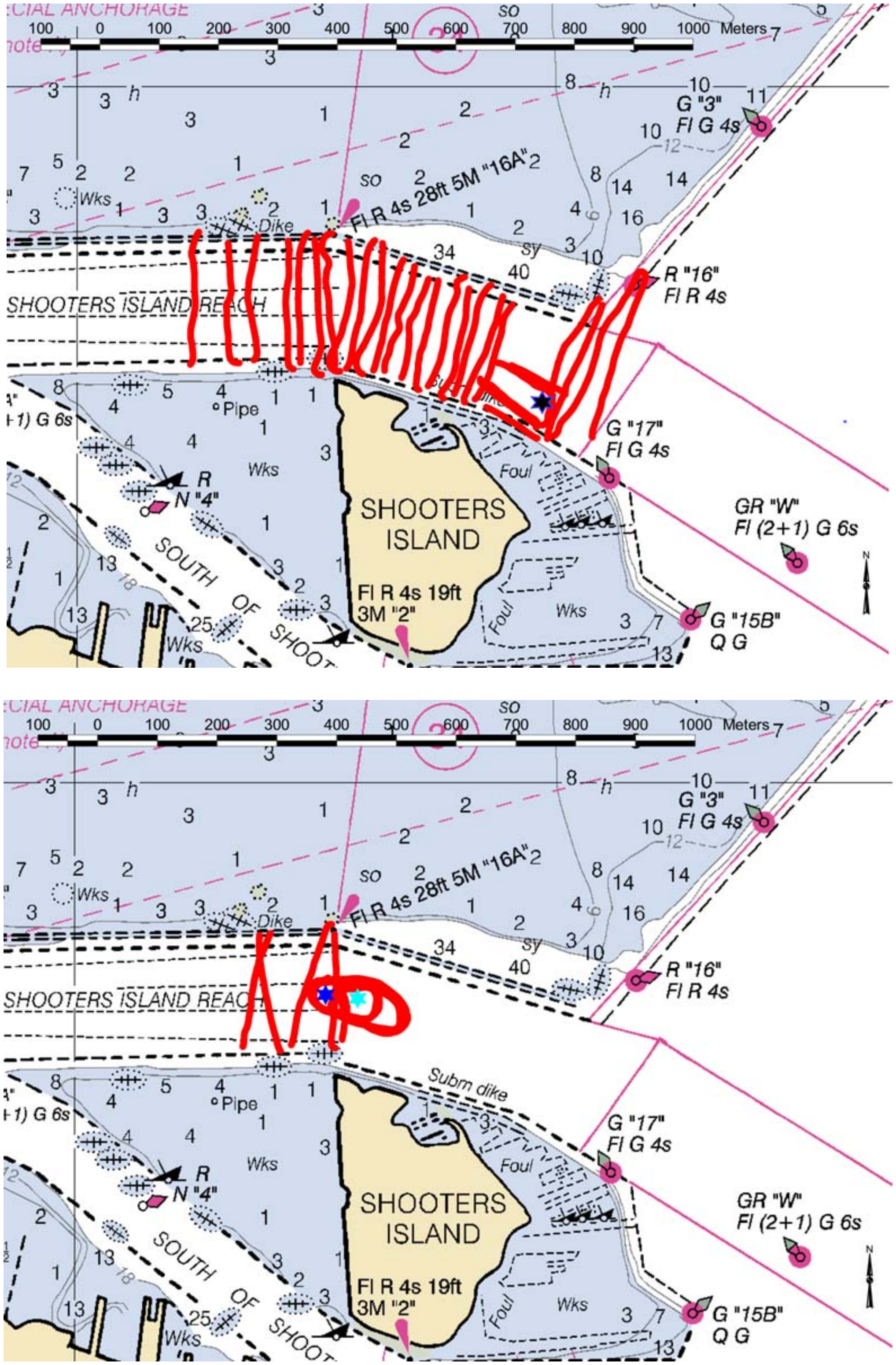


Figure 5. Layout of transects for flood tide surveys NJFD (top) and NJAB (bottom). Dredge location identified by blue star. Note that during the course of Survey NJAB, the dredge advanced easterly from the location identified by the dark blue star to the light blue star.

Figure 6. Deployment of fixed buoys with turbidity sensors. In this deployment the tide was carrying the plume toward to foreground. A third buoy with turbidity sensors deployed on the up-current side of the dredge is visible in the background.

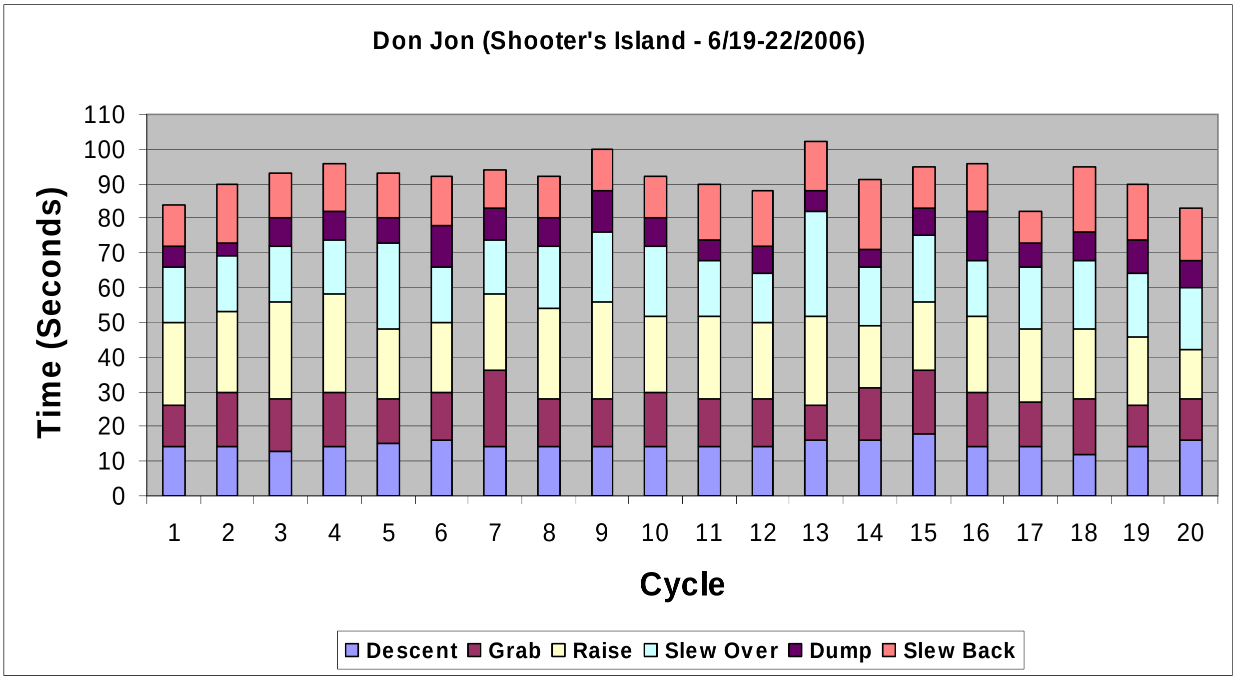
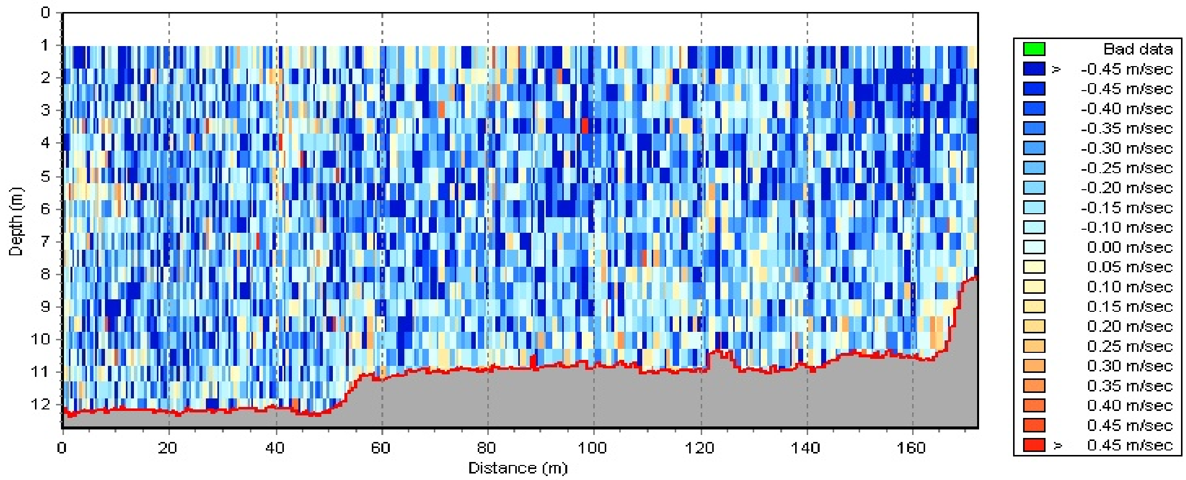


Figure 7. A series of 20 cable arm bucket cycles indicating the elapsed time for six separate components of each cycle; bucket descent, closure, ascent, slewing to barge, slewing back to water.



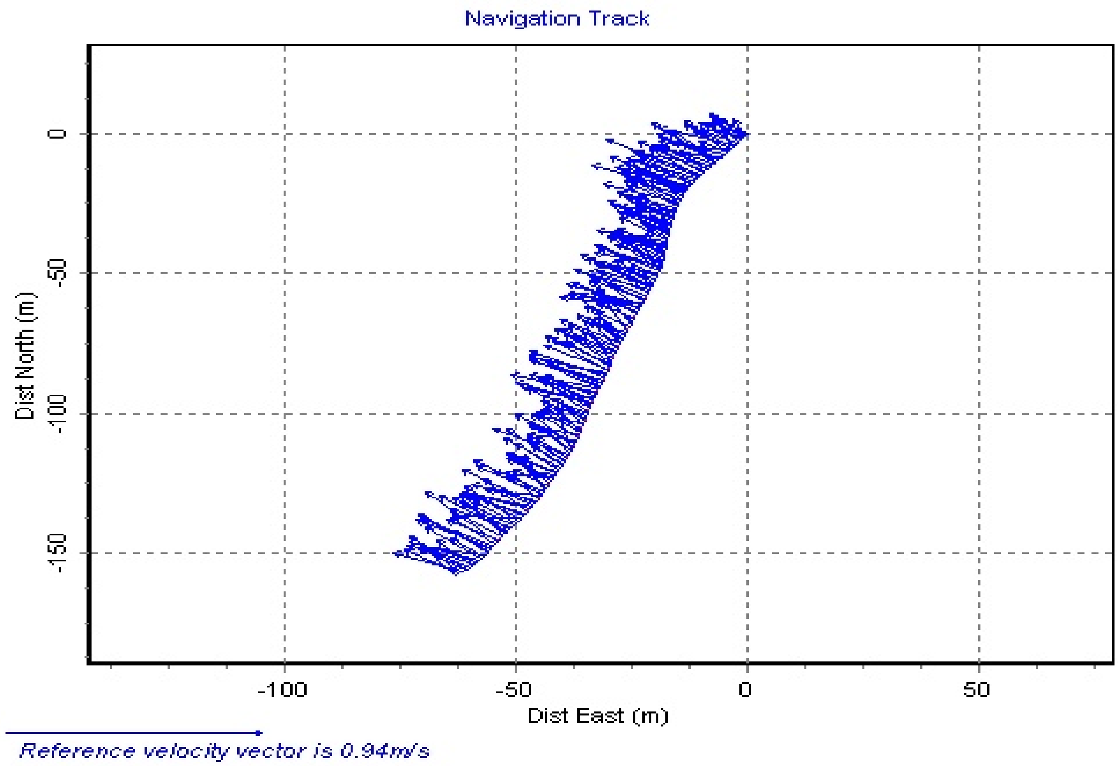
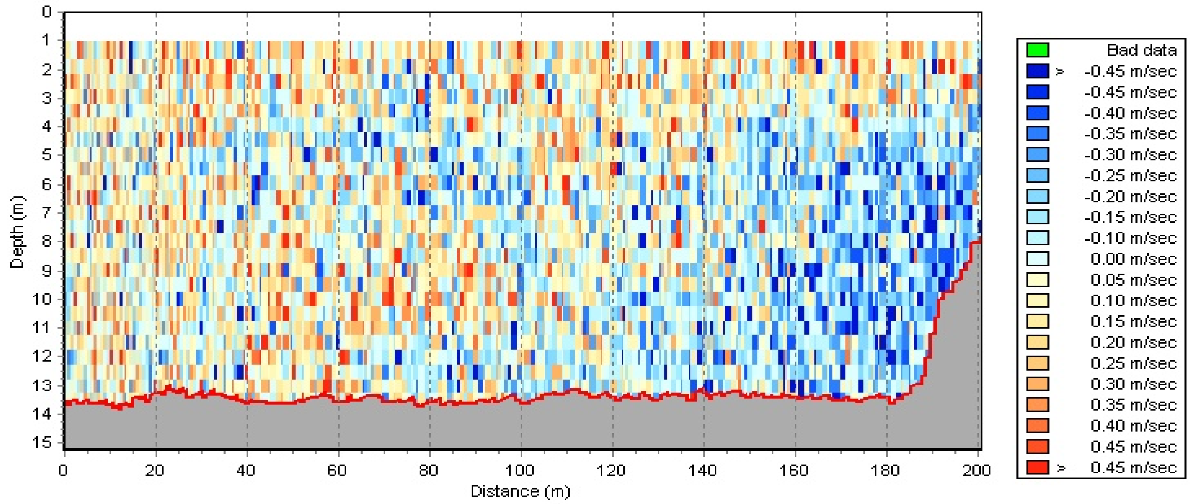


Figure 8. Vertical profile of current velocities across Shooters Island Reach (top) and current velocity and direction vectors (bottom) for Transect NJFA010, occupied 100 meters from the dredging operation during a **flooding tide**.



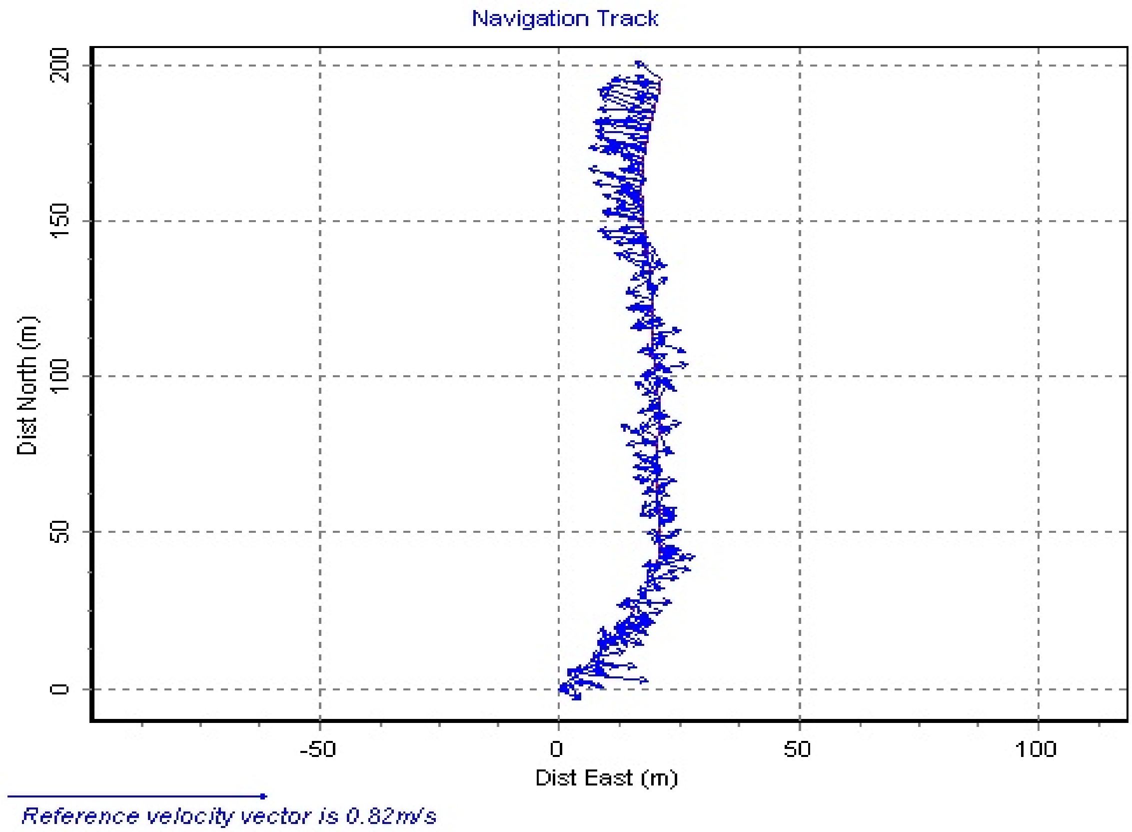


Figure 9. Vertical profile of current velocities across Shooters Island Reach (top) and current velocity and direction vectors (bottom) for Transect NJEA000, occupied 150 meters from the dredging operation during an **ebbing tide.**

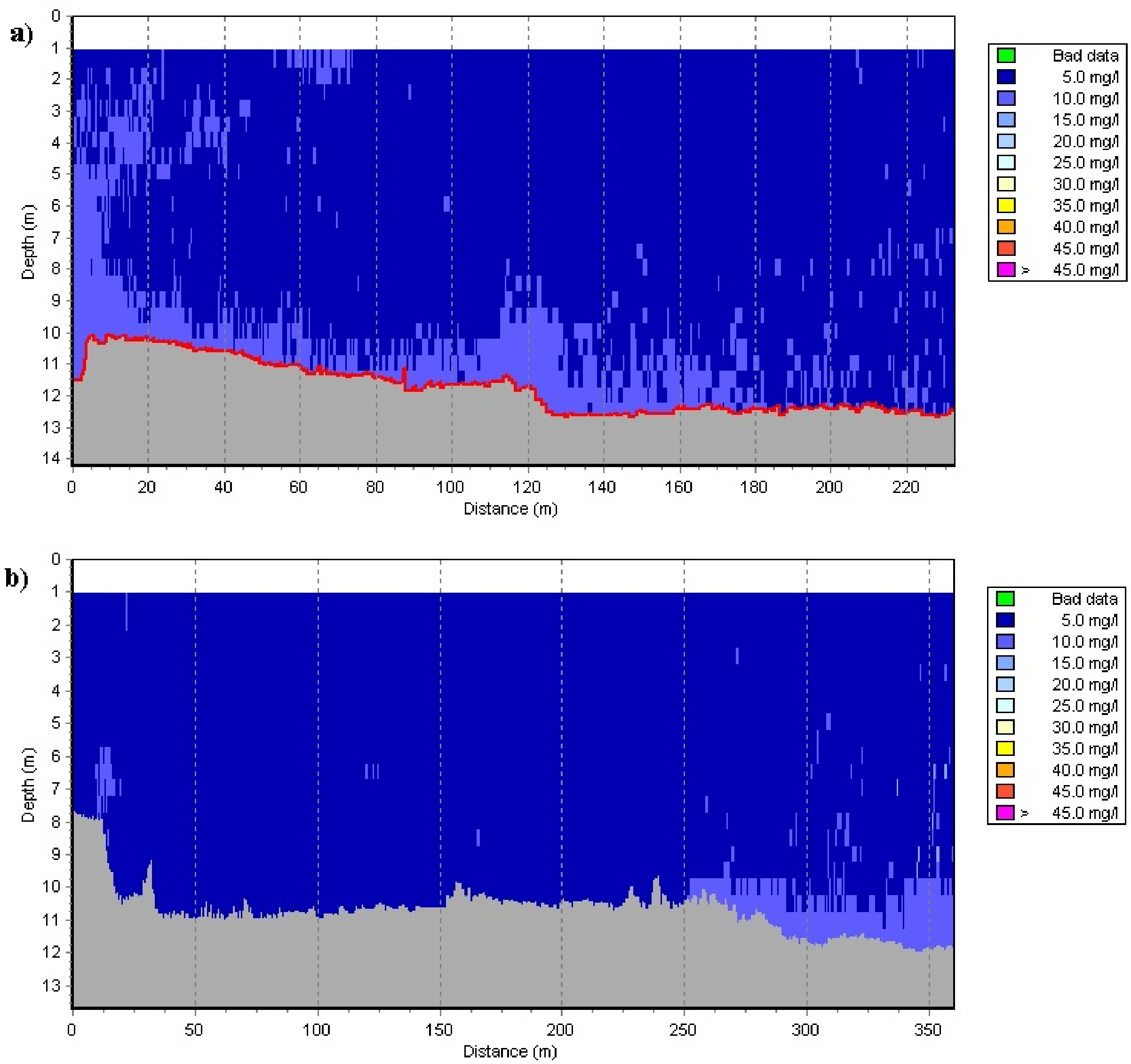


Figure 10. Representative examples of vertical profiles of ambient TSS concentrations across the Shooters Island Reach during a flooding tide on 19 June (top) and an ebbing tide (bottom) on 22 June 2006.

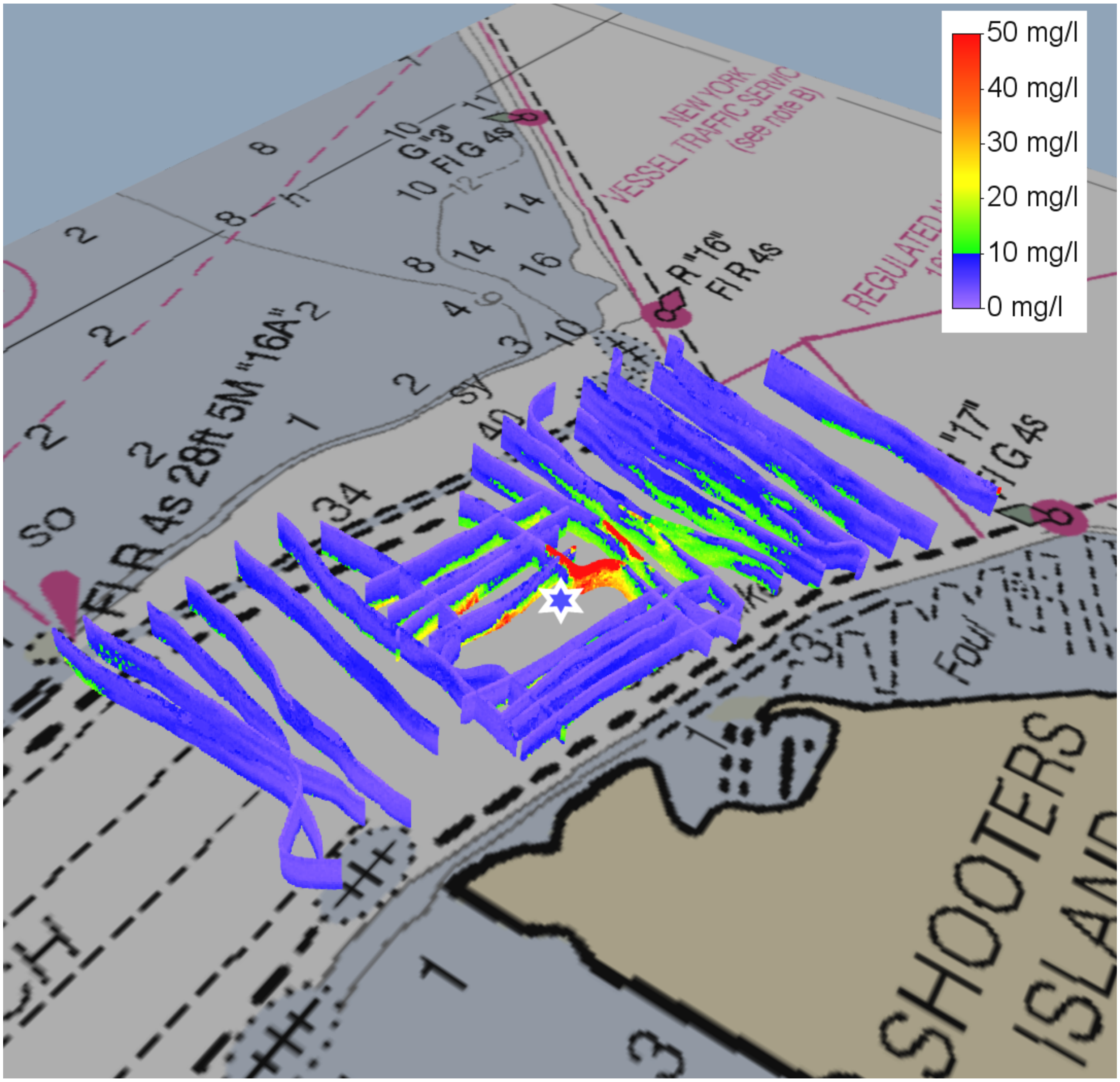


Figure 11. Three dimensional depiction of suspended sediment concentrations for ebbing tide ADCP Survey NJEA. Dredge position indicated by star.

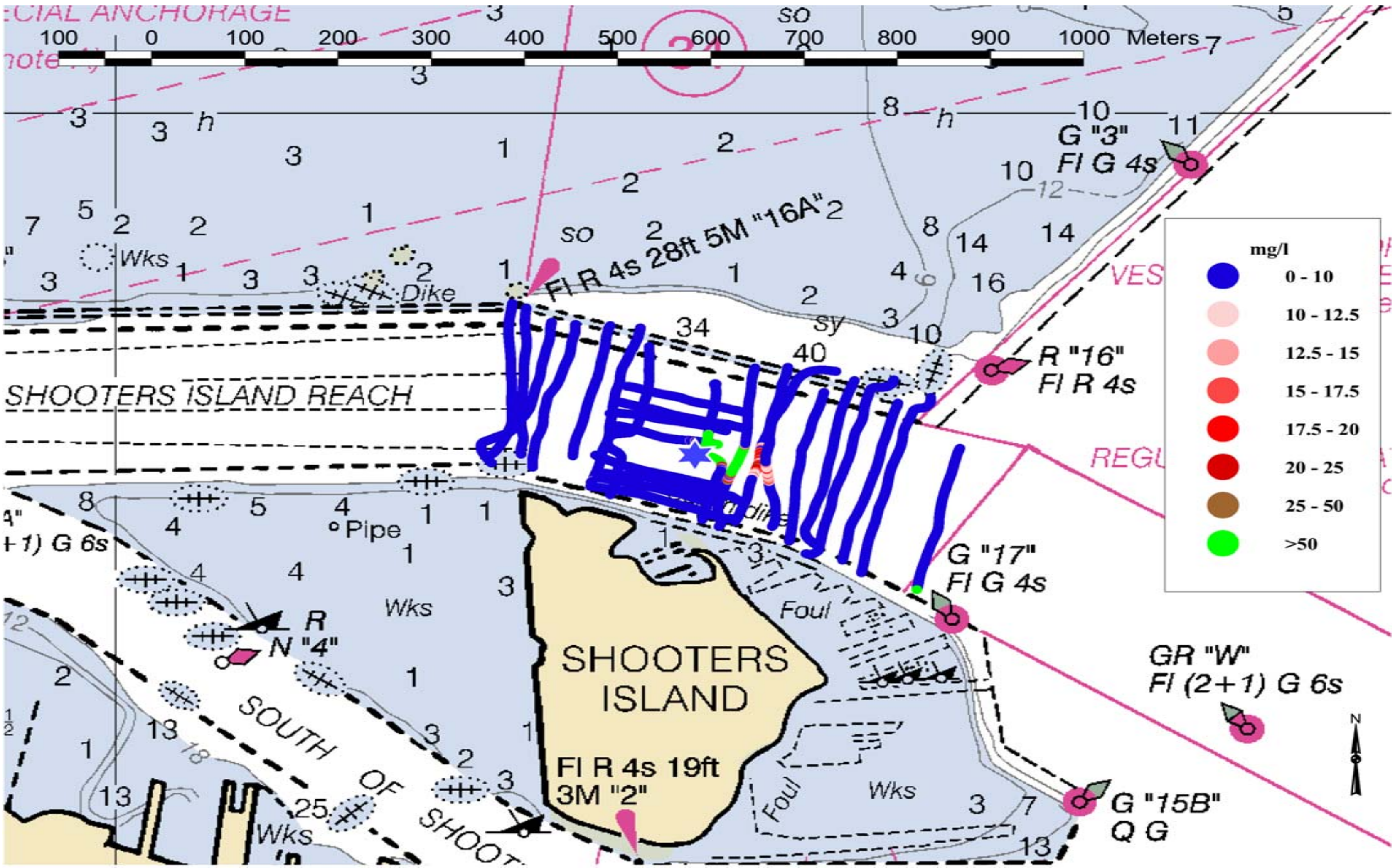


Figure 12. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 2 meters for Survey NJEA, completed during an ebbing tide on 19 June 2006. Dredge location indicated by star.

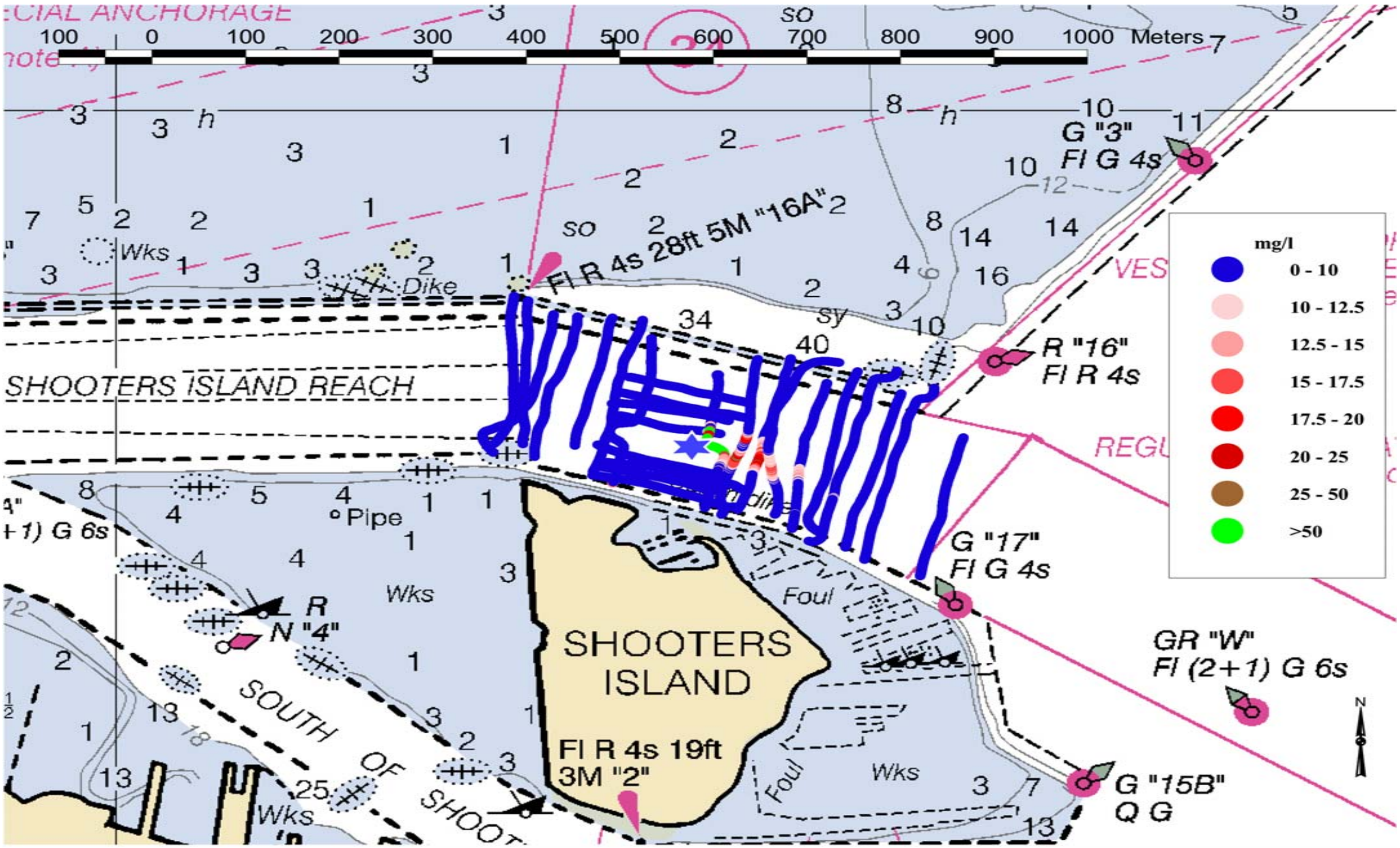


Figure 13. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 4 meters for Survey NJEA, completed during an ebbing tide on 19 June 2006.

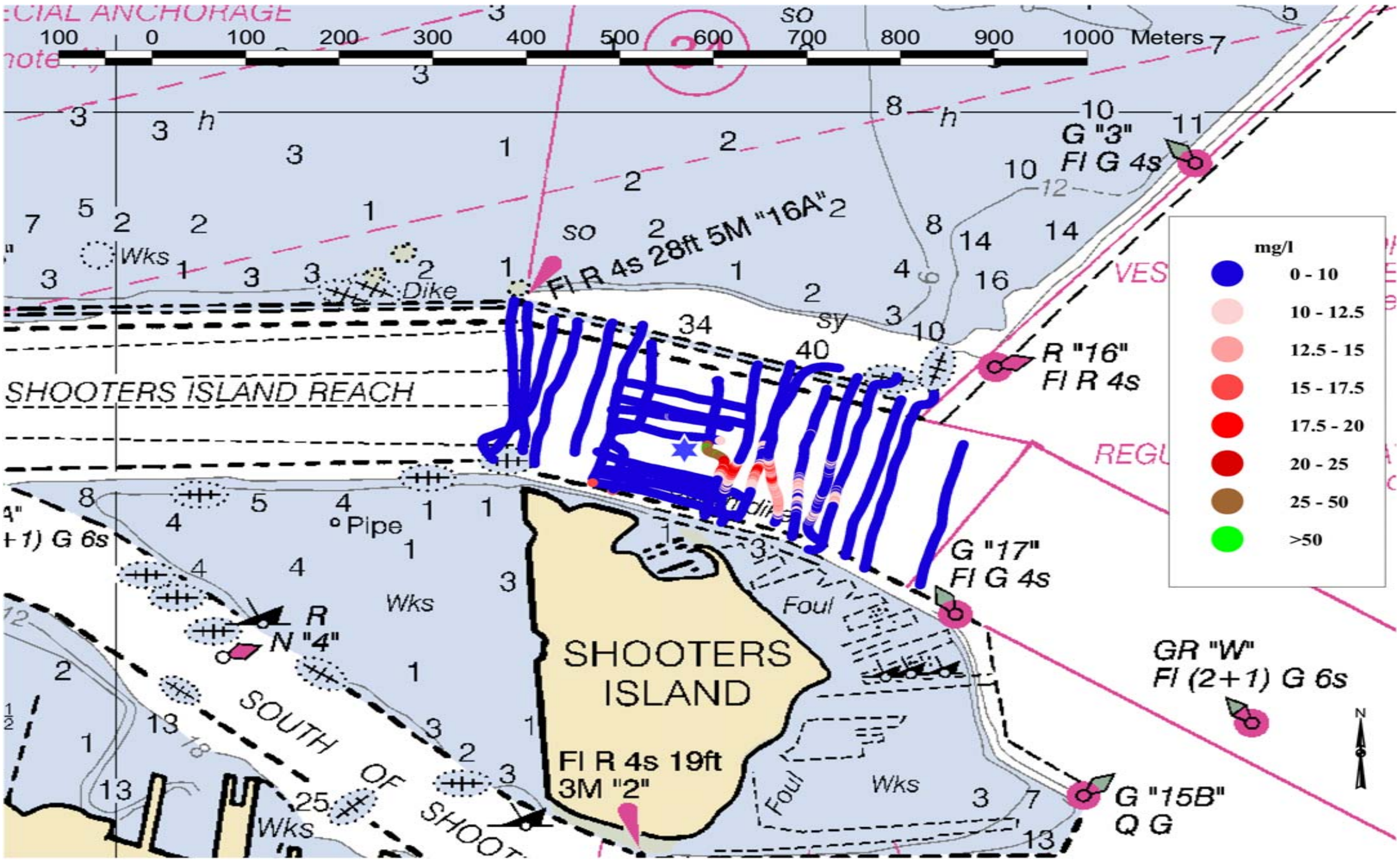


Figure 14. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 6 meters for Survey NJEA, completed during an ebbing tide on 19 June 2006.

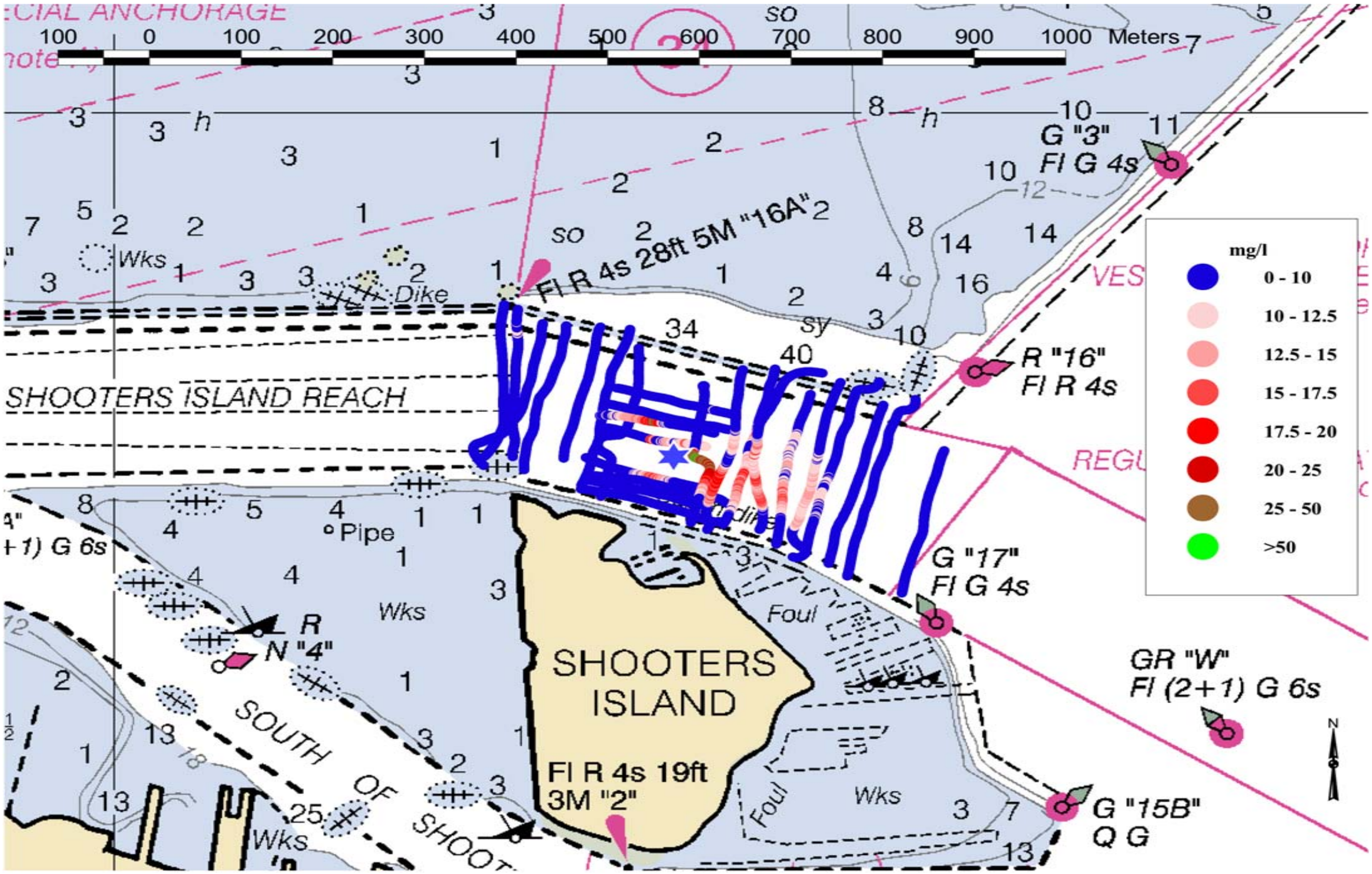


Figure 15. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 8 meters for Survey NJEA, completed during an ebbing tide on 19 June 2006.

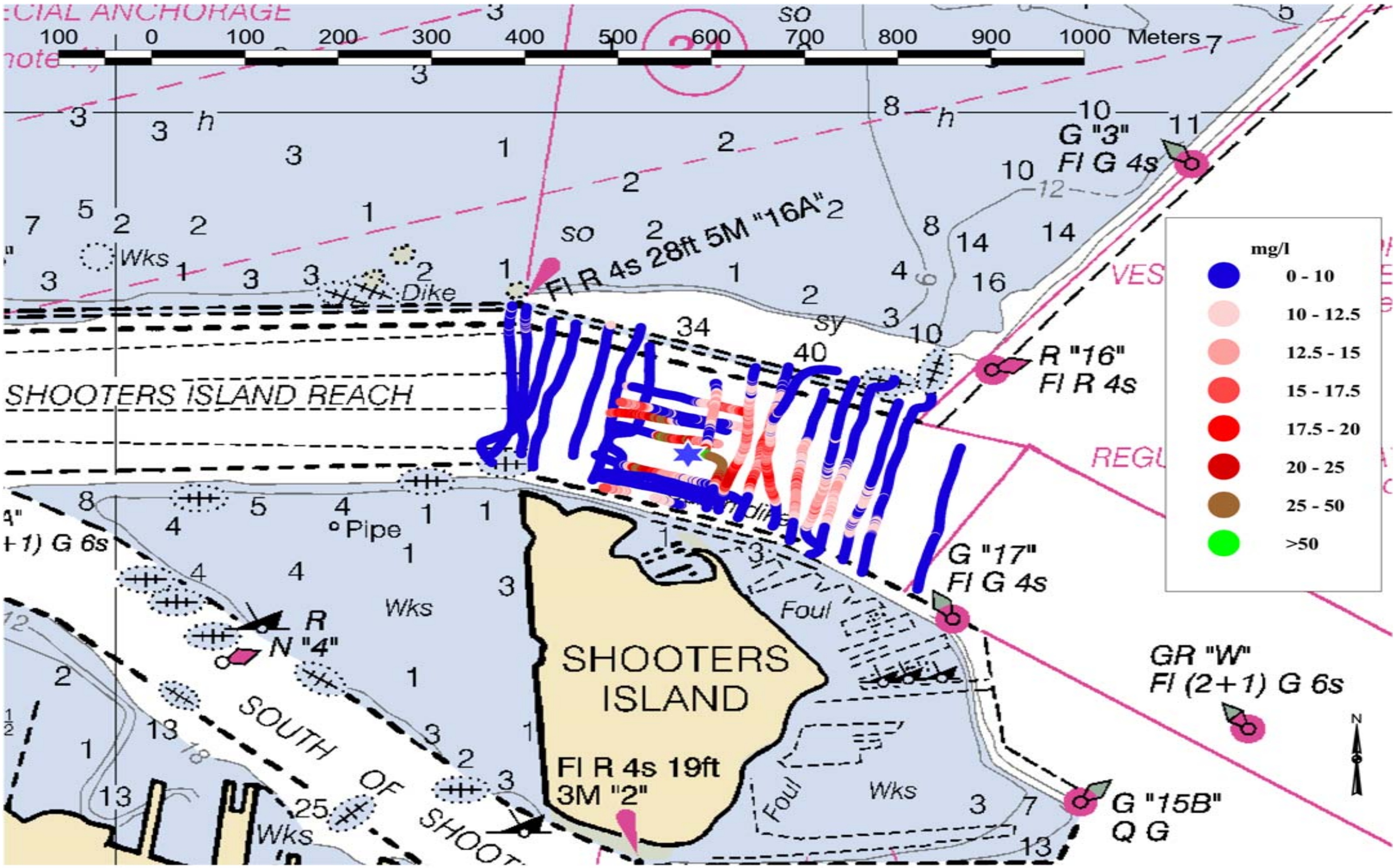


Figure 16. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 10 meters for Survey NJEA, completed during an ebbing tide on 19 June 2006.

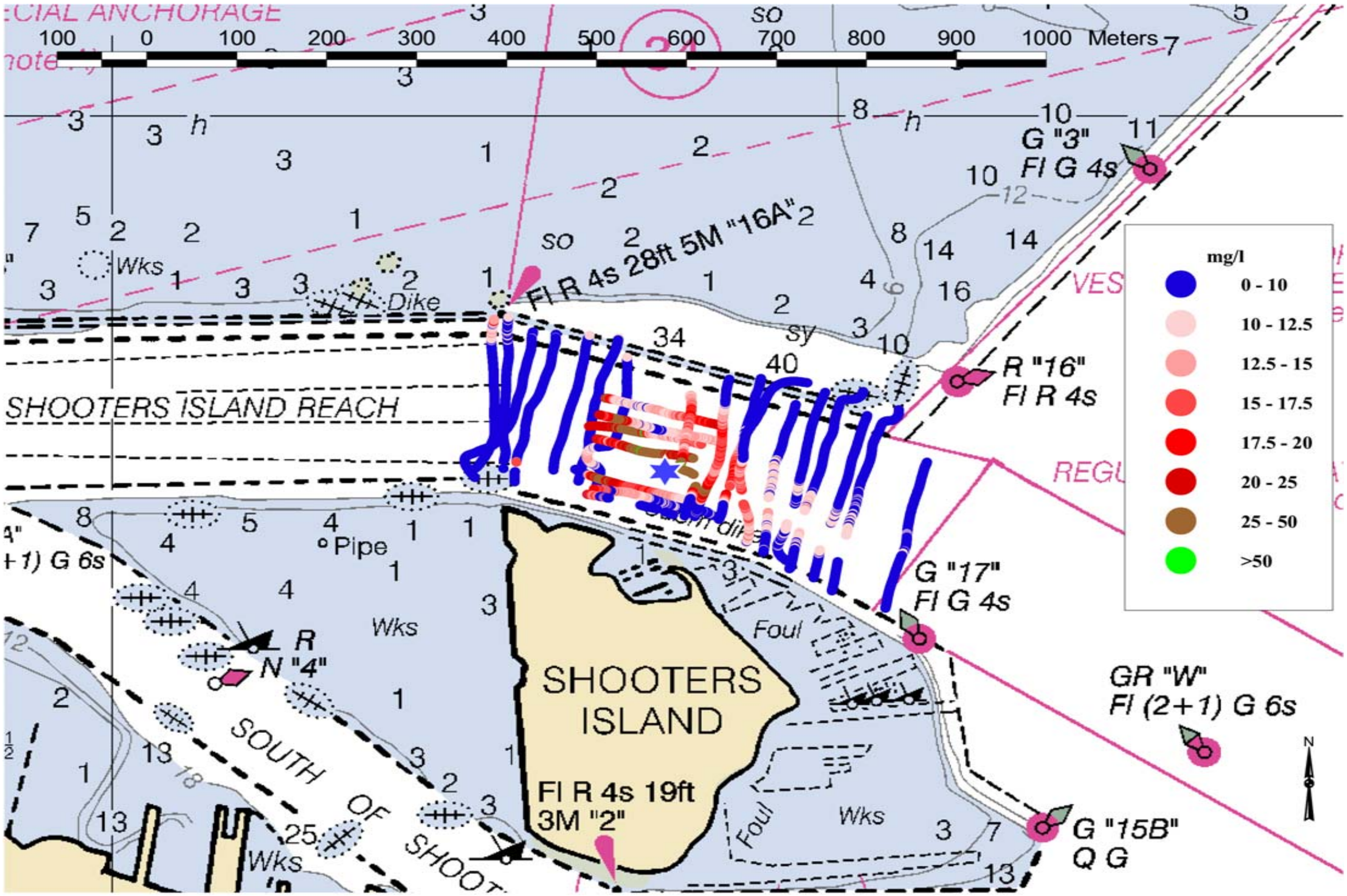


Figure 17. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 12 meters for Survey NJEA, completed during an ebbing tide on 19 June 2006.

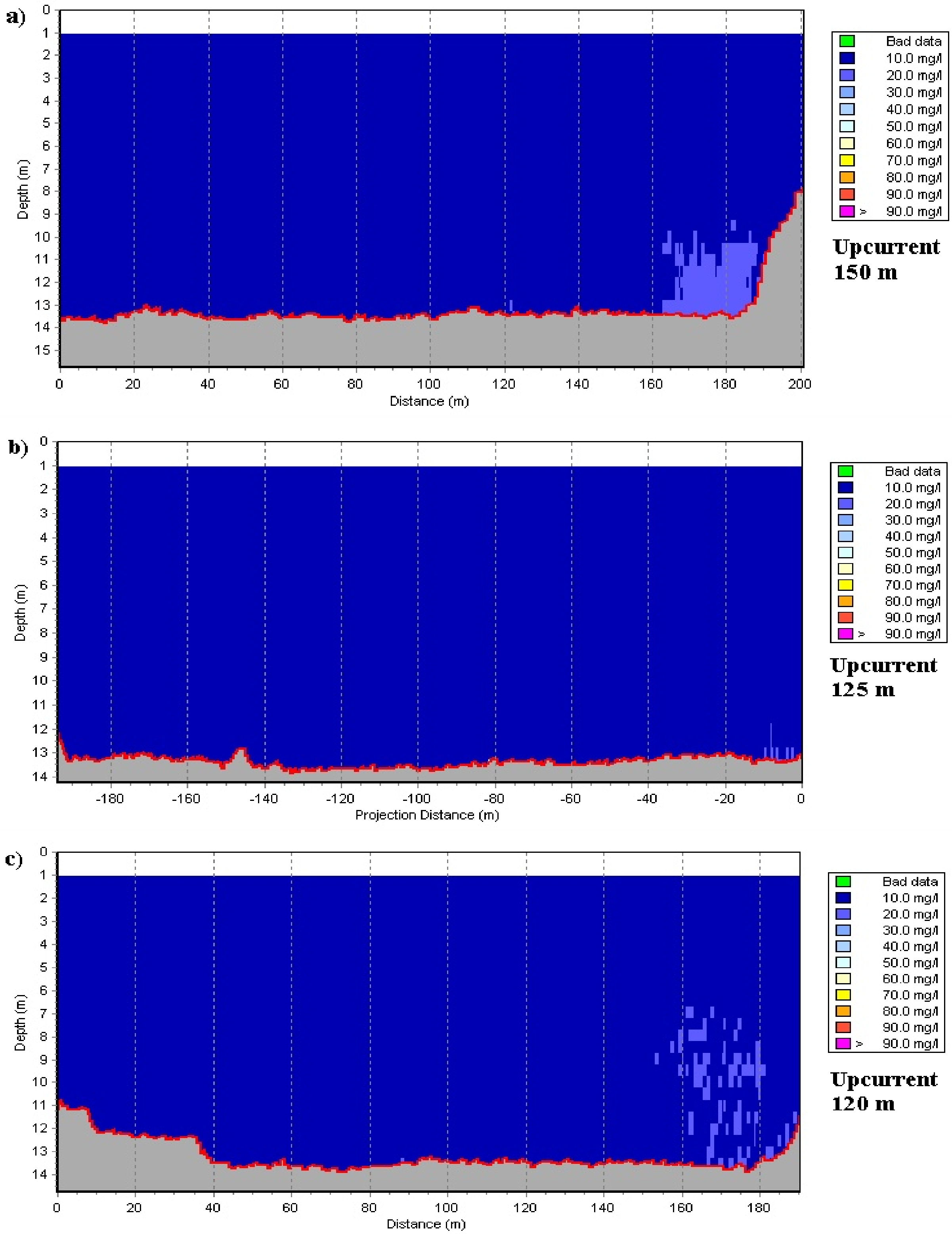


Figure 18. Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

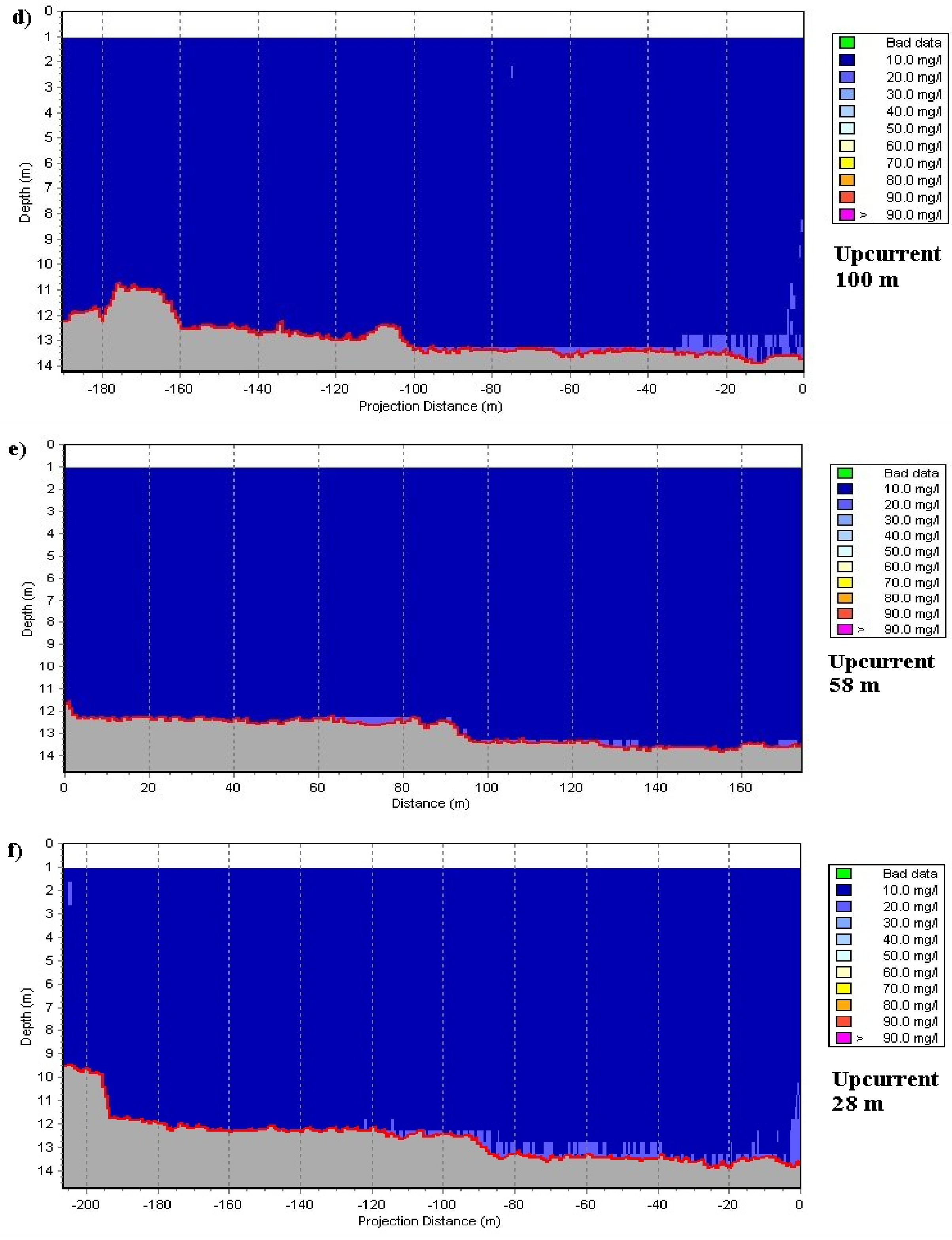


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

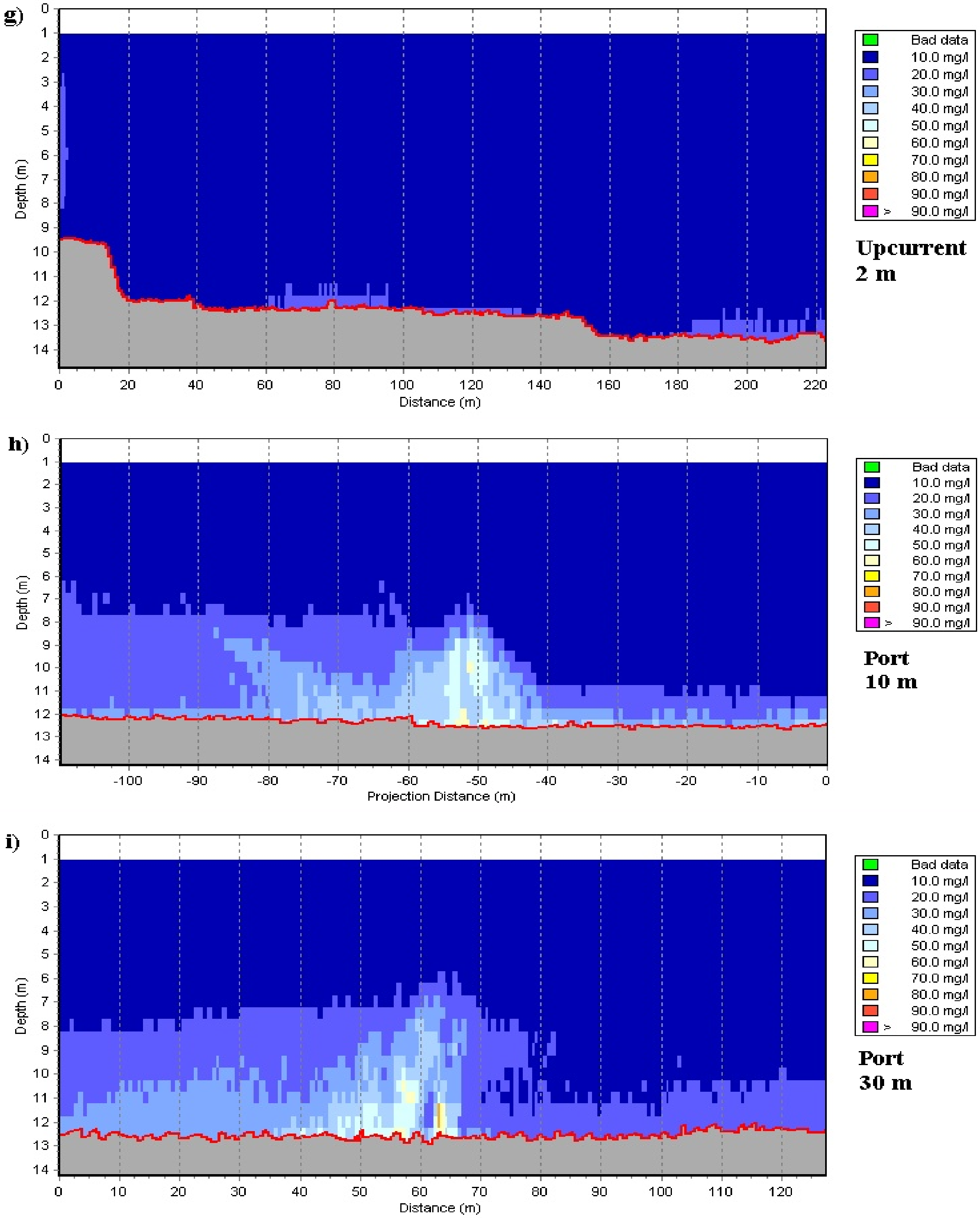


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

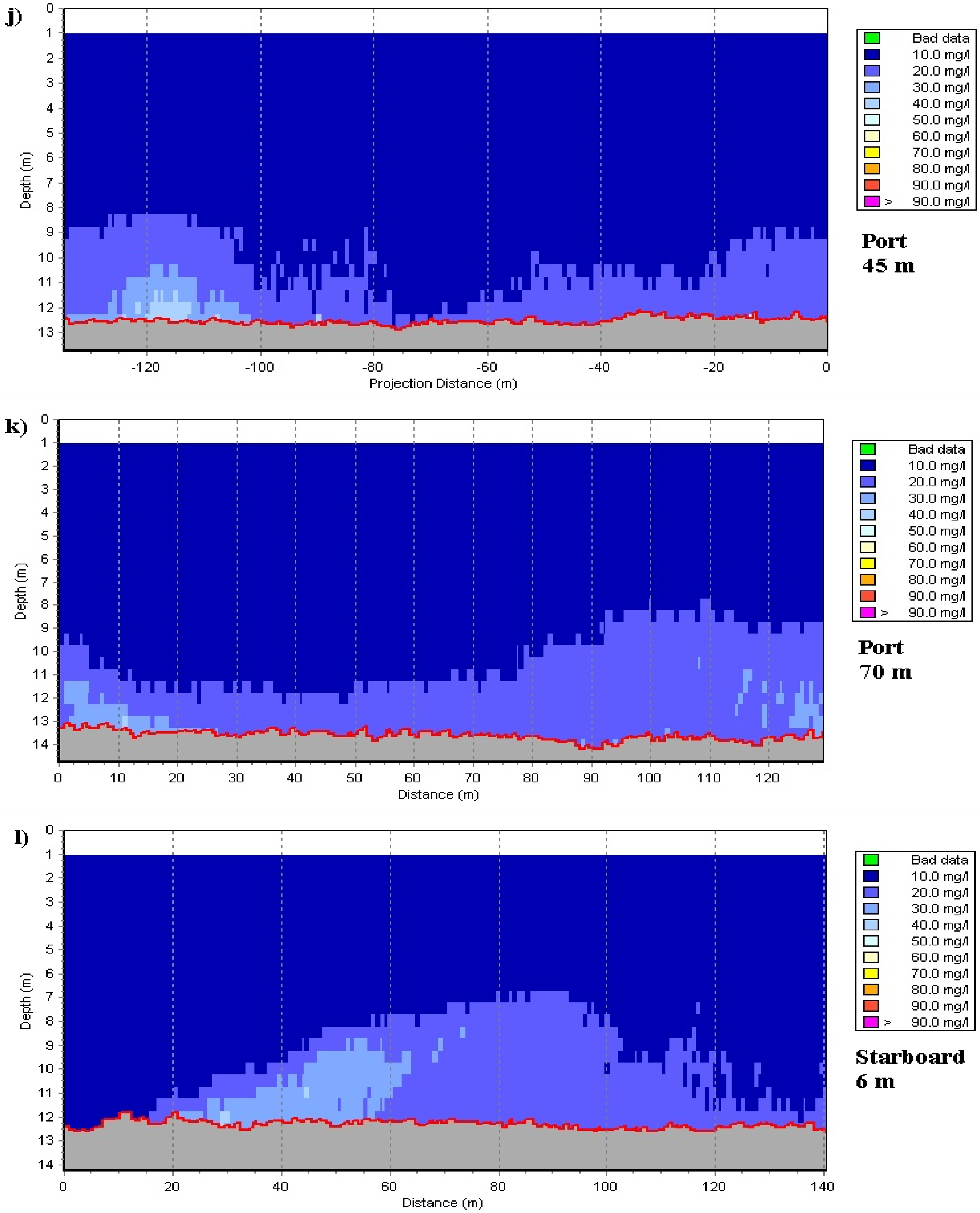


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

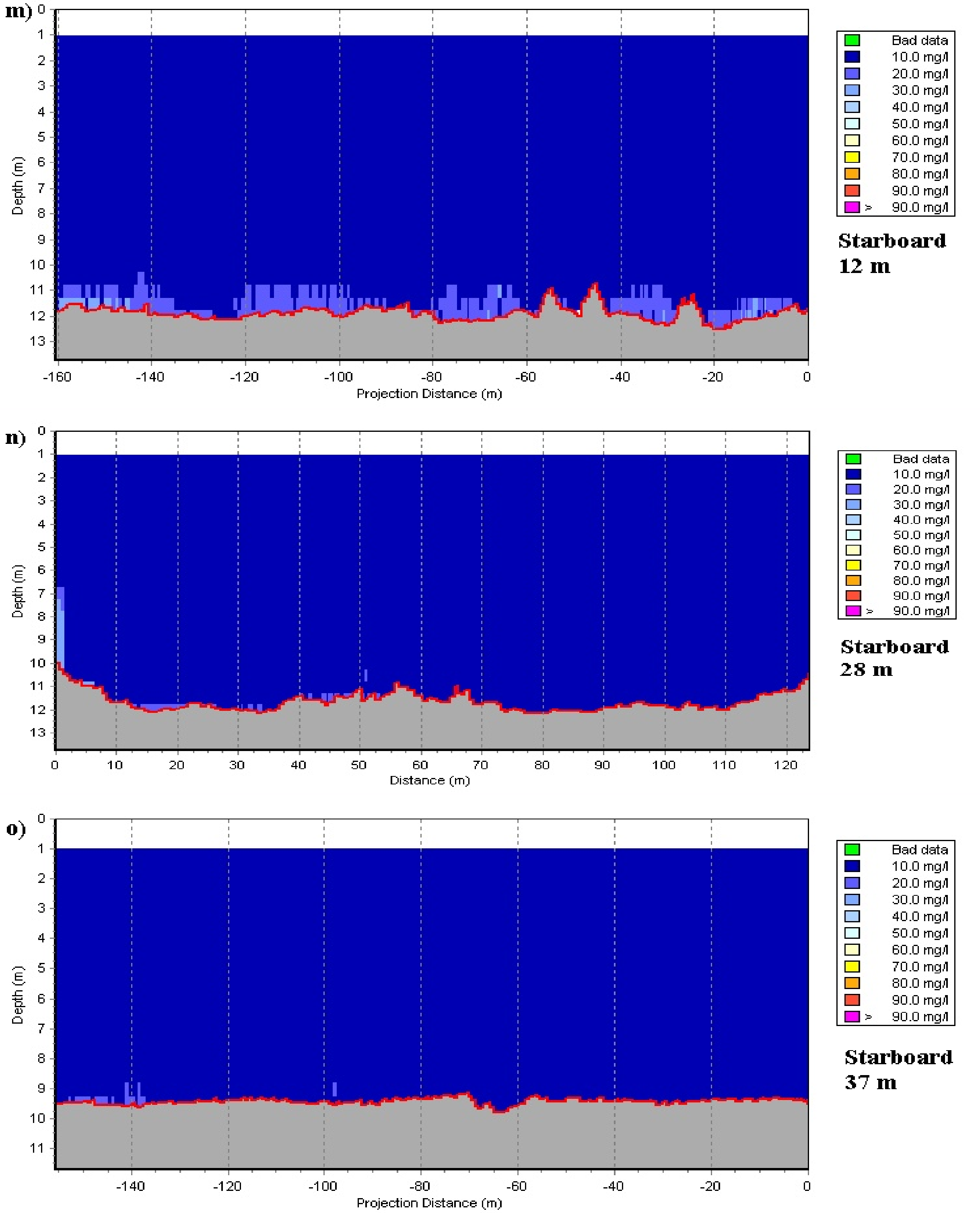


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

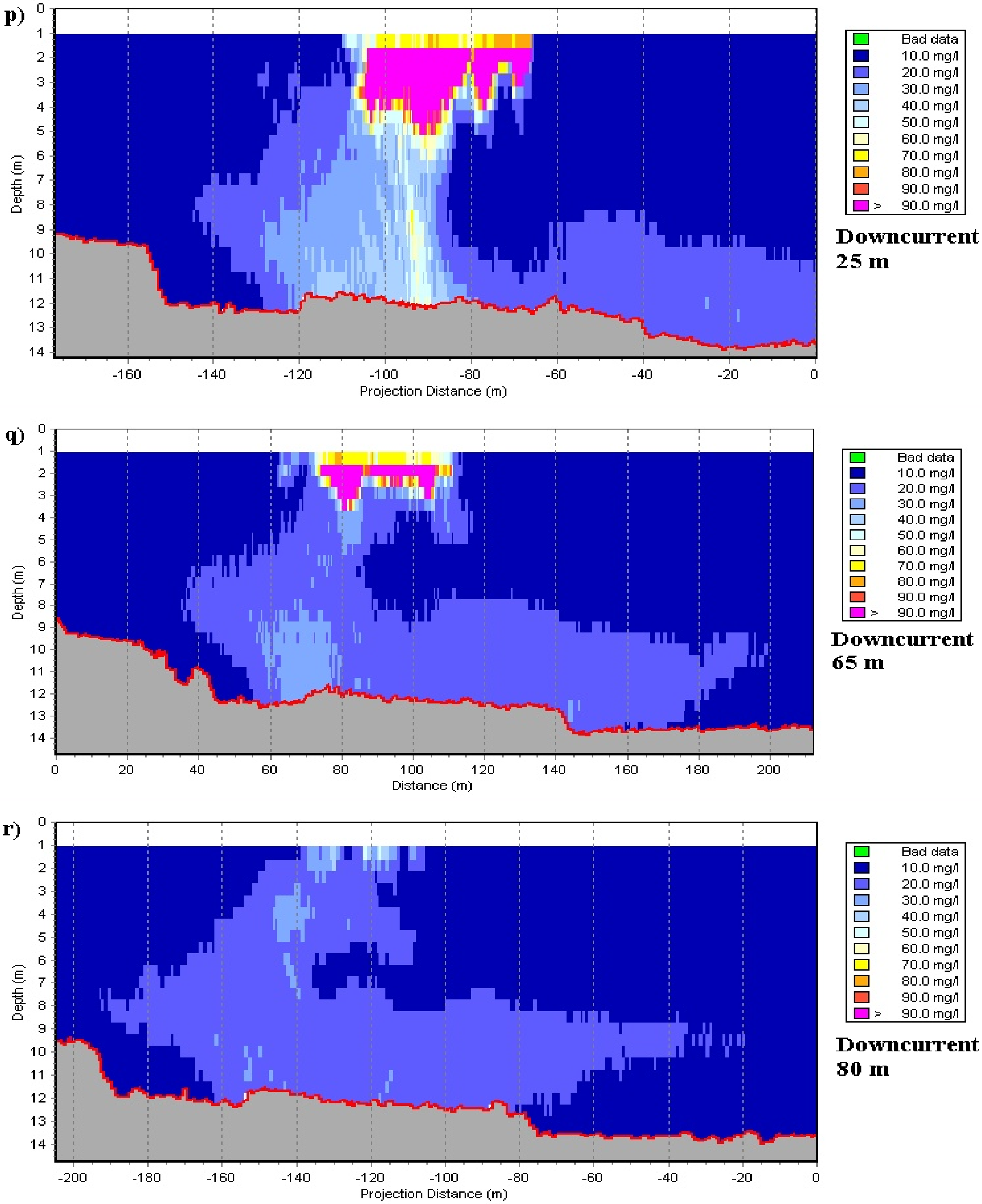


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

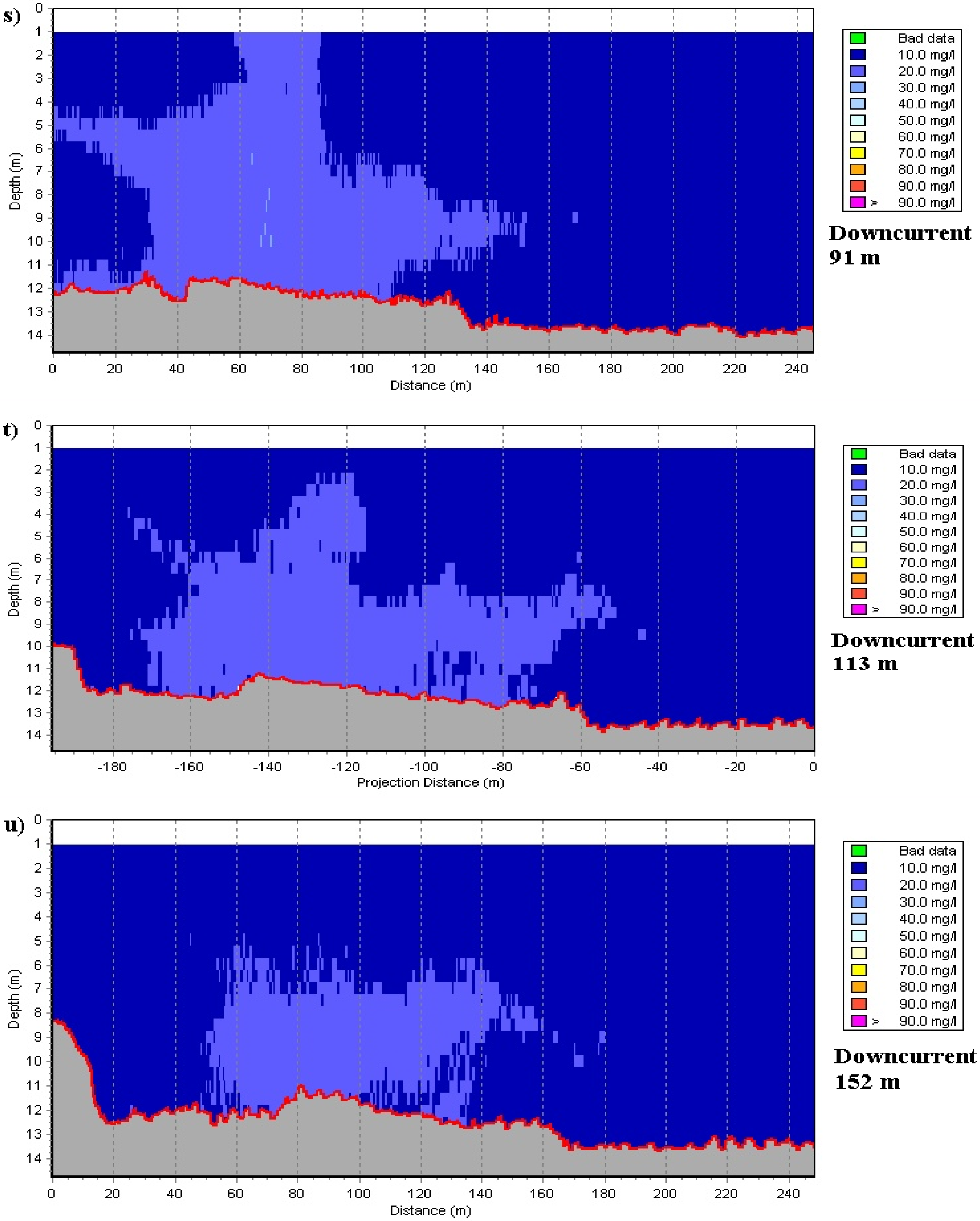


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

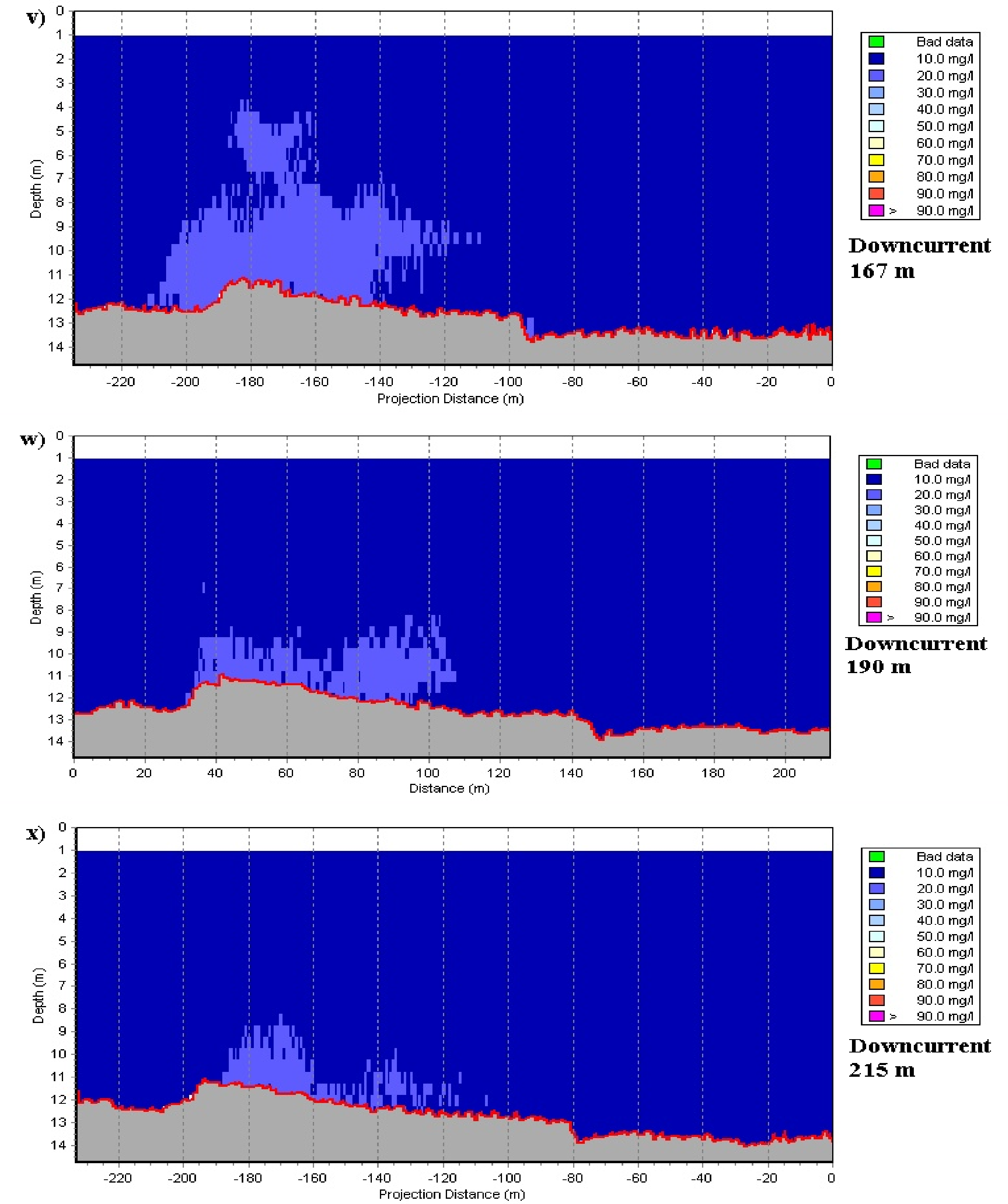
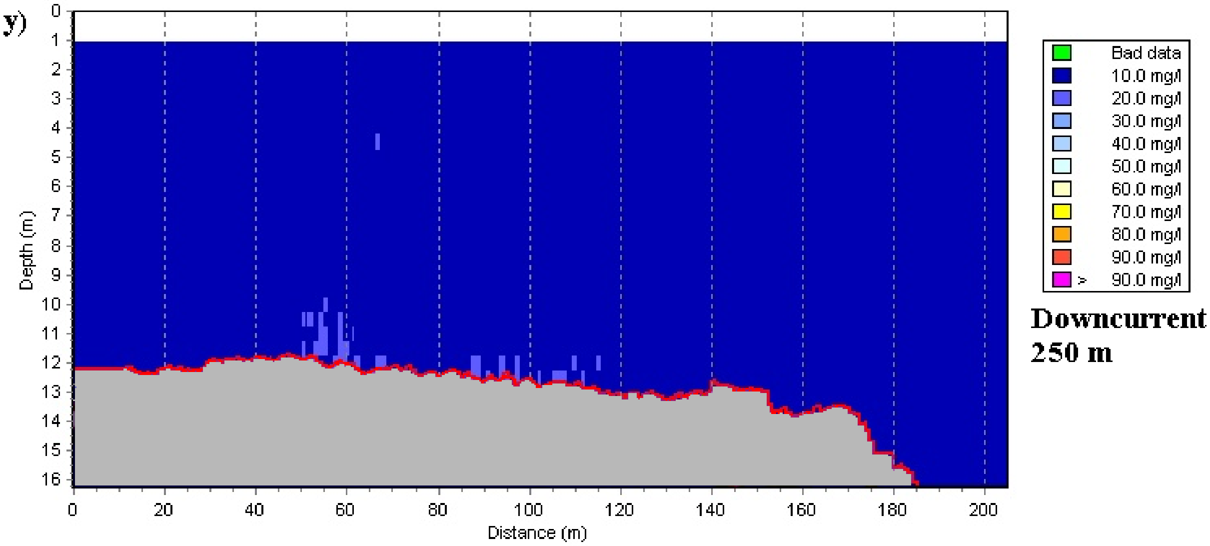


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

y)



z)

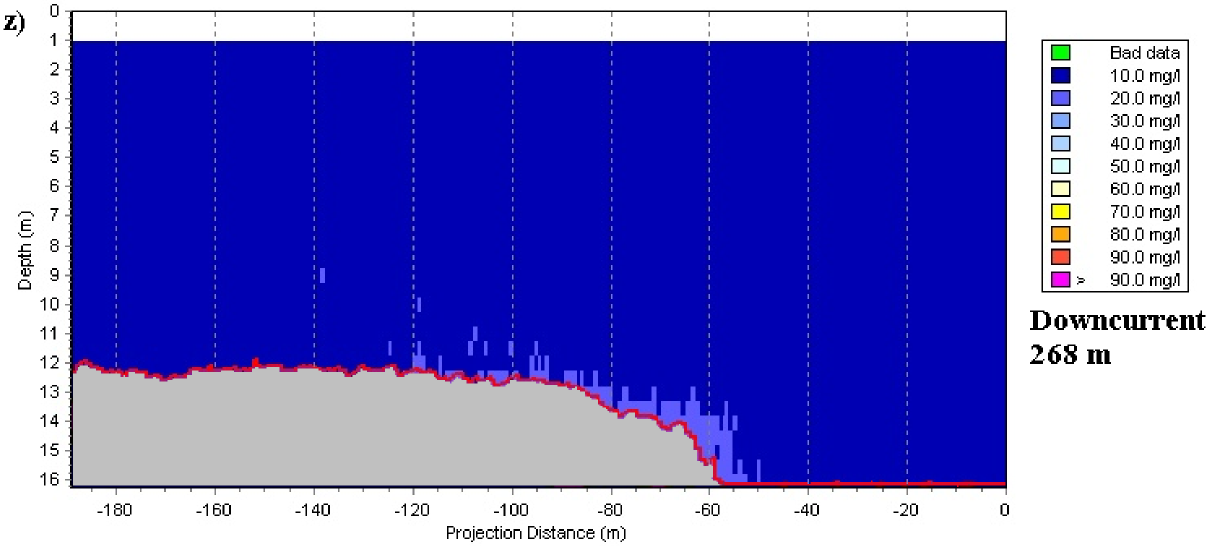


Figure 18 (cont.). Vertical profiles (Survey NJEA) of TSS concentrations across Shooters Island Reach during an ebbing tide on 19 June 2006. Distances from the source are given for each transect below the legend at the right of the graph.

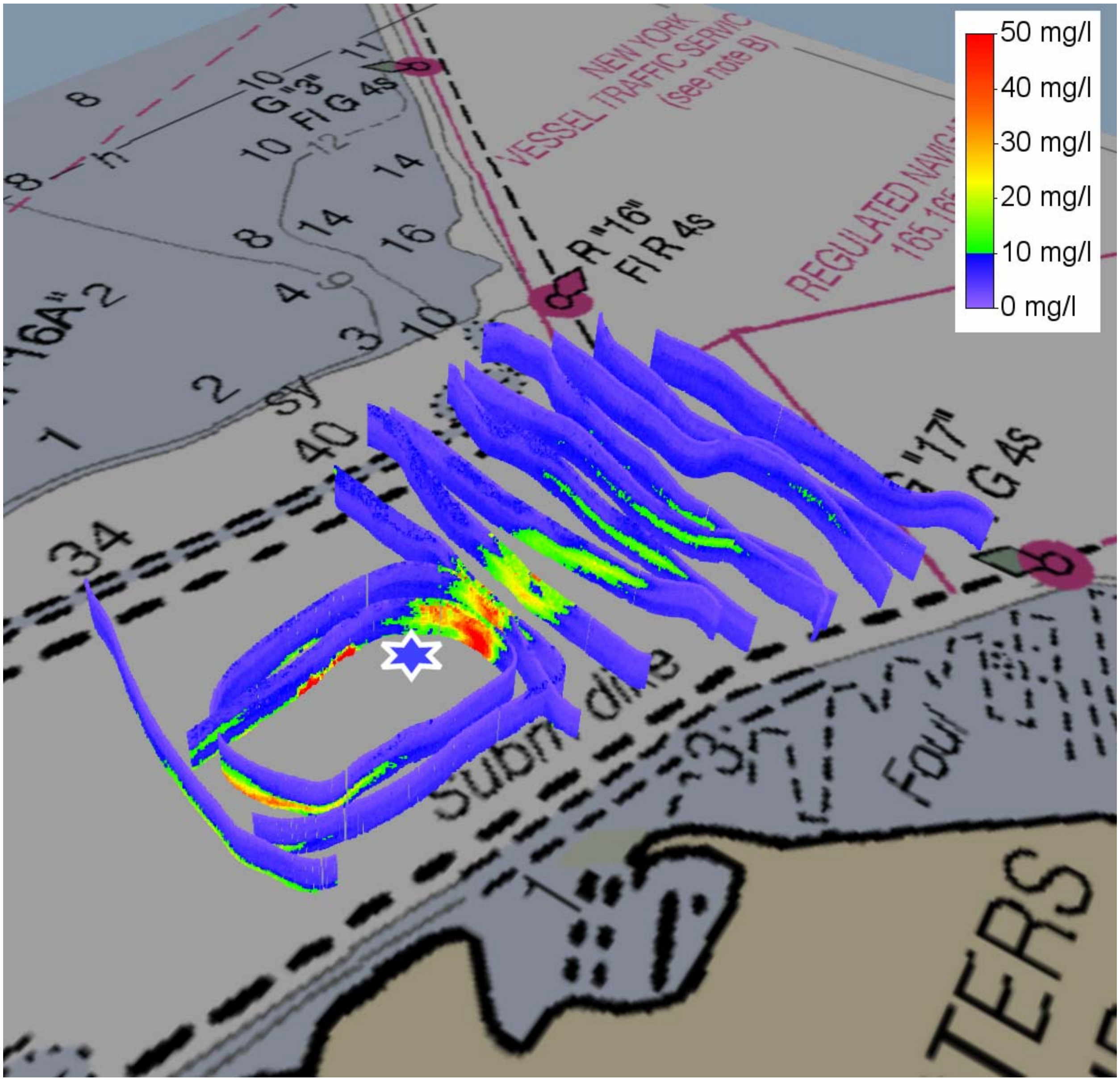


Figure 19. Suspended sediment concentrations for Survey NJEB plotted with respect to their x, y and z coordinates. (Dredge position indicated by star).

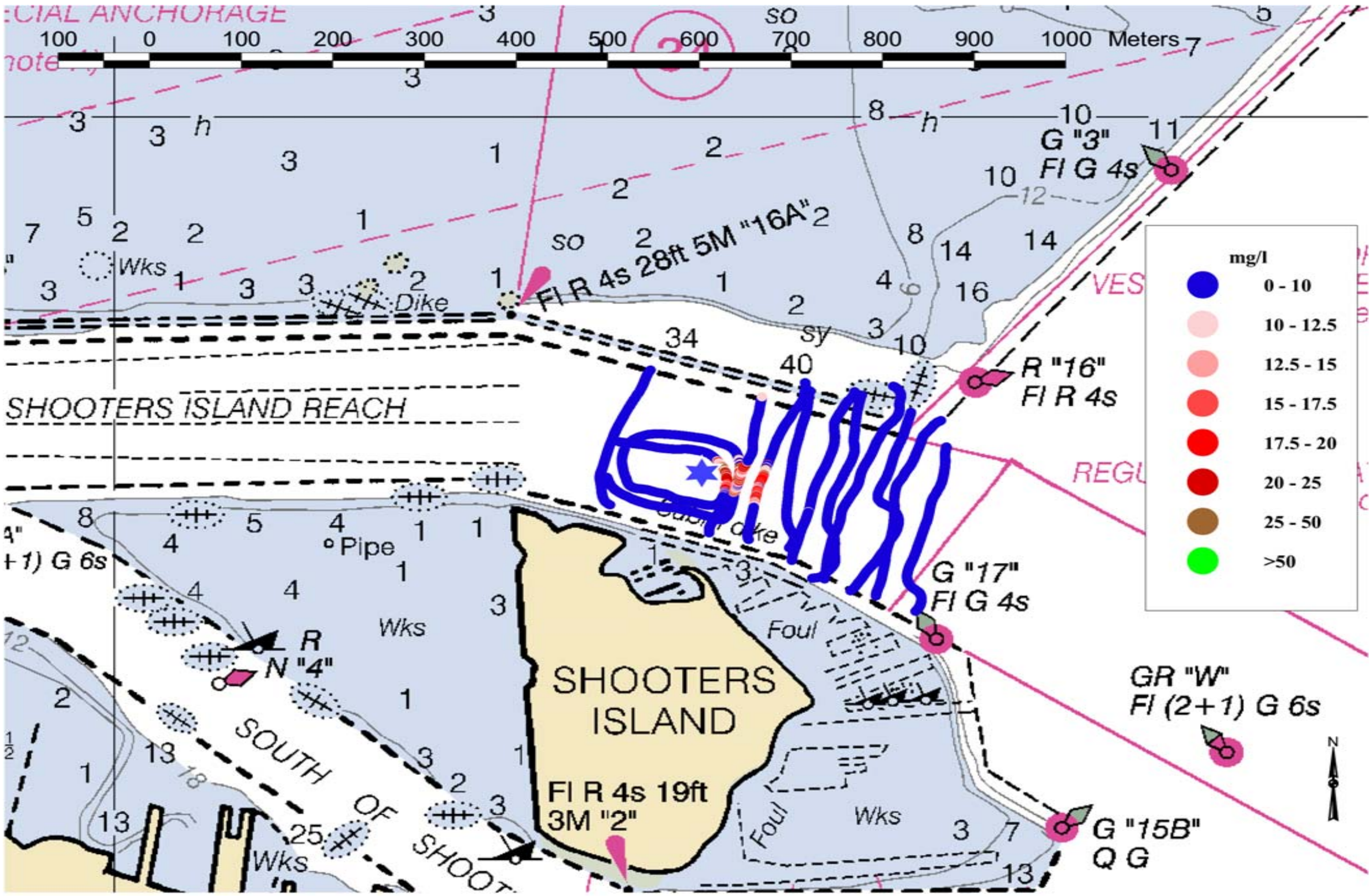


Figure 20. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 2 meters for Survey NJEB, completed during an ebbing tide on 19 June 2006.

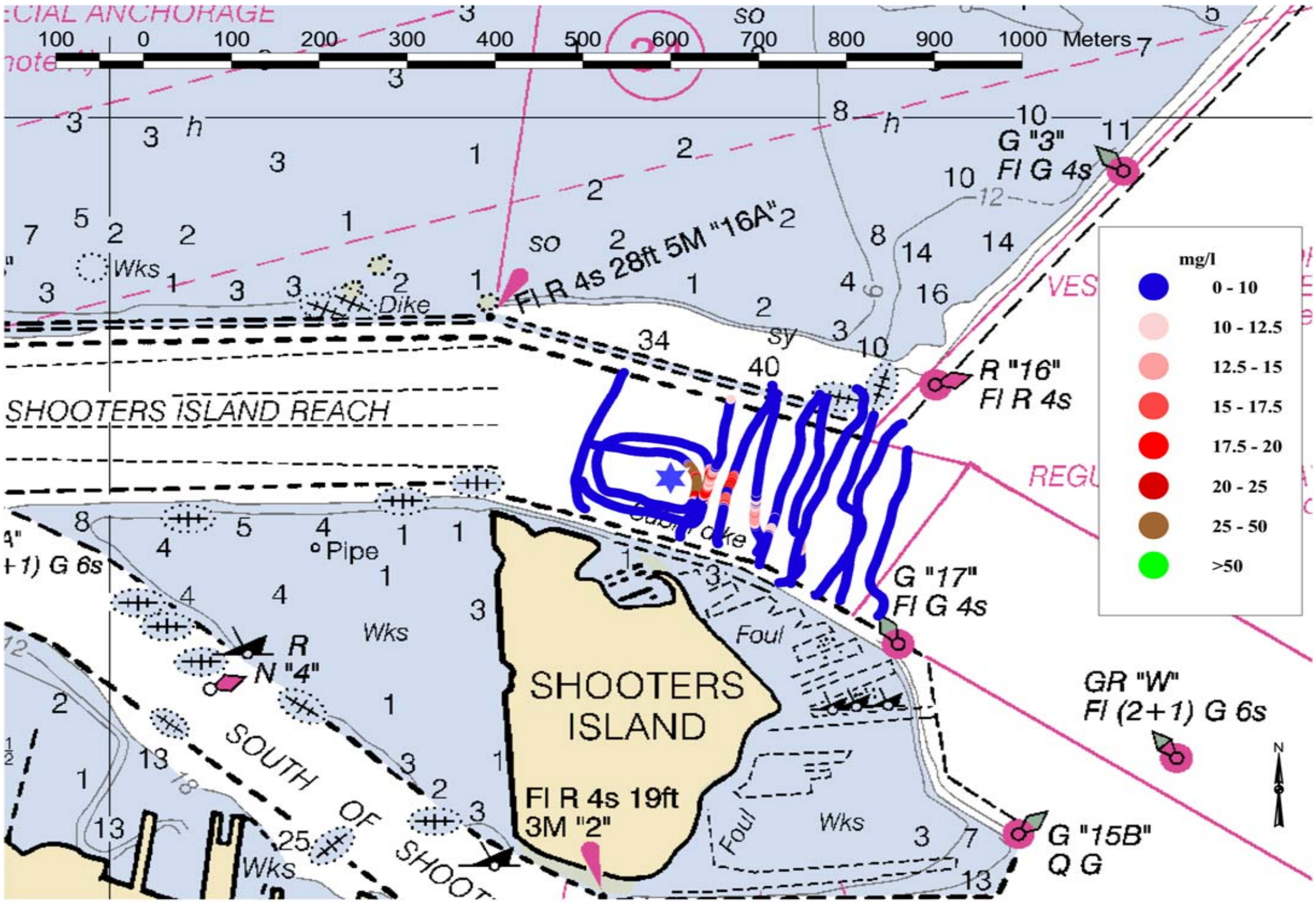


Figure 21. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 4 meters for Survey NJEB, completed during an ebbing tide on 19 June 2006.

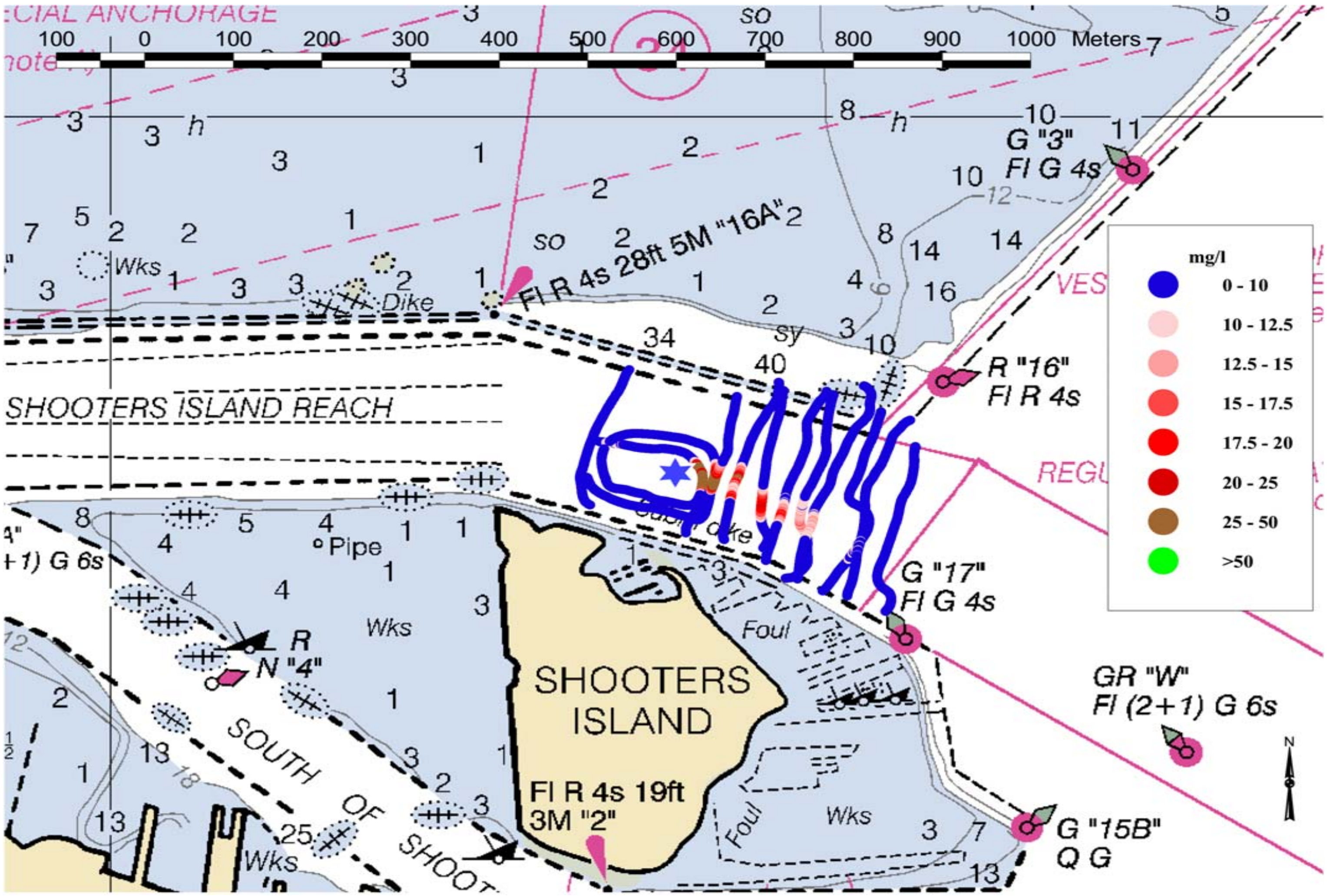


Figure 22. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 6 meters for Survey NJEB, completed during an ebbing tide on 19 June 2006.

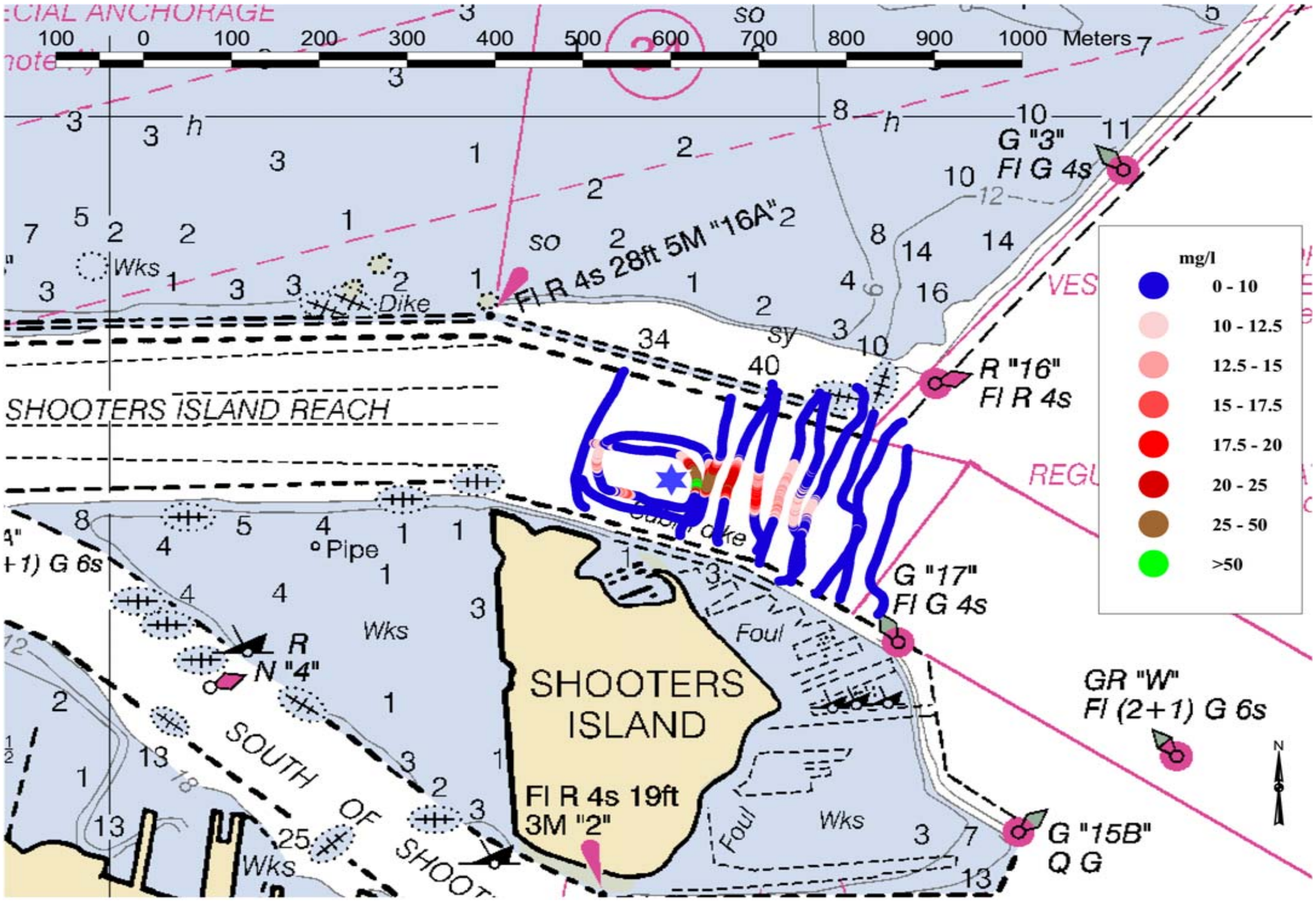


Figure 23. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 8 meters for Survey NJEB, completed during an ebbing tide on 19 June 2006.

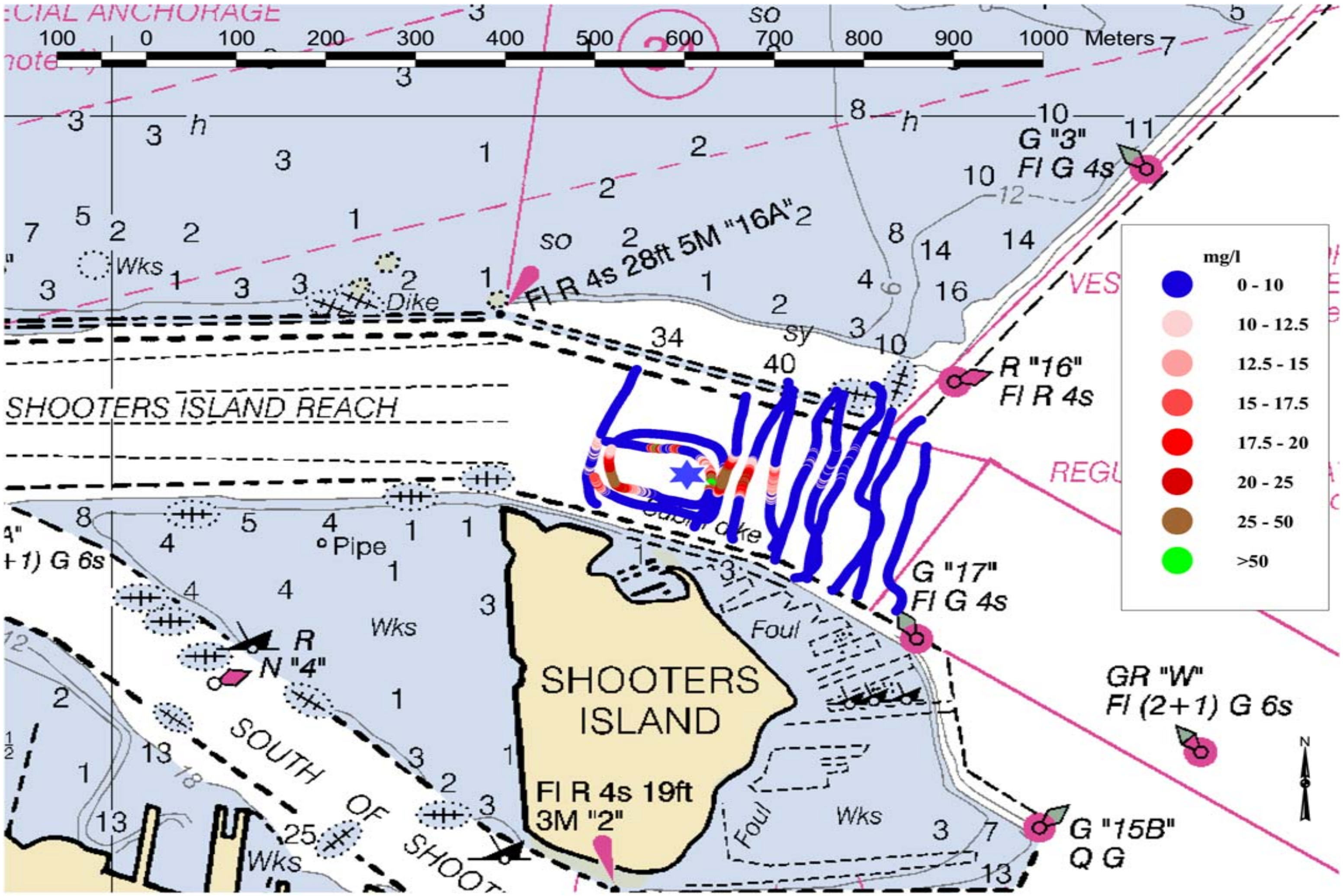


Figure 24. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 10 meters for Survey NJEB, completed during an ebbing tide on 19 June 2006.

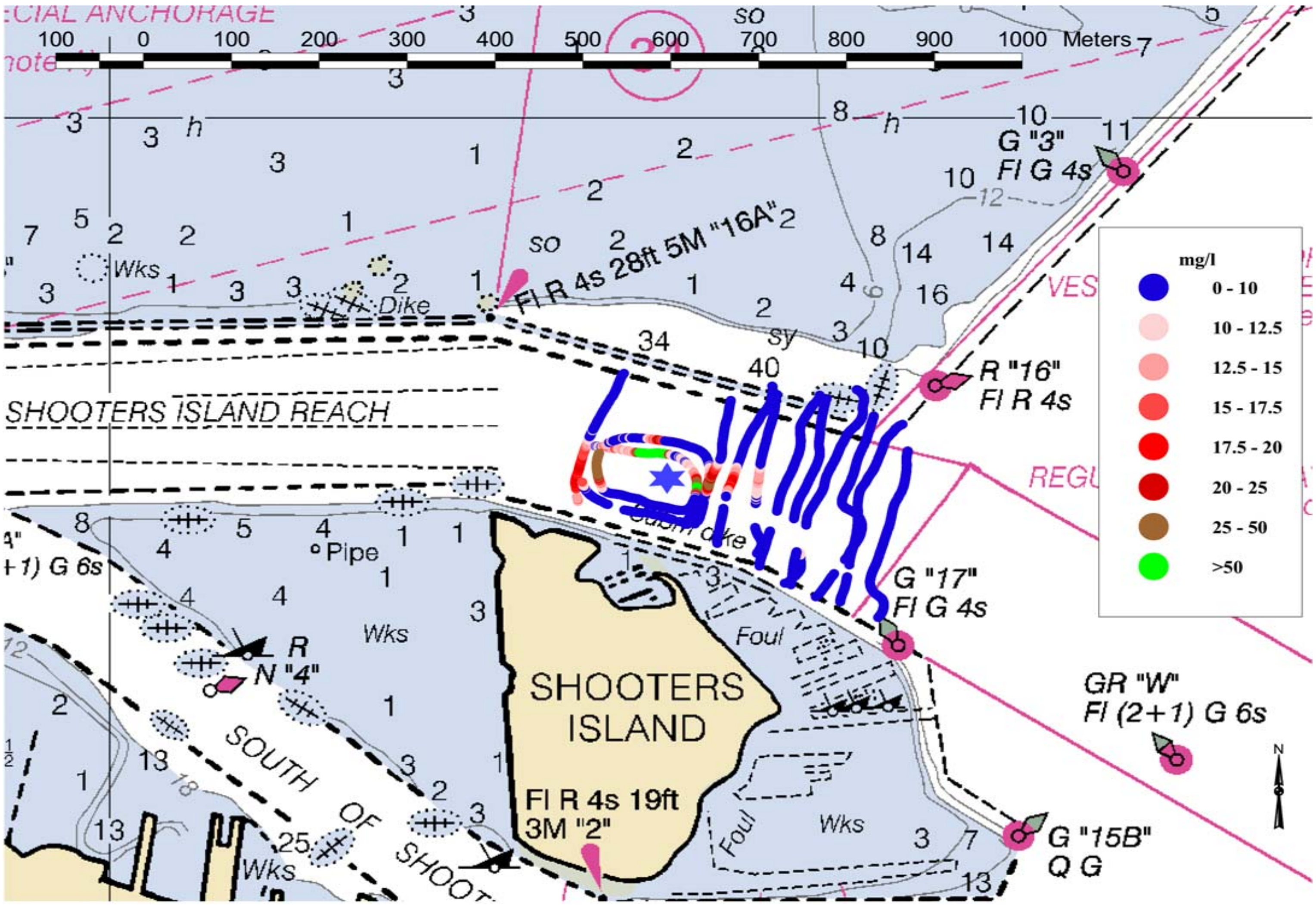


Figure 25. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 12 meters for Survey NJEB, completed during an ebbing tide on 19 June 2006.

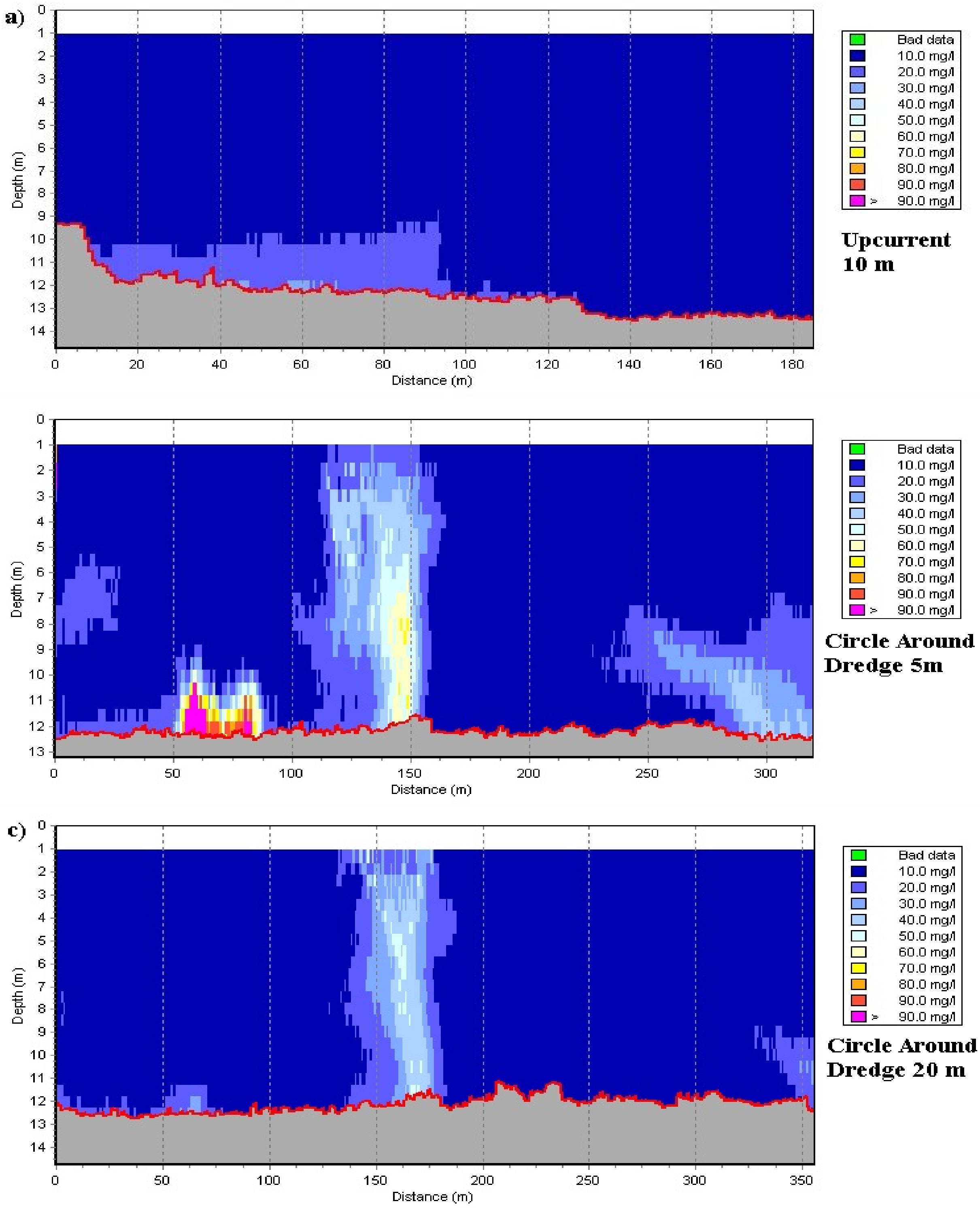


Figure 26. Vertical profiles (Survey NJEB) of TSS concentration across Shooters Island Reach during an ebbing tide, 19 June 2006.

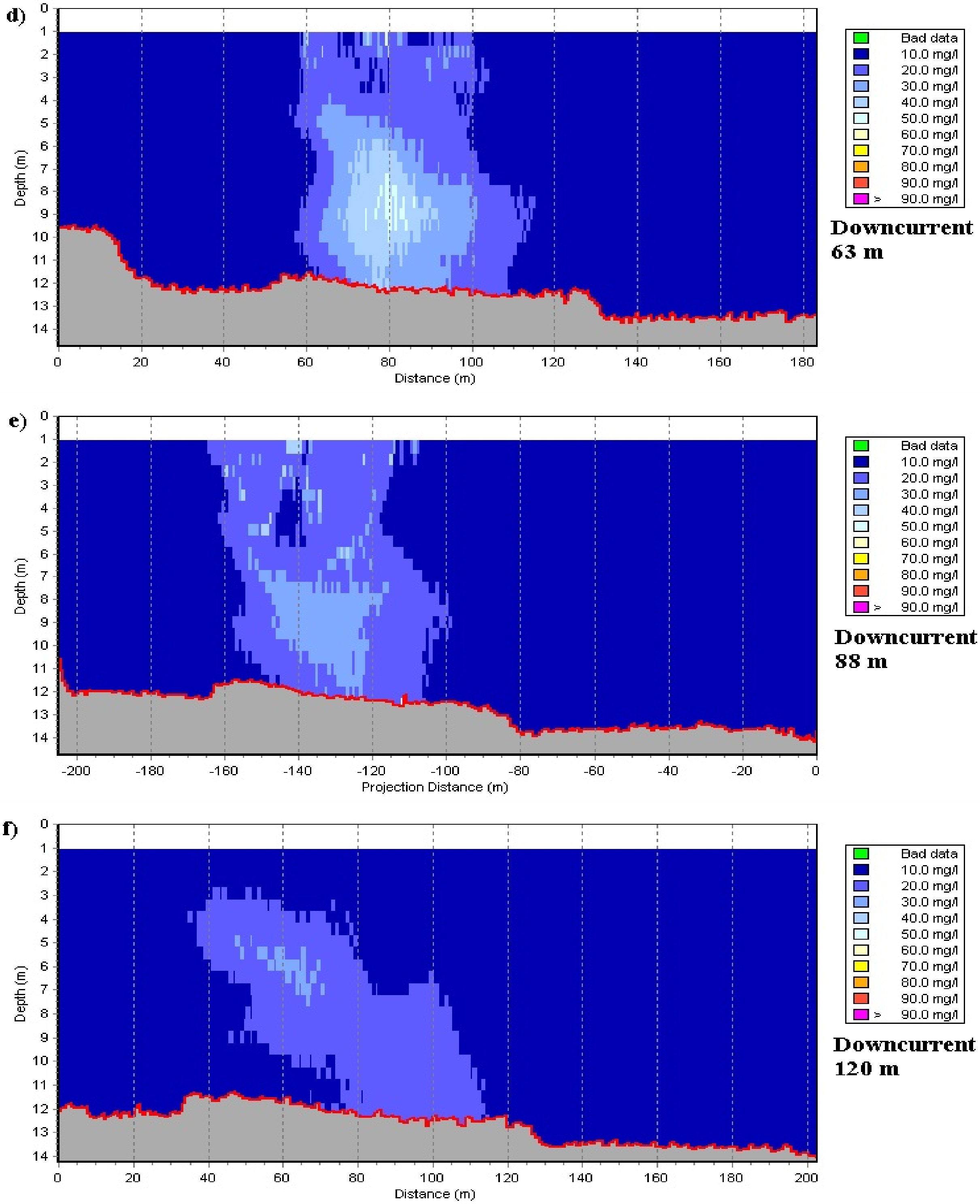


Figure 26 (cont.). Vertical profiles (Survey NJEB) of TSS concentration across Shooters Island Reach during an ebbing tide, 19 June 2006.

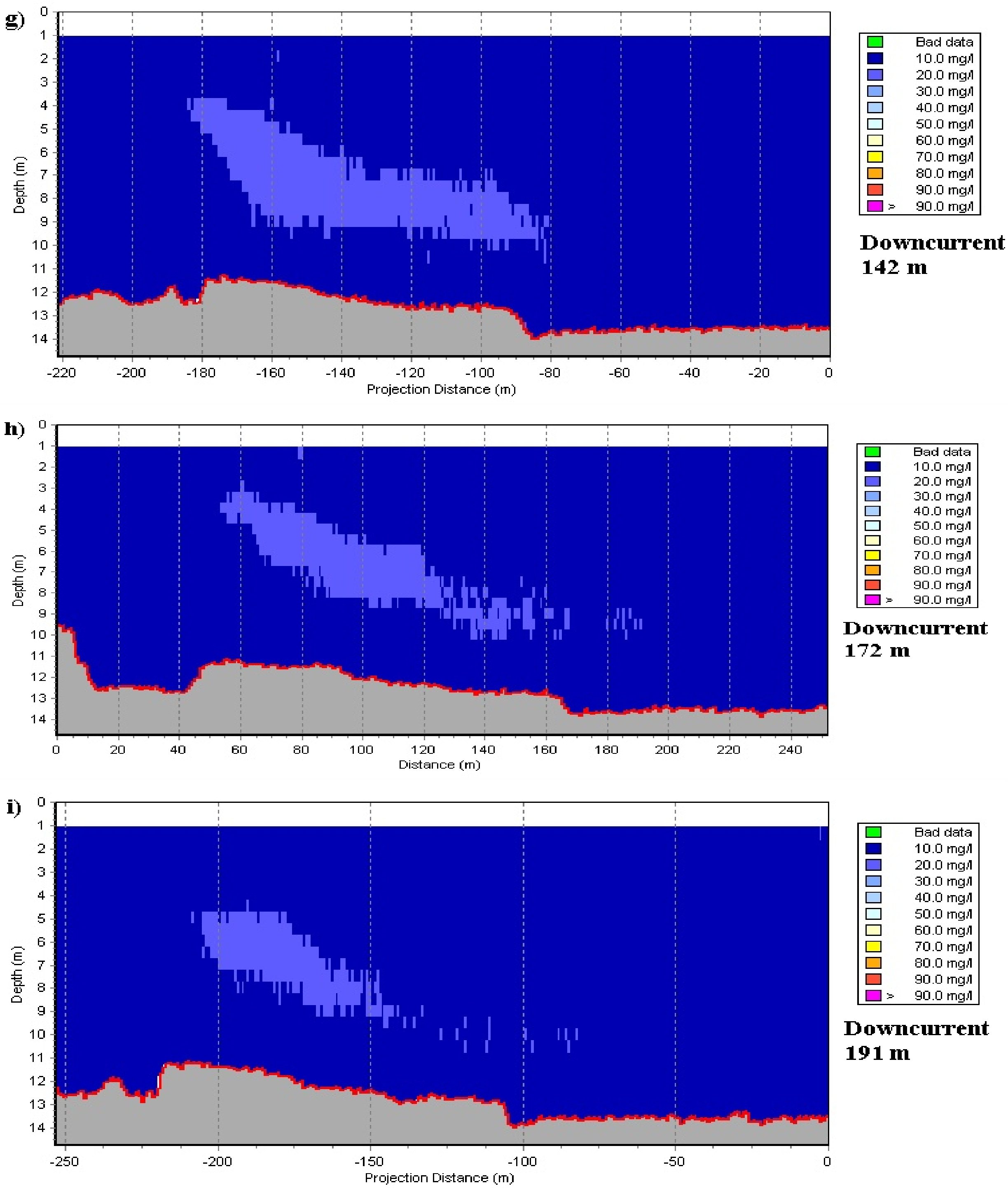


Figure 26 (cont.). Vertical profiles (Survey NJEB) of TSS concentration across Shooters Island Reach during an ebbing tide, 19 June 2006.

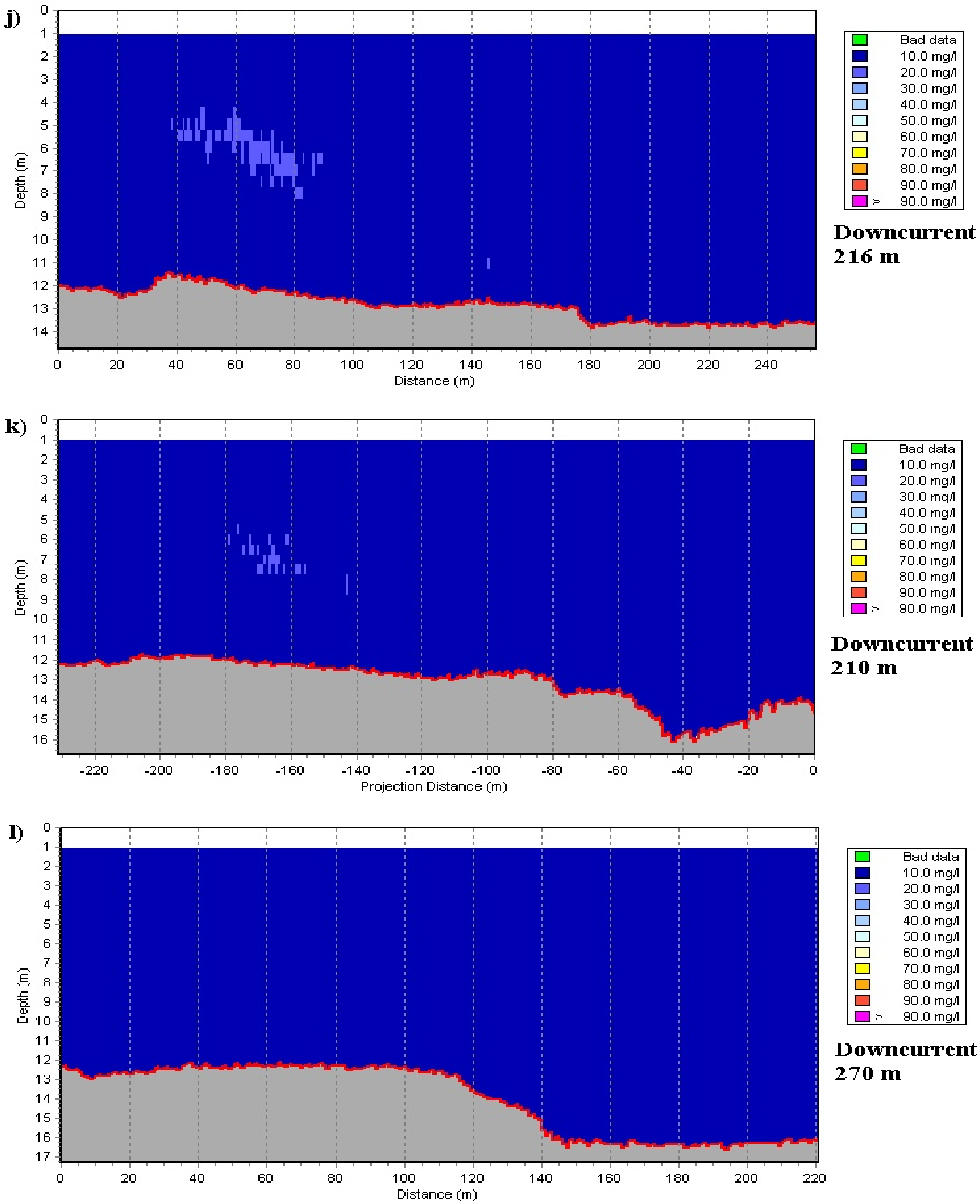


Figure 26 (cont.). Vertical profiles (Survey NJEB) of TSS concentration across Shooters Island Reach during an ebbing tide, 19 June 2006.

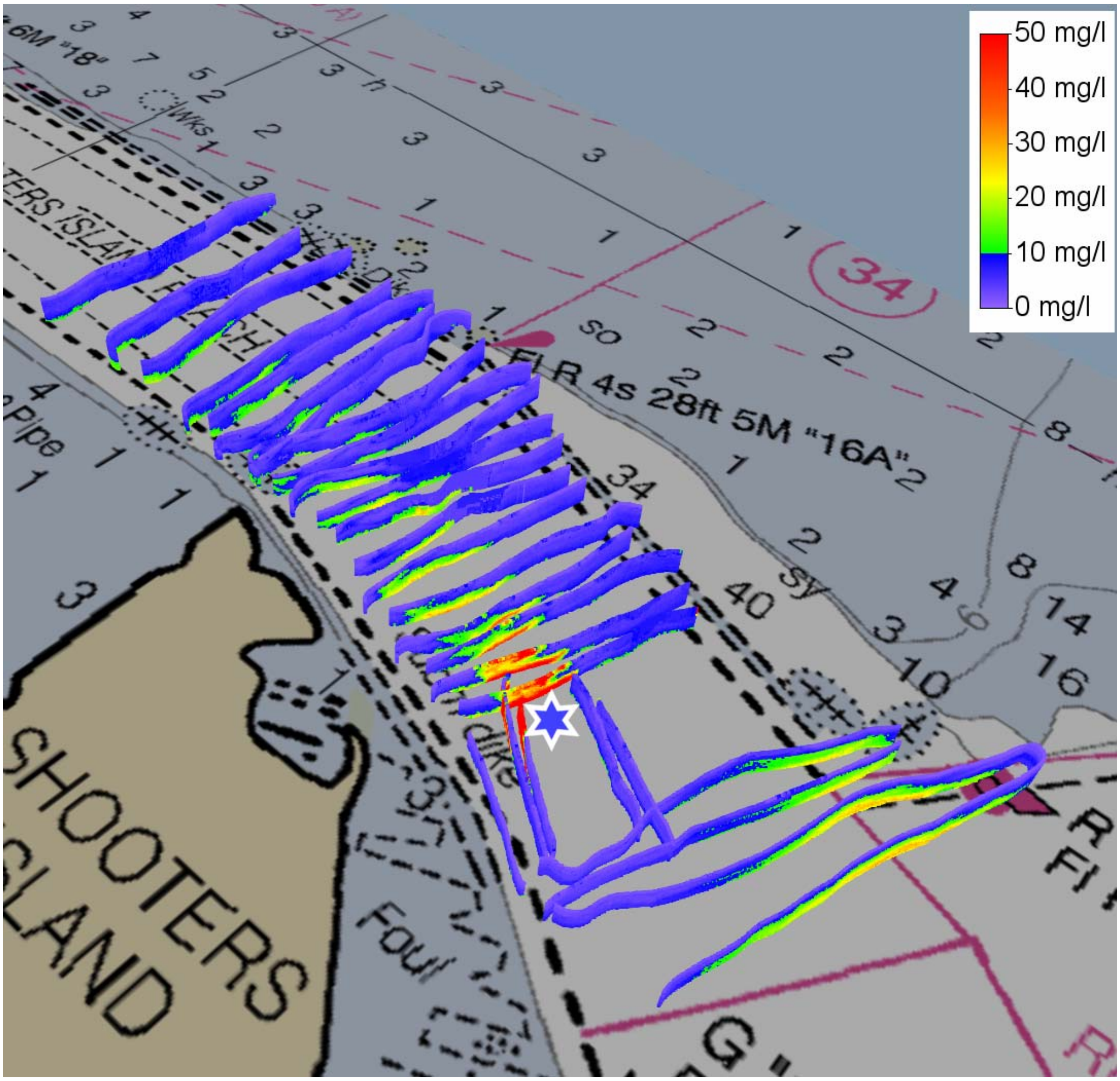


Figure 27. TSS concentrations for Survey NJFD plotted in x, y z coordinates. (Dredge location indicated by star).

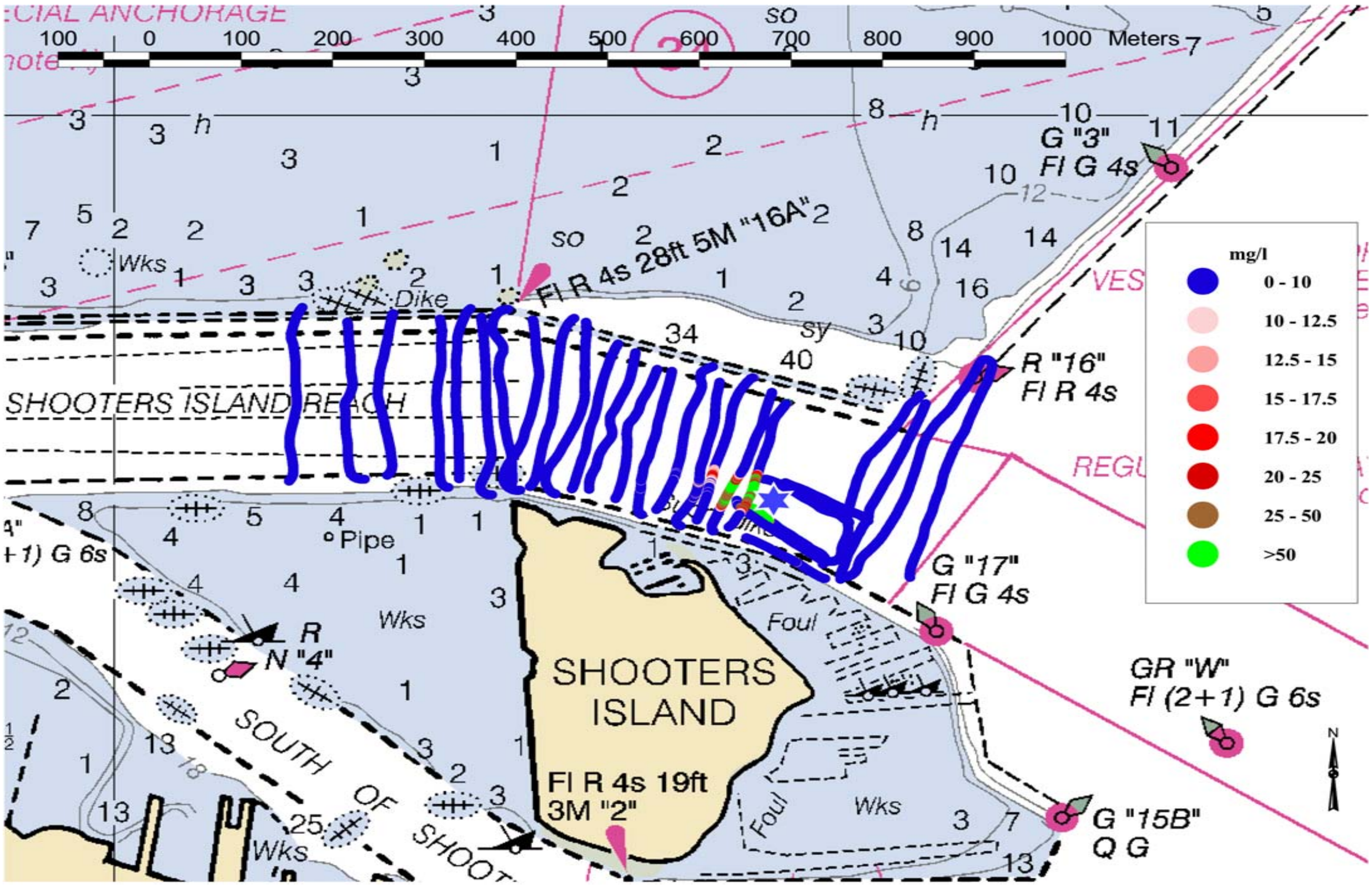


Figure 28. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 2 meters for Survey NJFD, completed during a flooding tide on 20 June 2006.

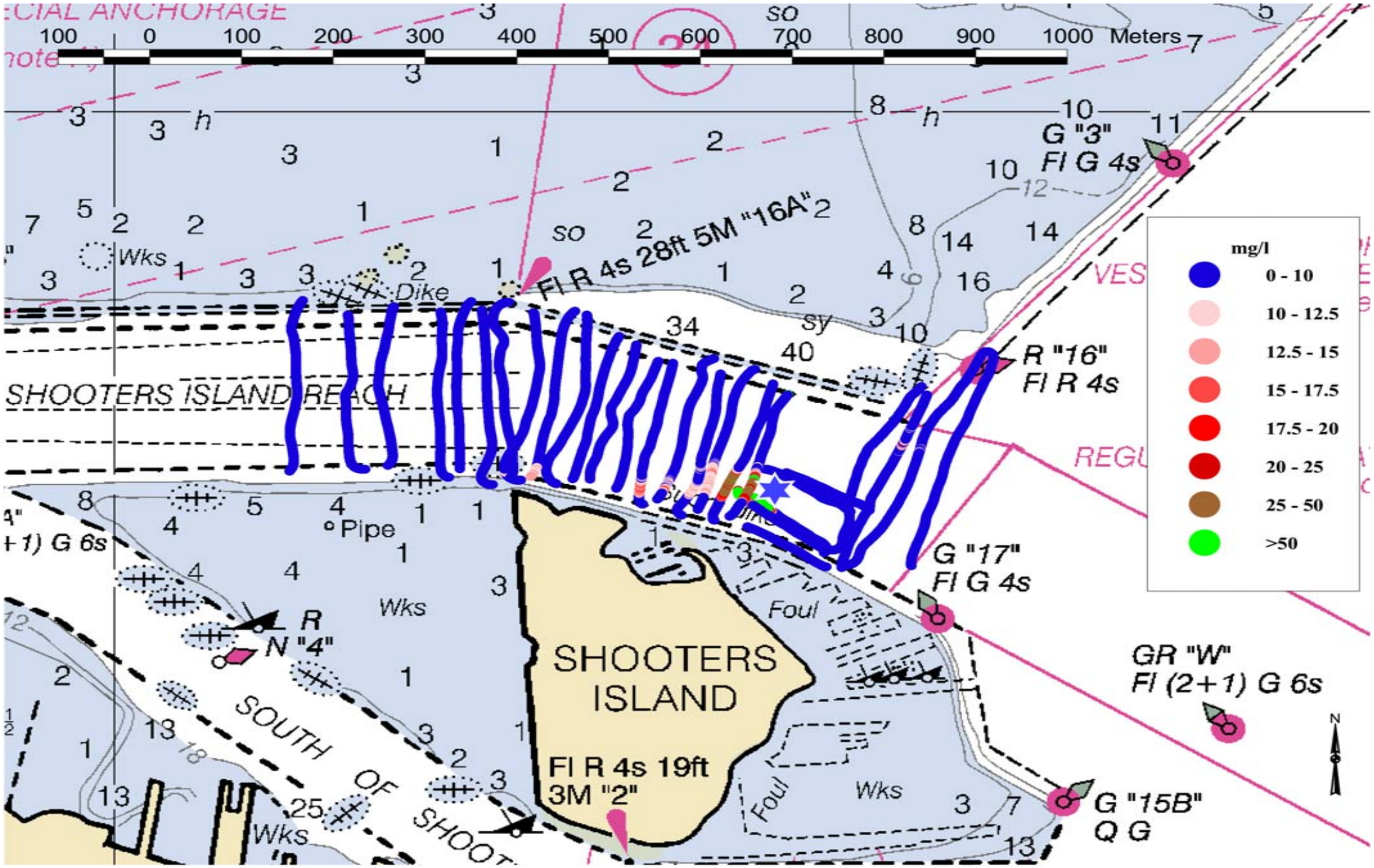


Figure 29. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 4 meters for Survey NJFD, completed during a flooding tide on 20 June 2006.

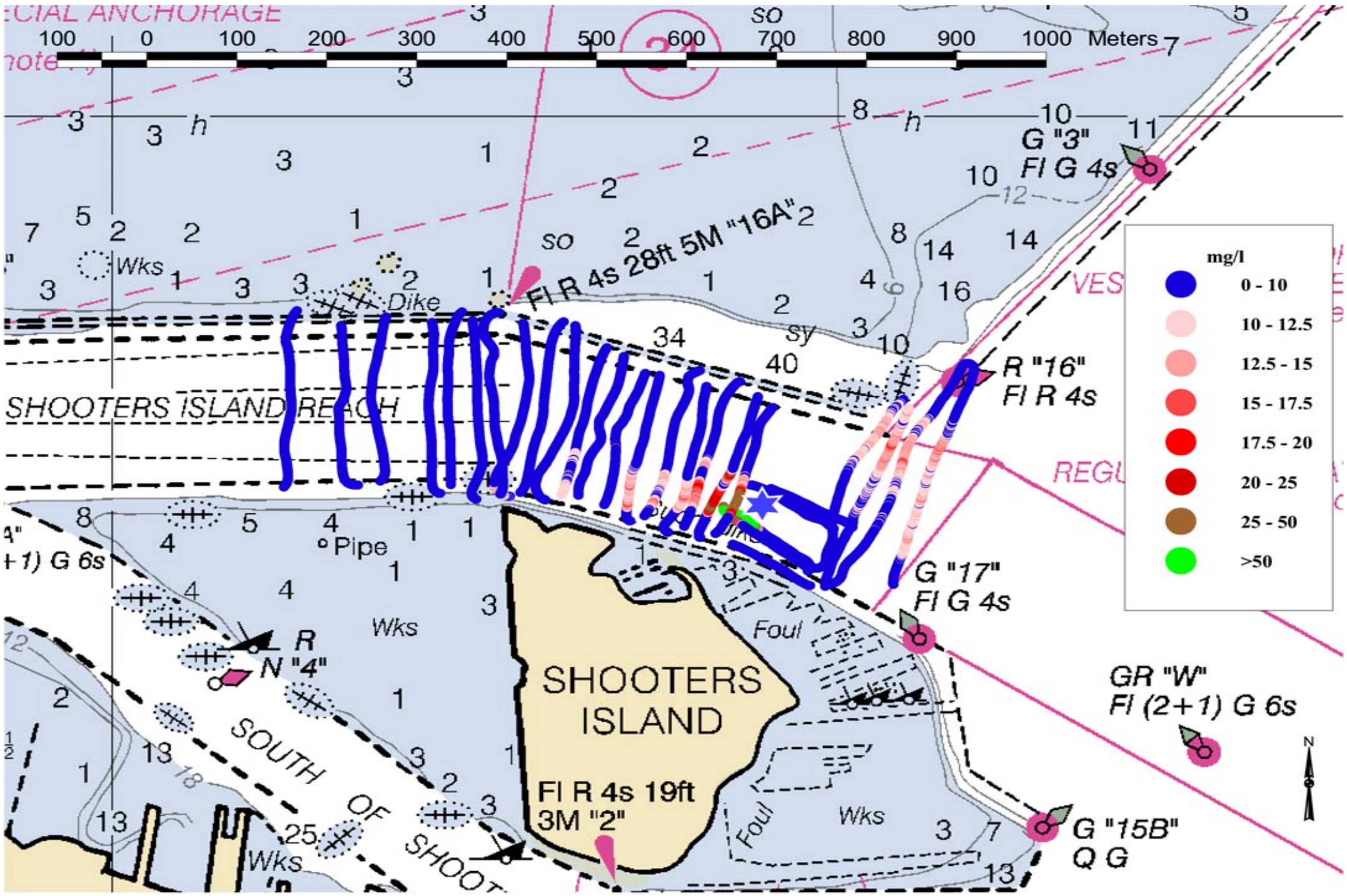


Figure 30. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 6 meters for Survey NJFD, completed during a flooding tide on 20 June 2006.

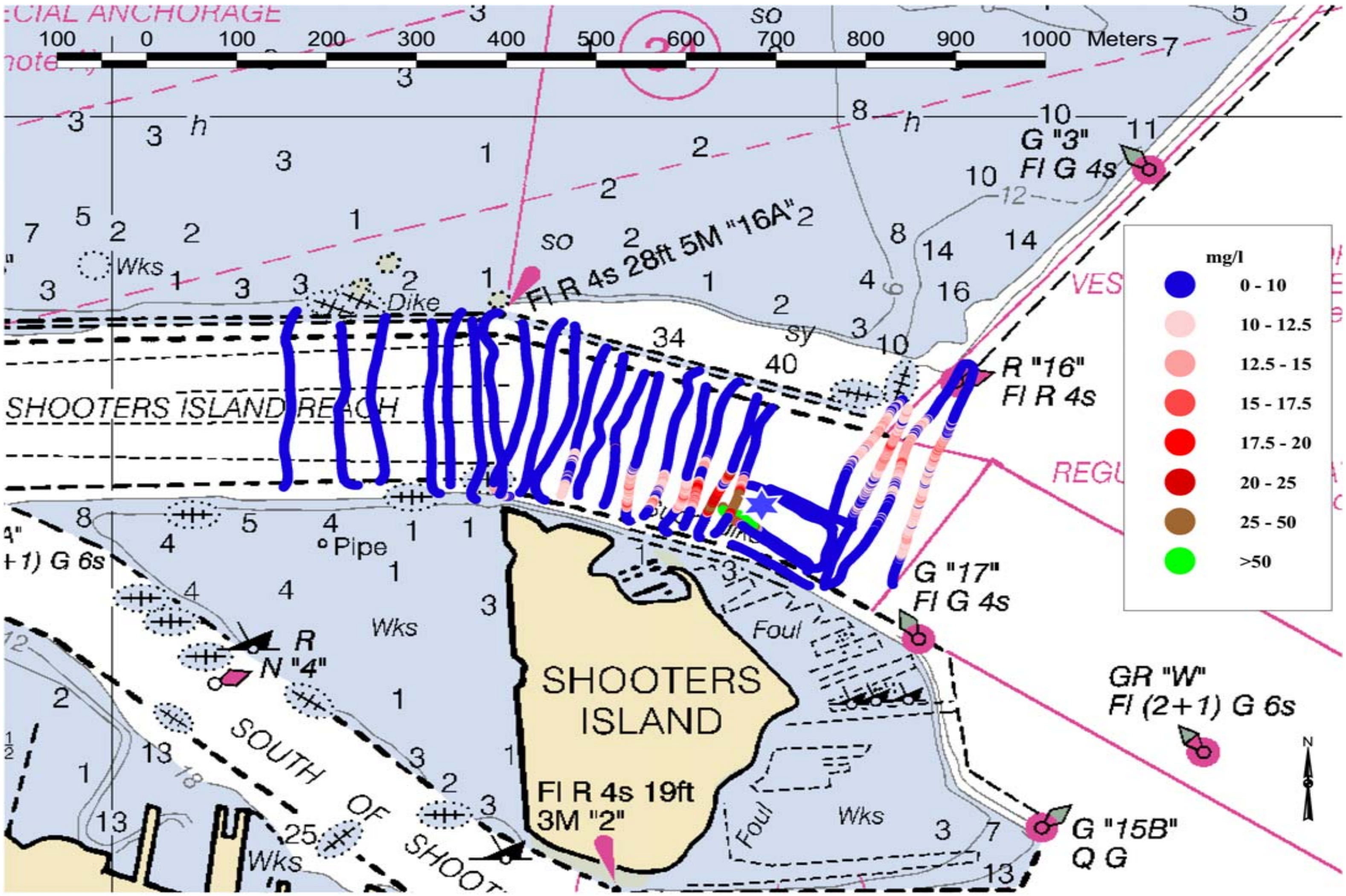


Figure 31. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 8 meters for Survey NJFD, completed during a flooding tide on 20 June 2006.

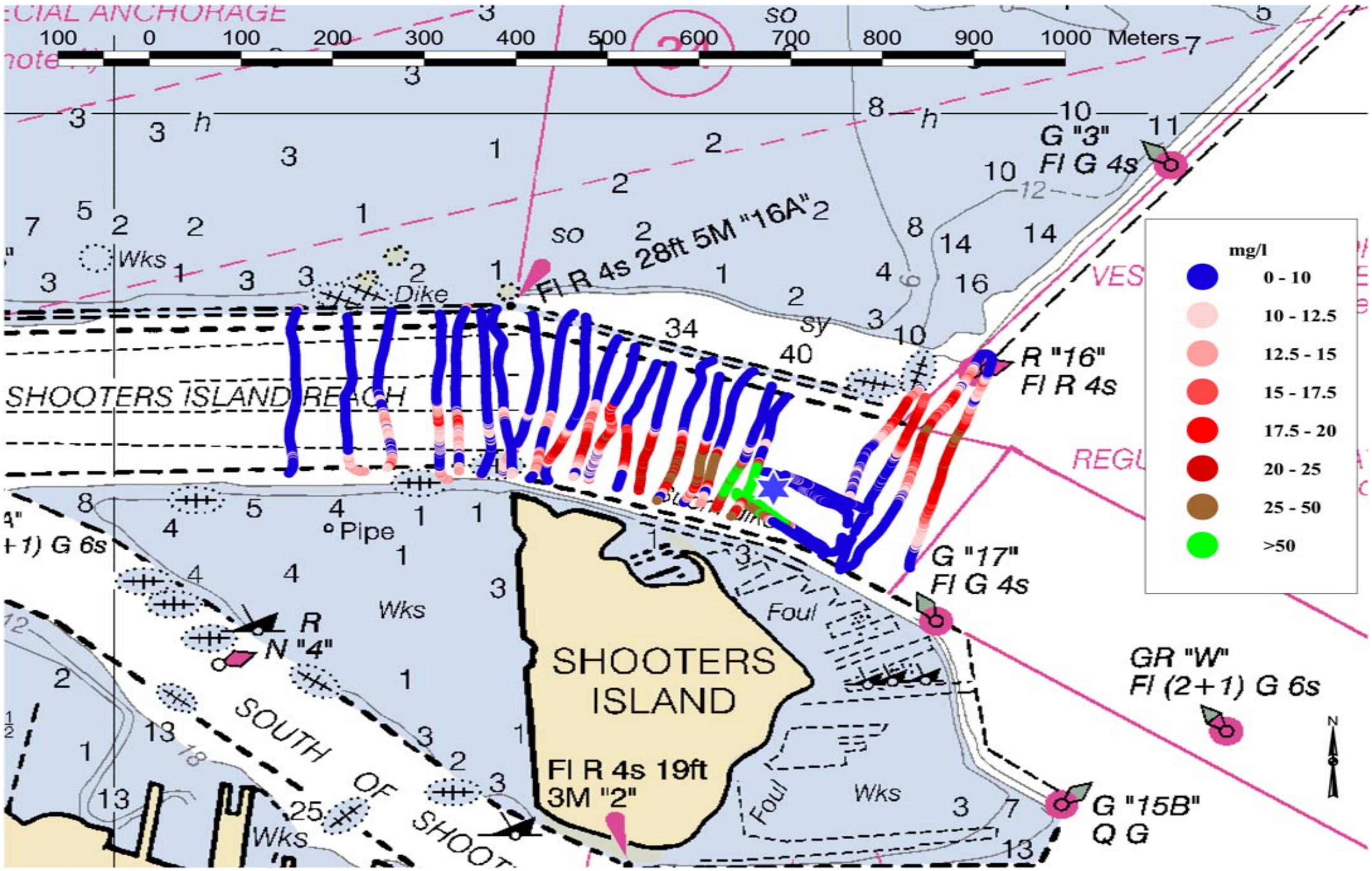


Figure 32. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 10 meters for Survey NJFD, completed during a flooding tide on 20 June 2006.

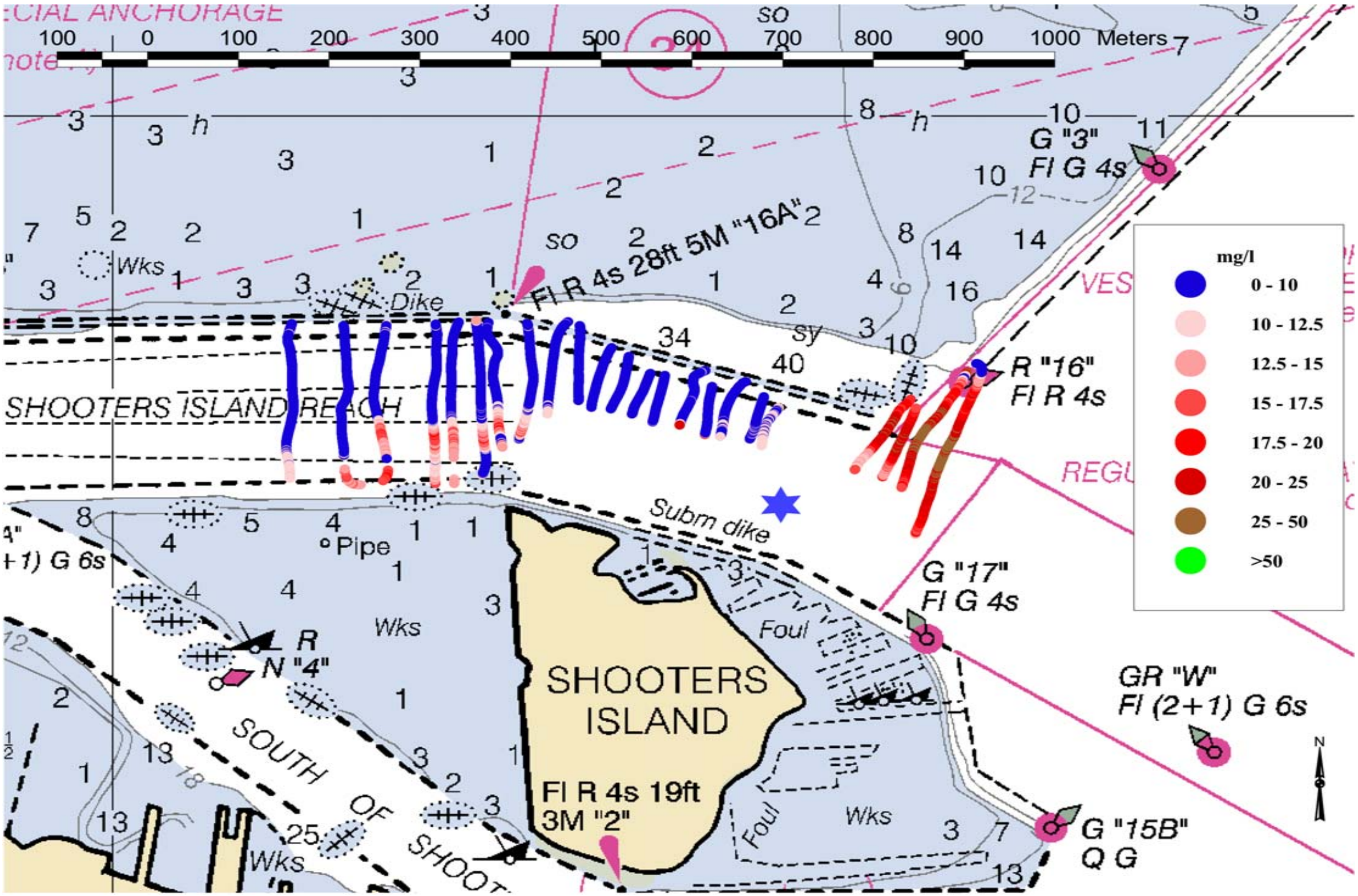


Figure 33. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 12 meters for Survey NJFD, completed during a flooding tide on 20 June 2006.

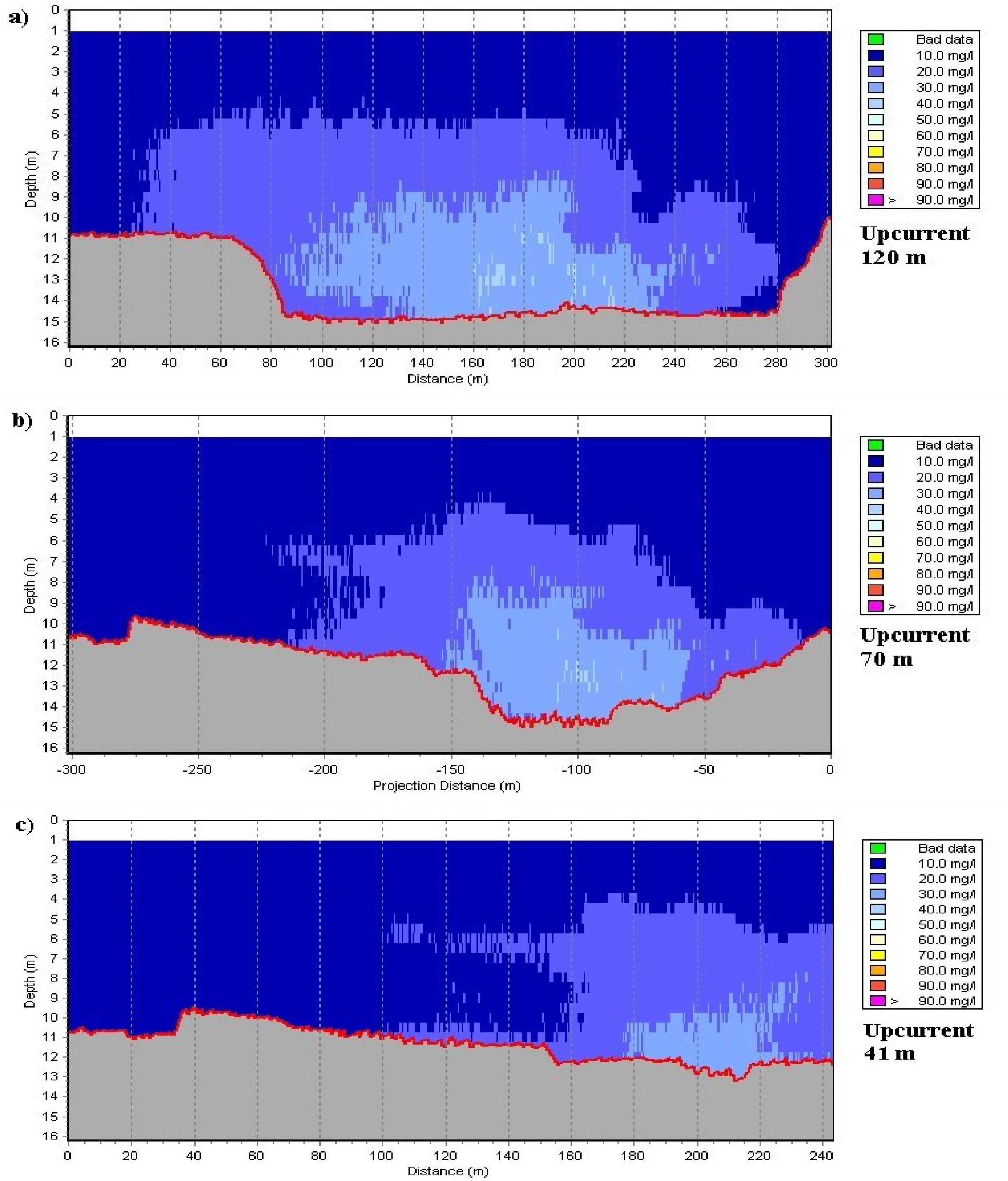


Figure 34. Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: "E" (10-350 mg/l), "F" (10-225 mg/l) and "J" (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

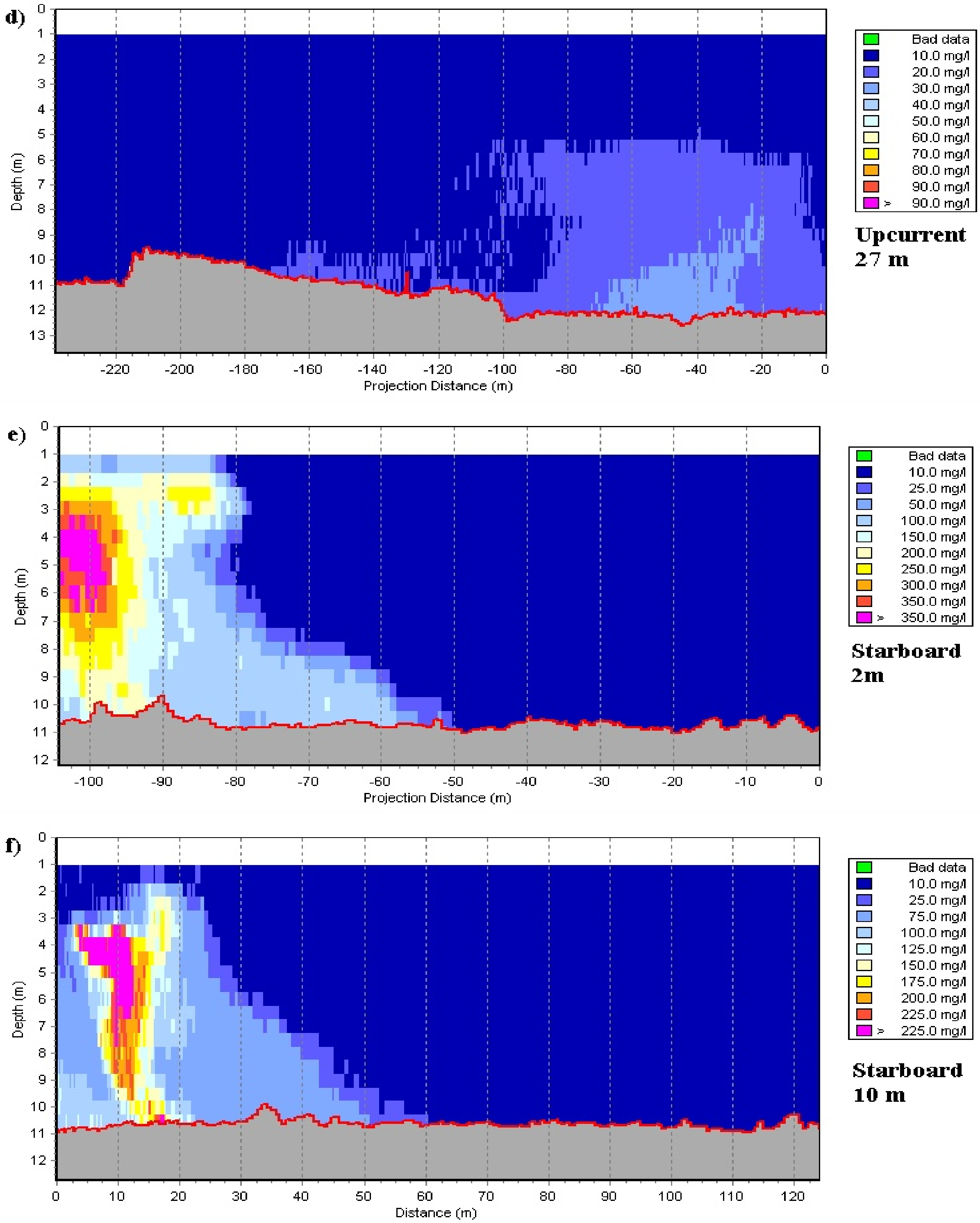


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: “E” (10-350 mg/l), “F” (10-225 mg/l) and “J” (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

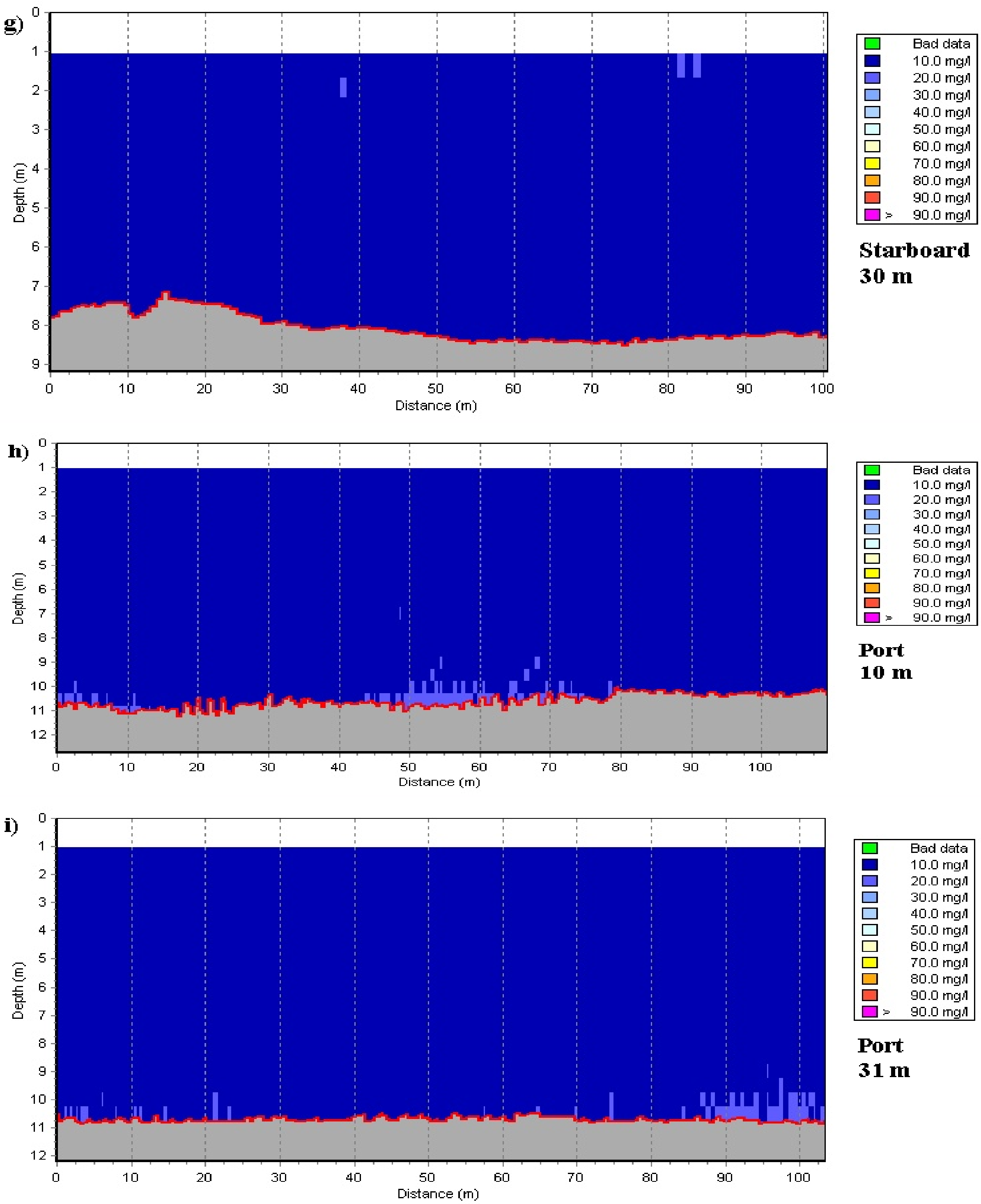


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: "E" (10-350 mg/l), "F" (10-225 mg/l) and "J" (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

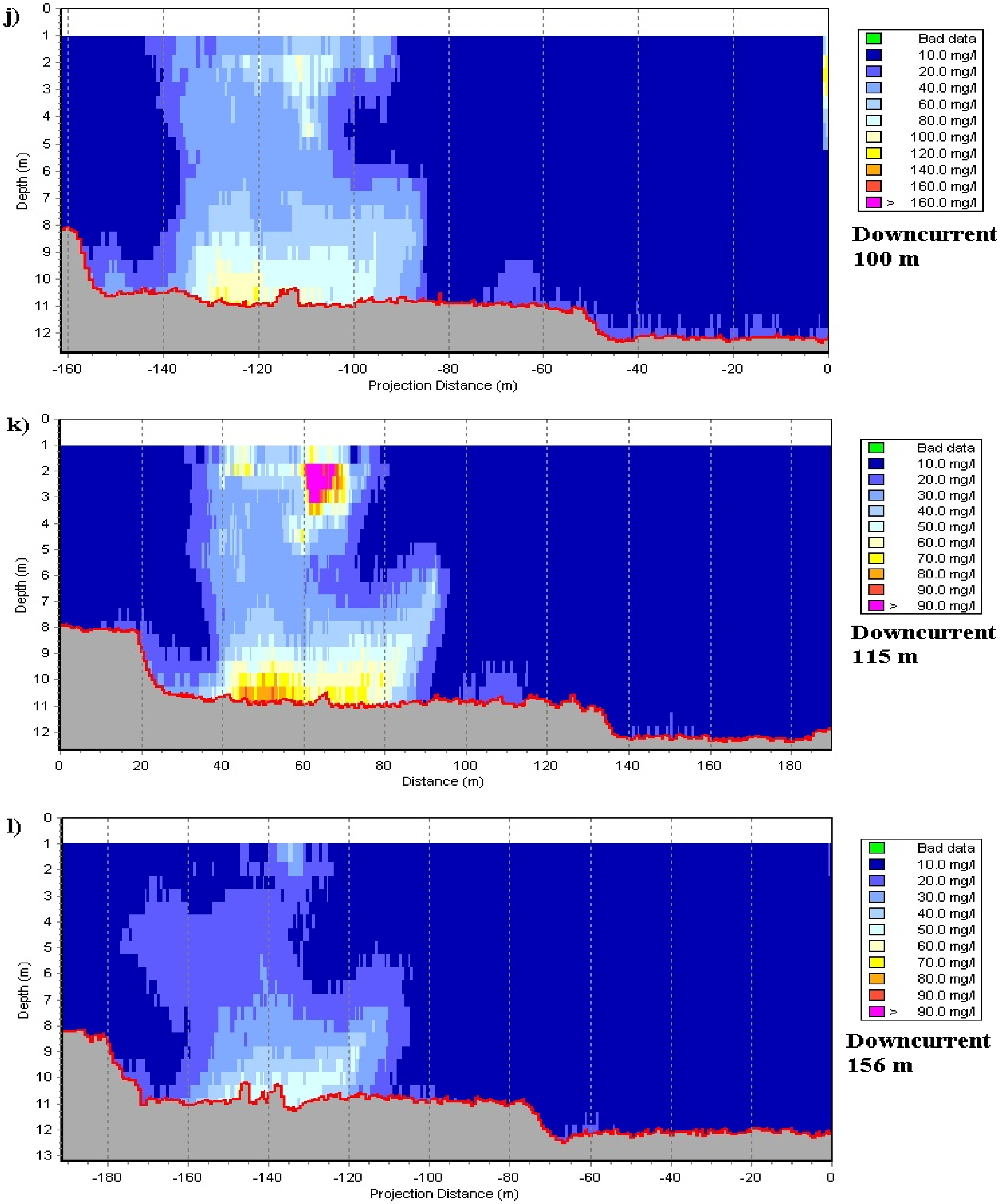


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: "E" (10-350 mg/l), "F" (10-225 mg/l) and "J" (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

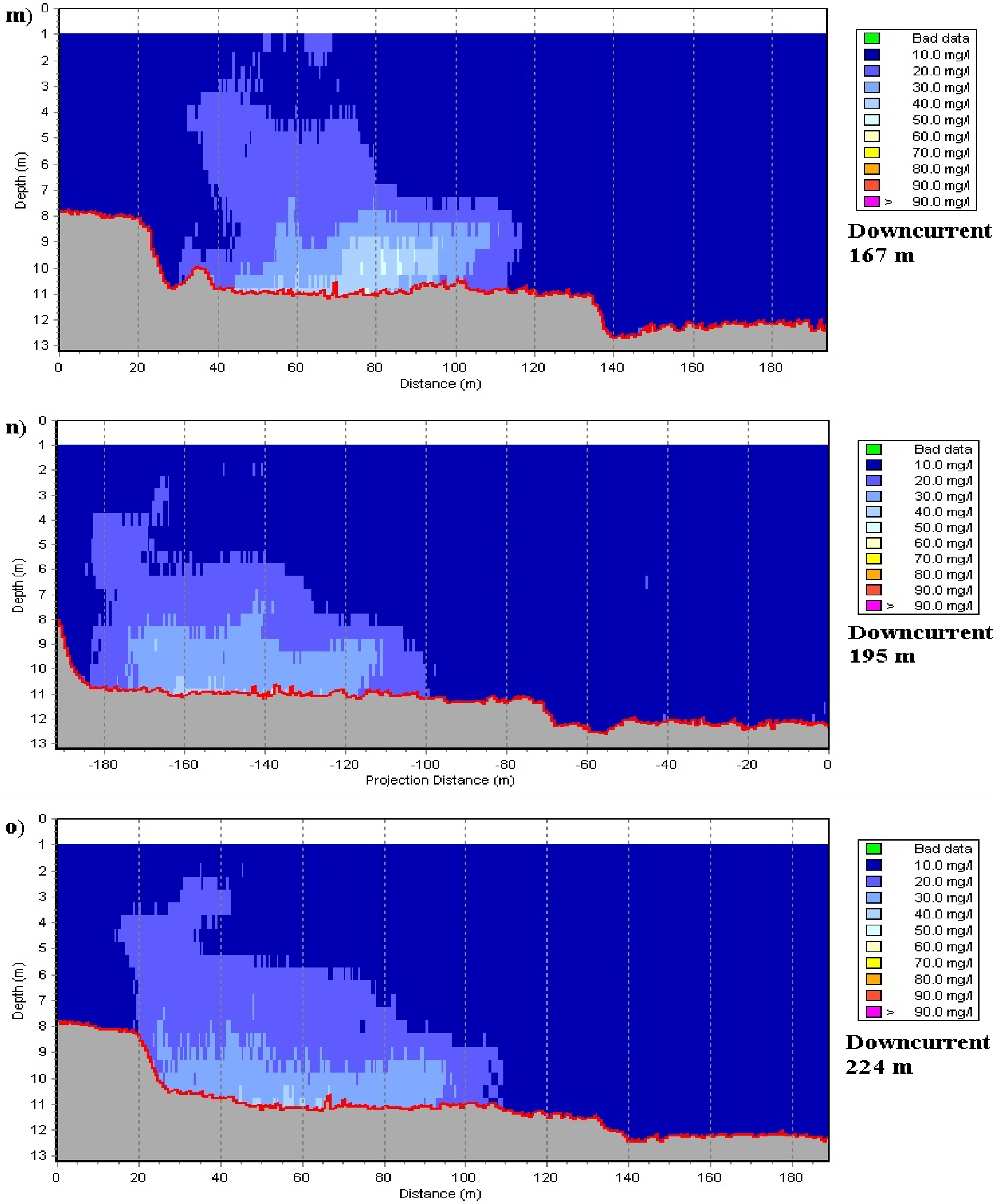


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: “E” (10-350 mg/l), “F” (10-225 mg/l) and “J” (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

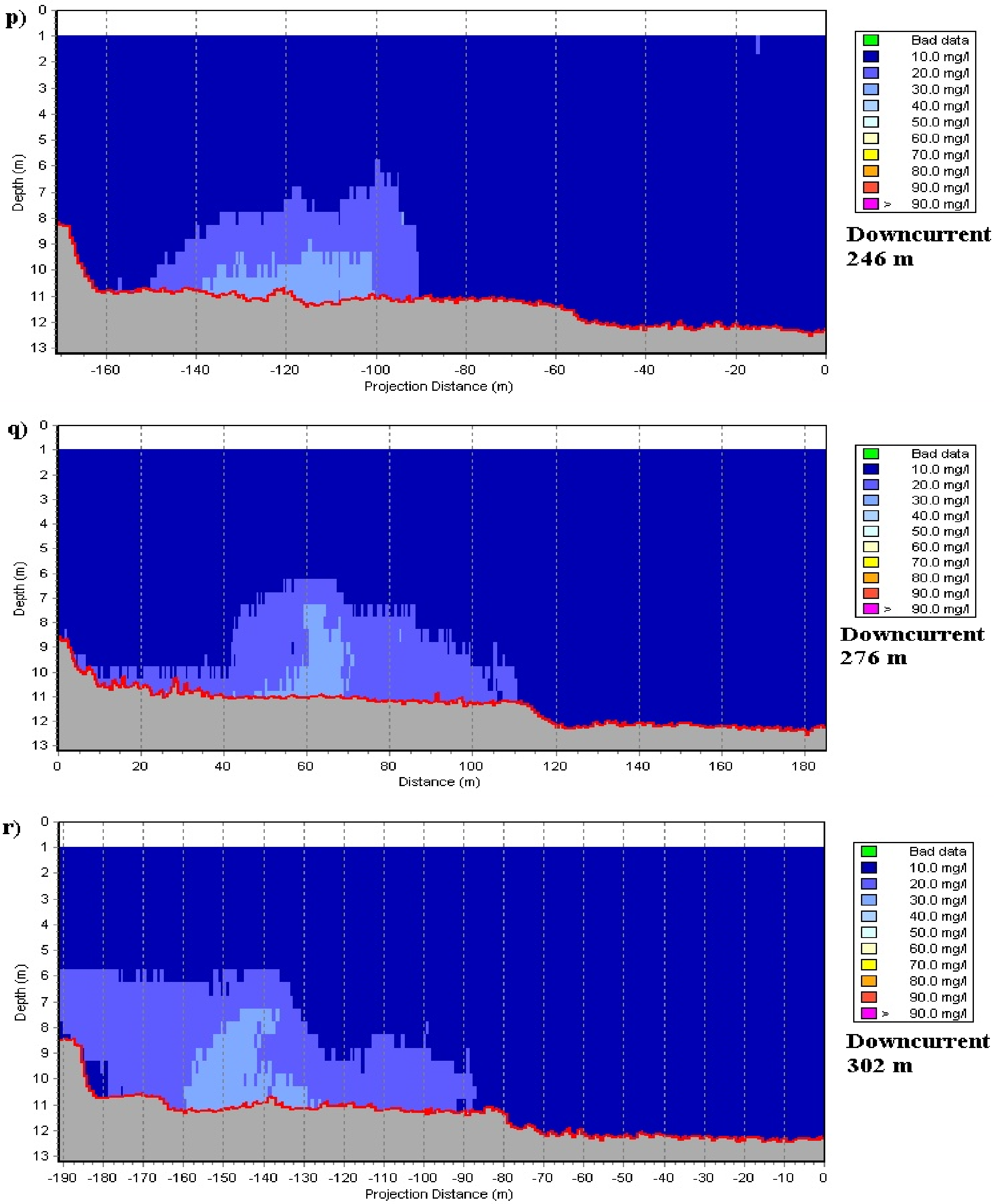
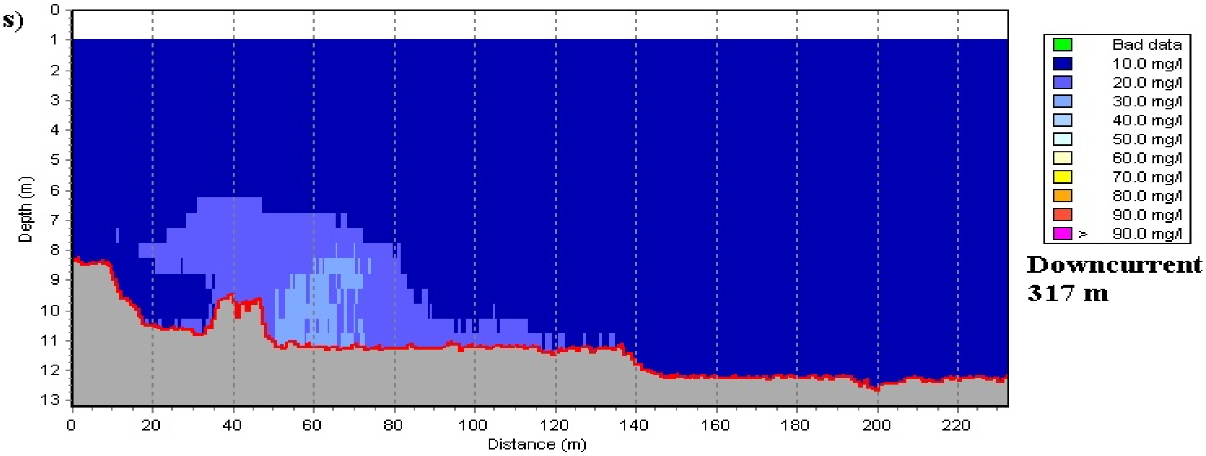
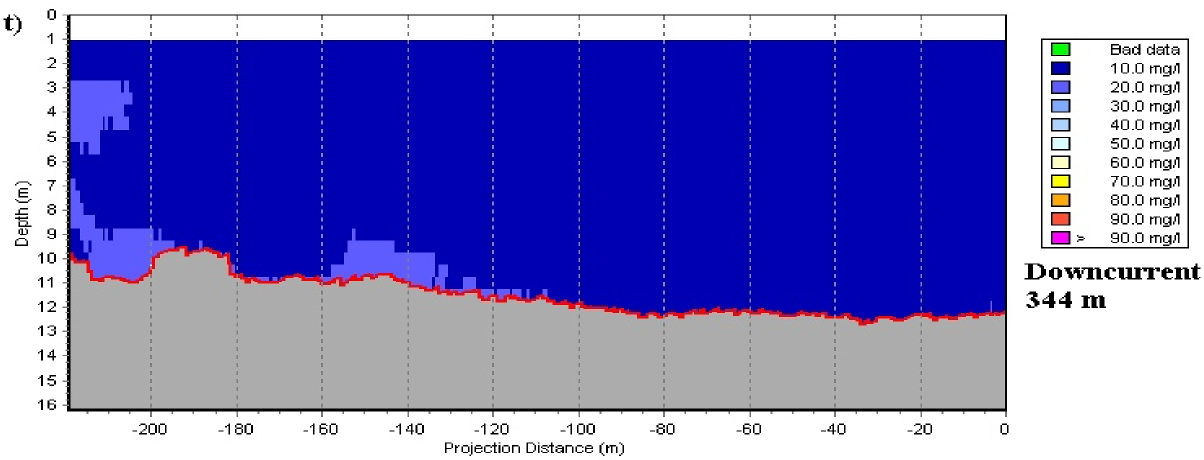


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: “E” (10-350 mg/l), “F” (10-225 mg/l) and “J” (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).





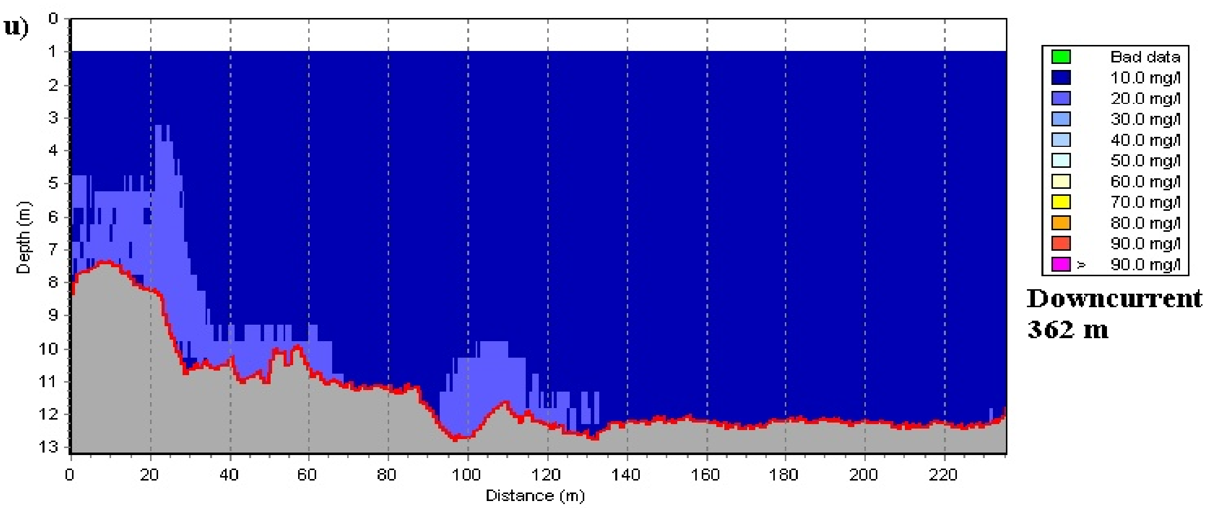


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: “E” (10-350 mg/l), “F” (10-225 mg/l) and “J” (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

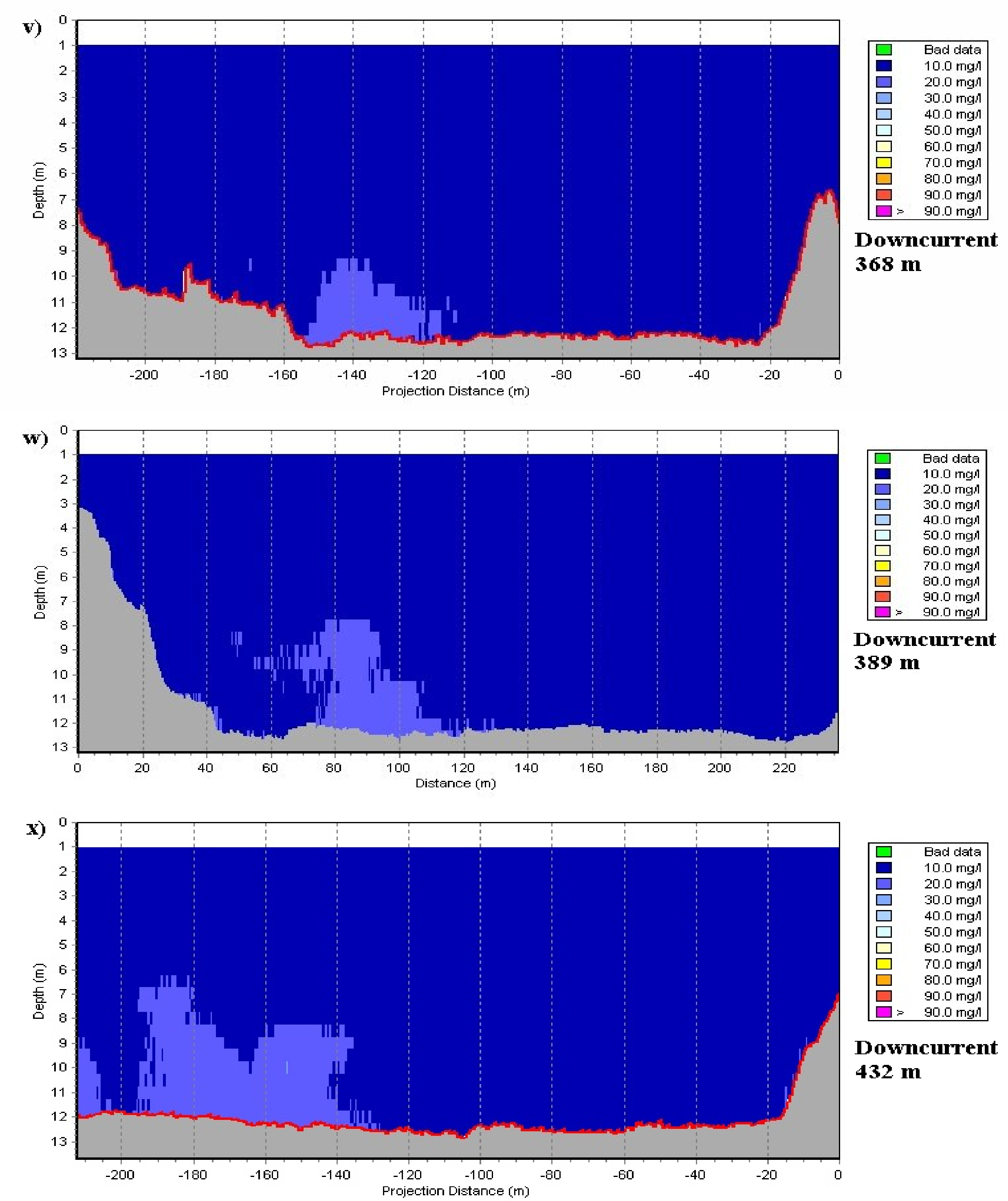


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: "E" (10-350 mg/l), "F" (10-225 mg/l) and "J" (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

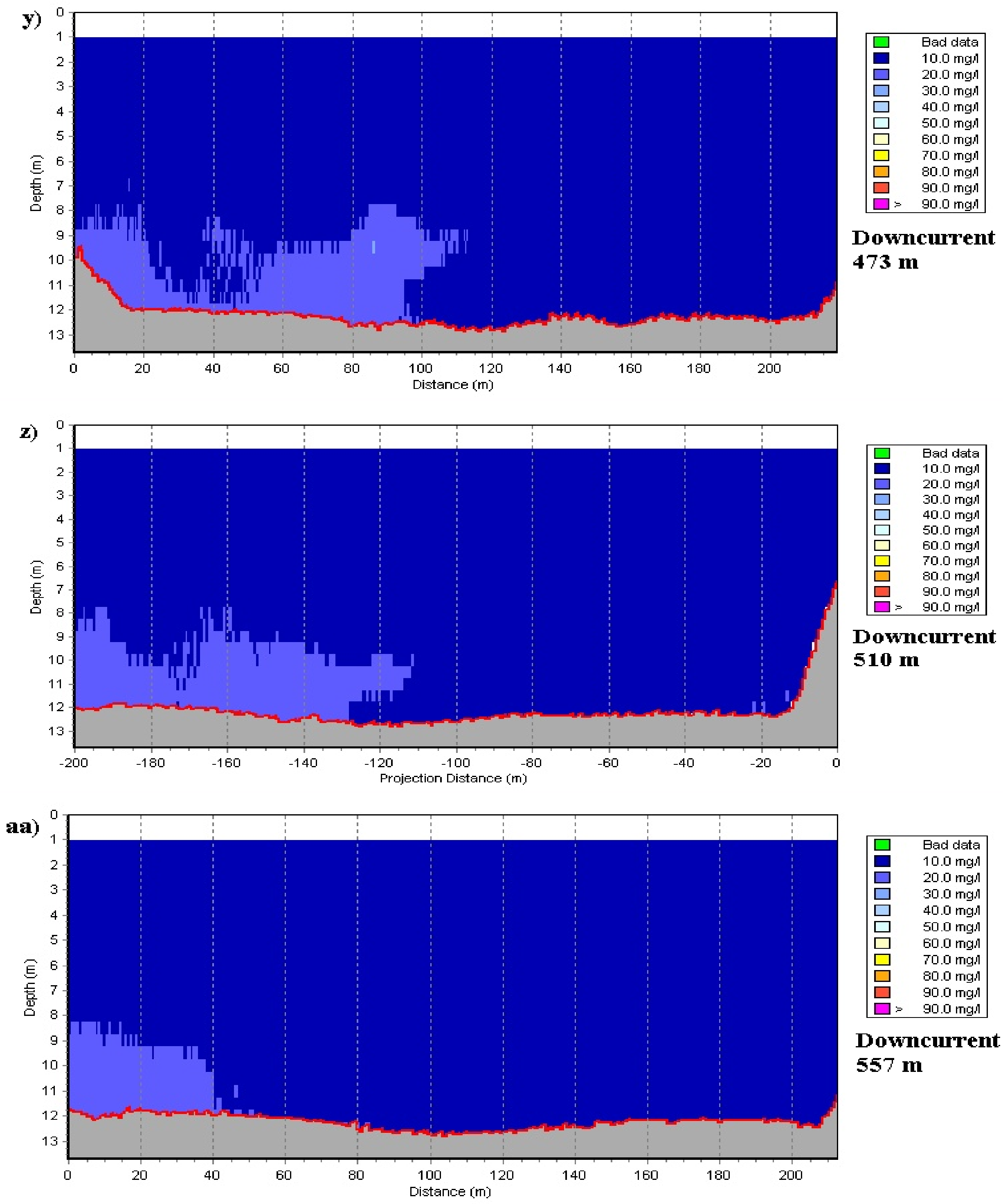


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: “E” (10-350 mg/l), “F” (10-225 mg/l) and “J” (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

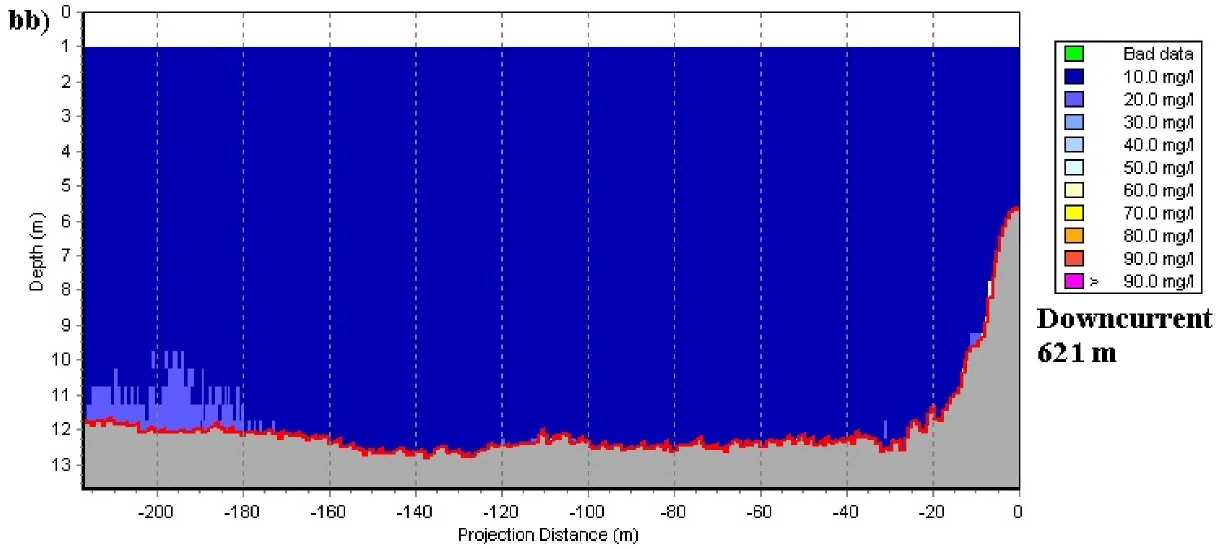


Figure 34 (cont.). Vertical profiles (Survey NJFD) of TSS concentrations across Shooters Island Reach during a flooding tide, 20 June 2006. Distances from the source are given for each transect in the legend at the right of the graph. Note that three vertical profiles: "E" (10-350 mg/l), "F" (10-225 mg/l) and "J" (10-160 mg/l) have different concentration scales when compared to all others in the series (10-90 mg/l).

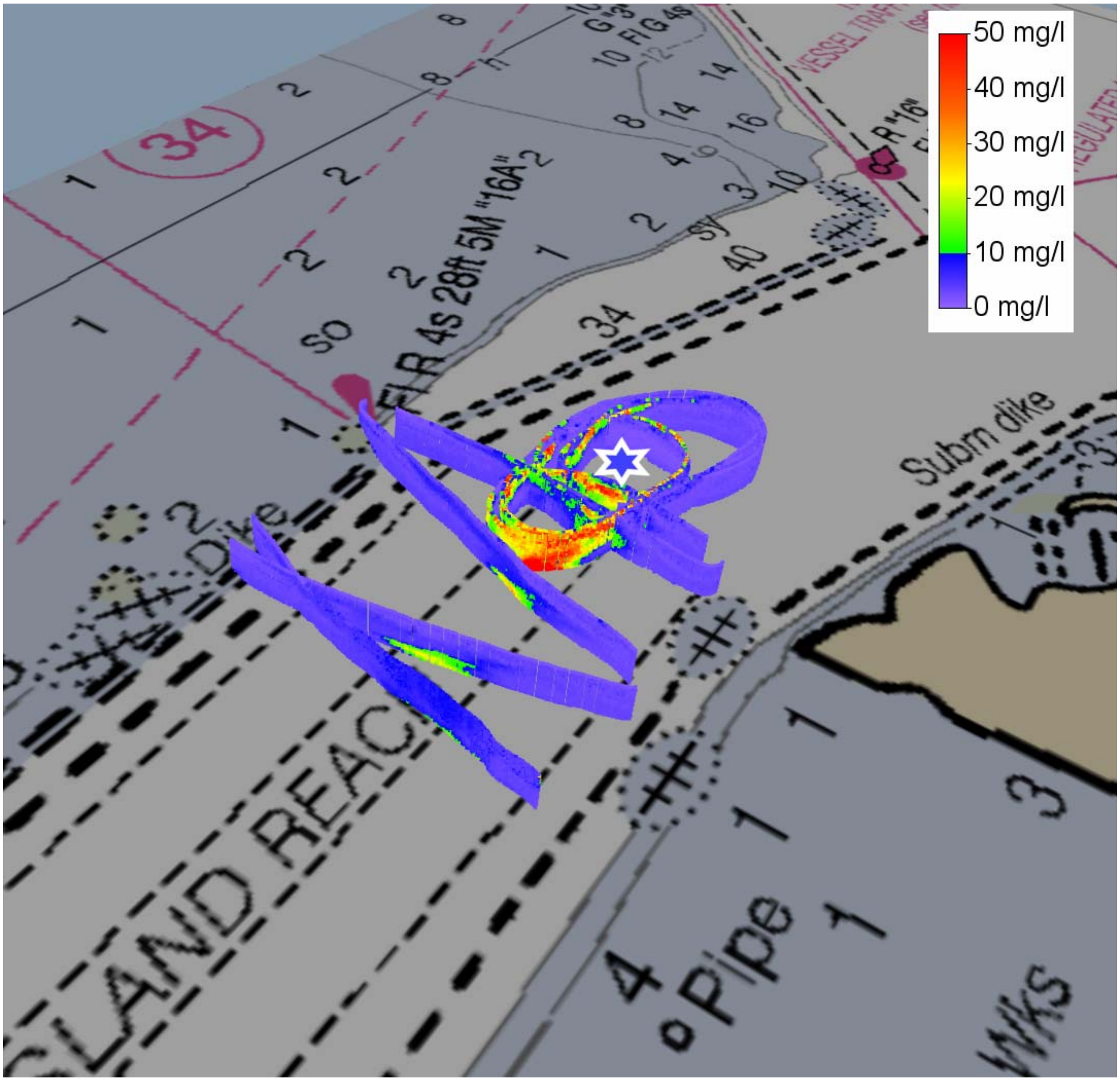


Figure 35. TSS concentrations for Survey NJAB plotted as to their x, y and z coordinates. (Note: dredge position indicated by star.)

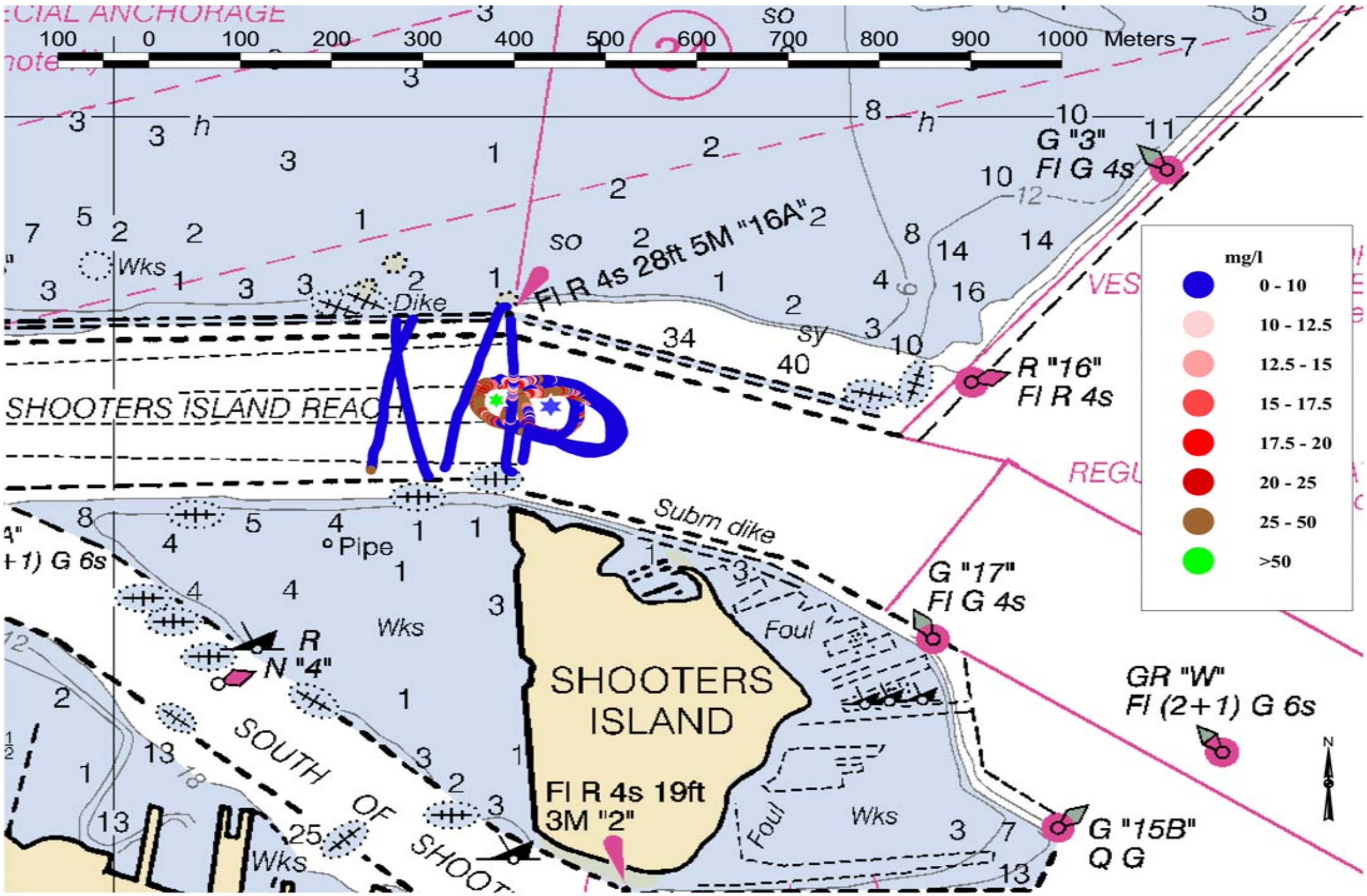


Figure 36. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 2 meters for Survey NJAB, completed during a flooding tide on 22 June 2006. Note: Initial dredge location indicated by a green star, and final position indicated by a blue star, as in following figures.

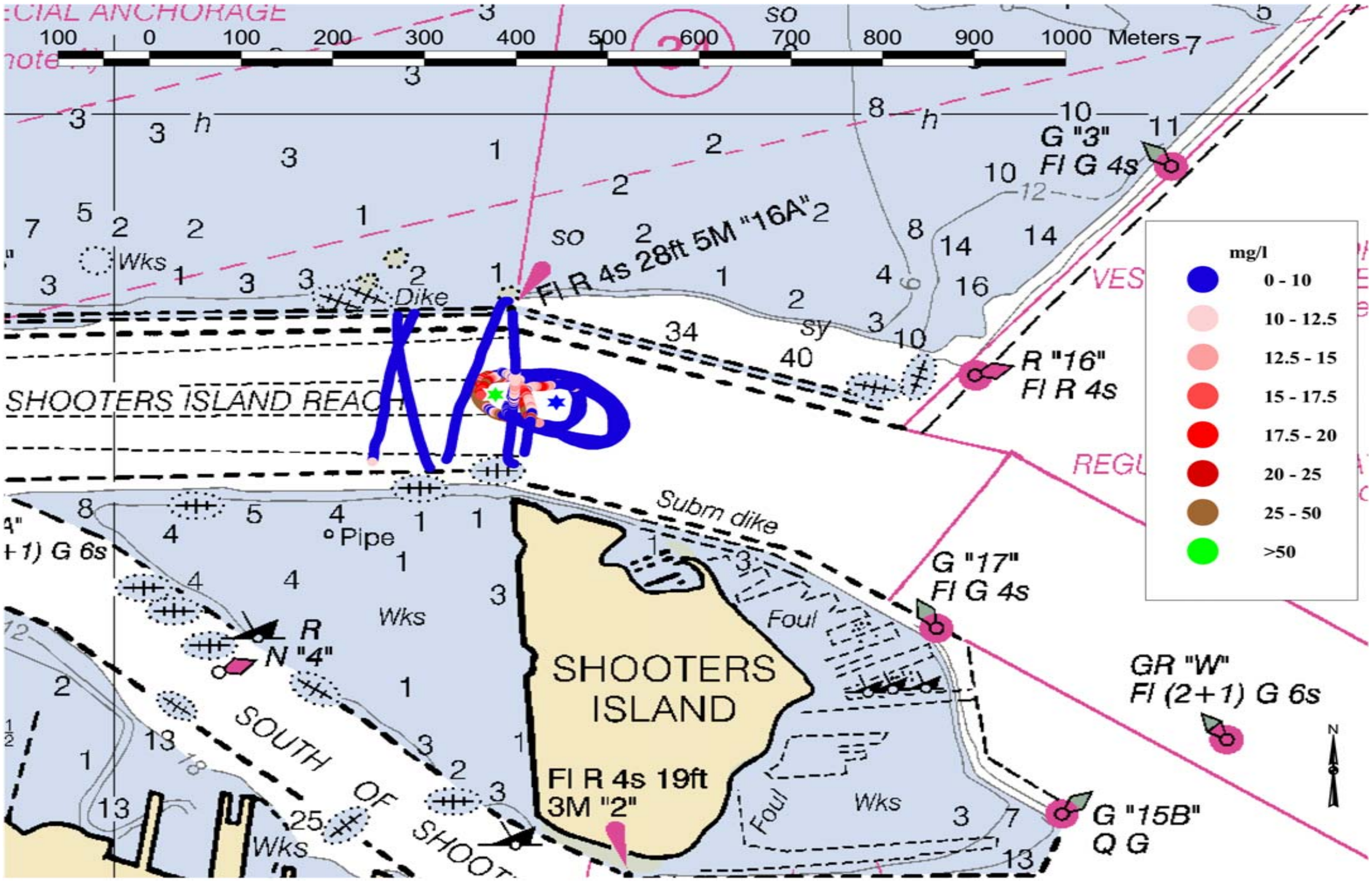


Figure 37. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 4 meters for Survey NJAB, completed during a flooding tide on 22 June 2006.

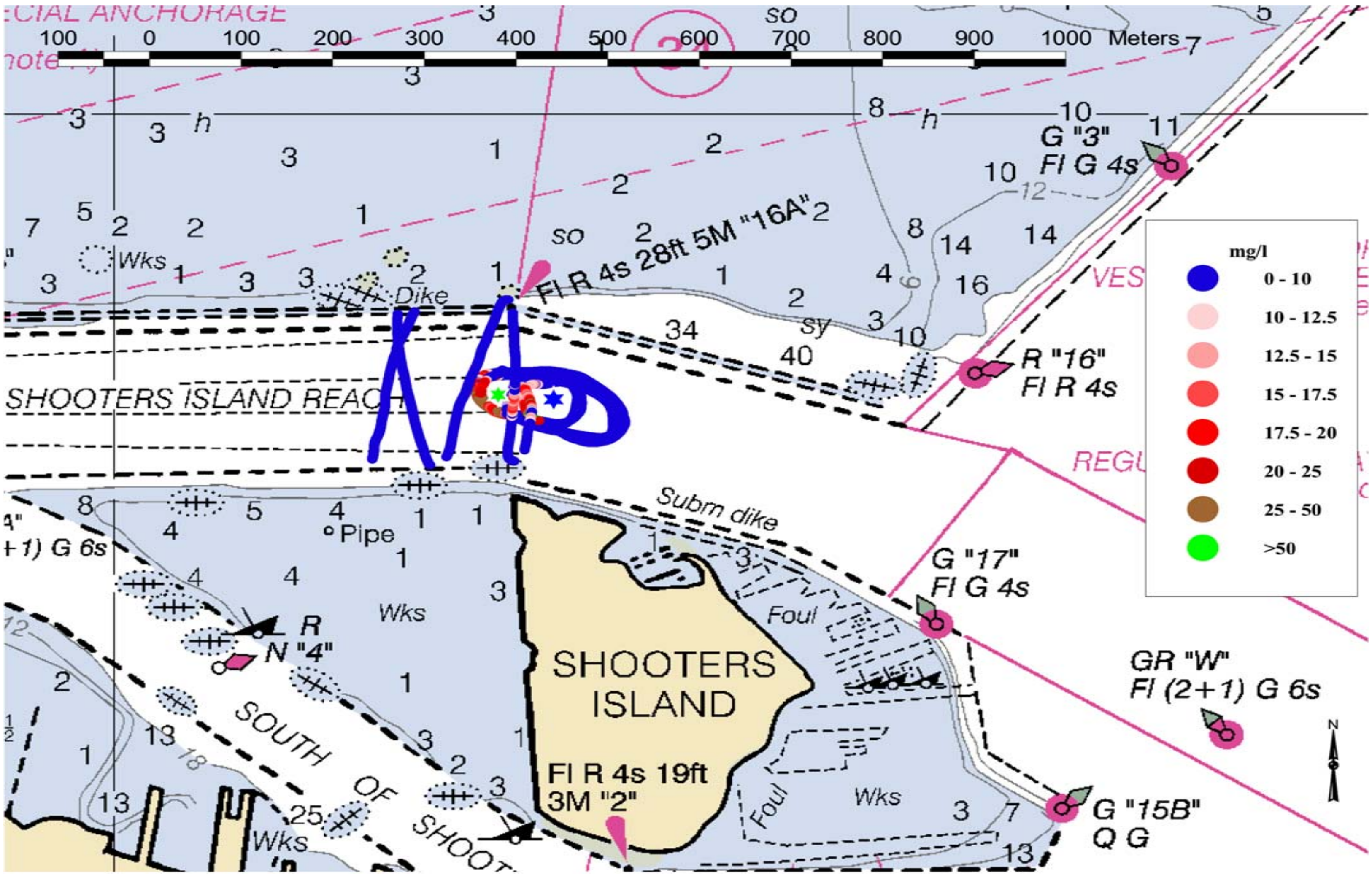


Figure 38. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 6 meters for Survey NJAB, completed during a flooding tide on 22 June 2006.

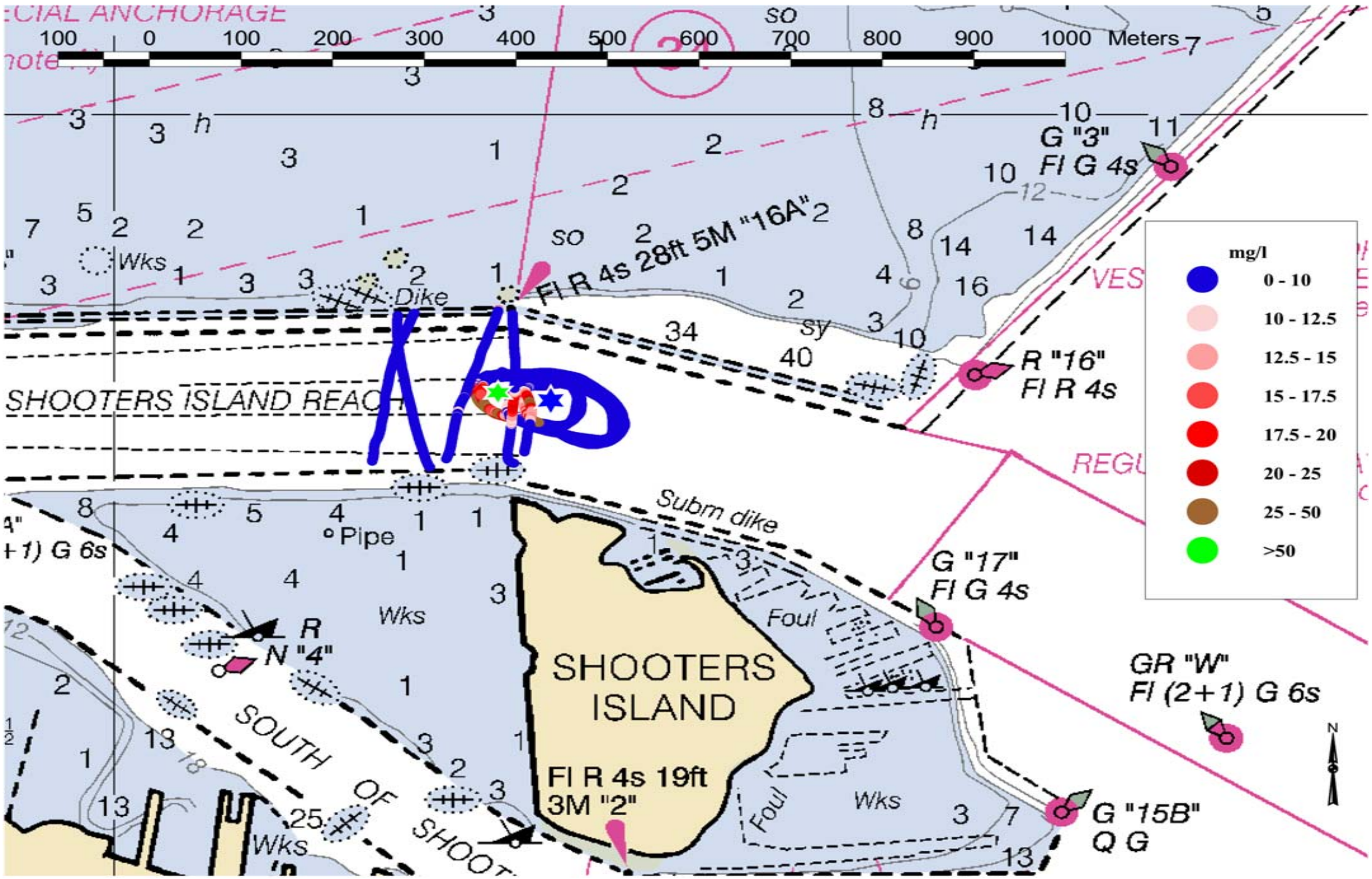


Figure 39. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 8 meters for Survey NJAB, completed during a flooding tide on 22 June 2006.

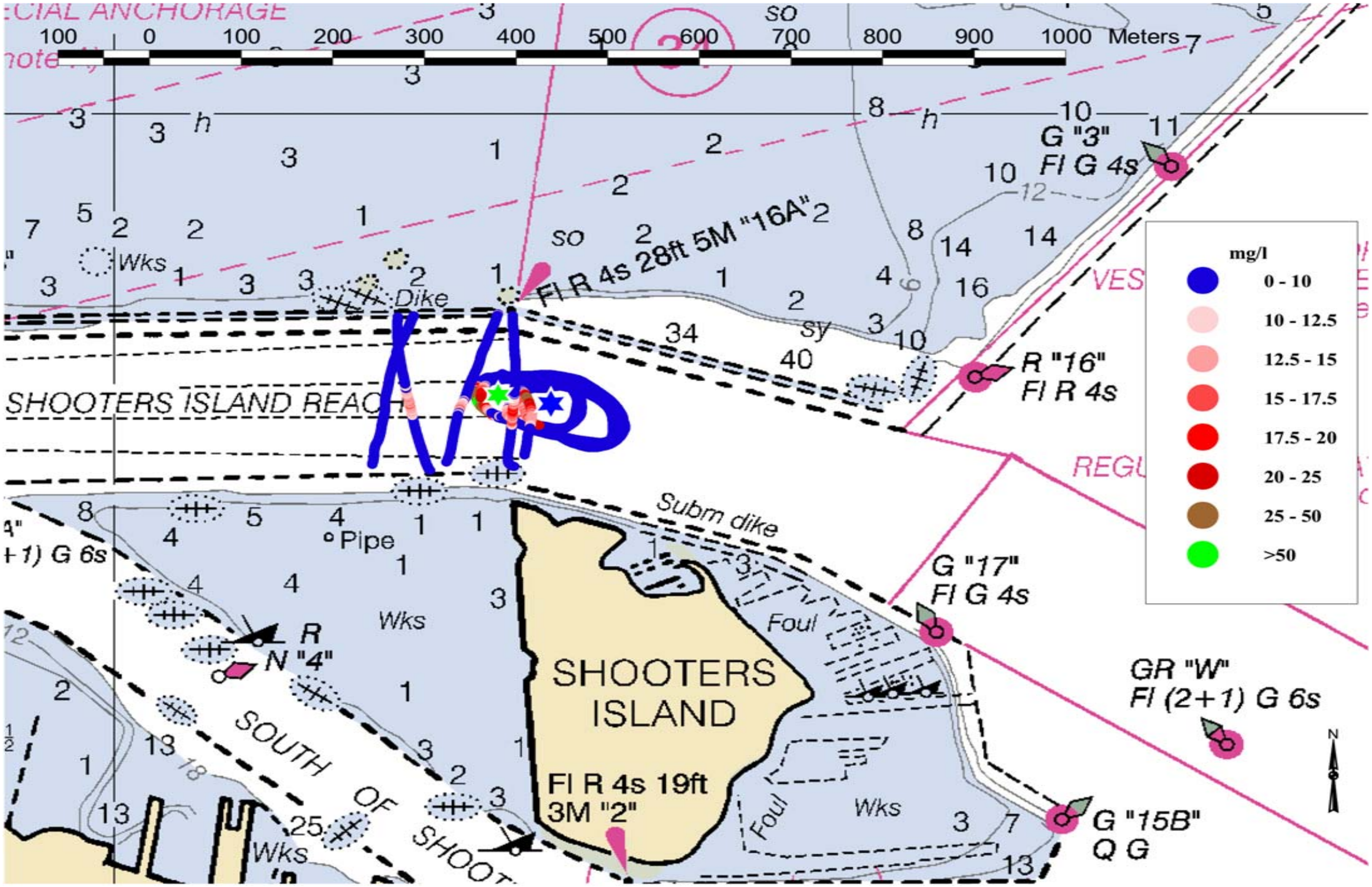


Figure 40. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 10 meters for Survey NJAB, completed during a flooding tide on 22 June 2006.

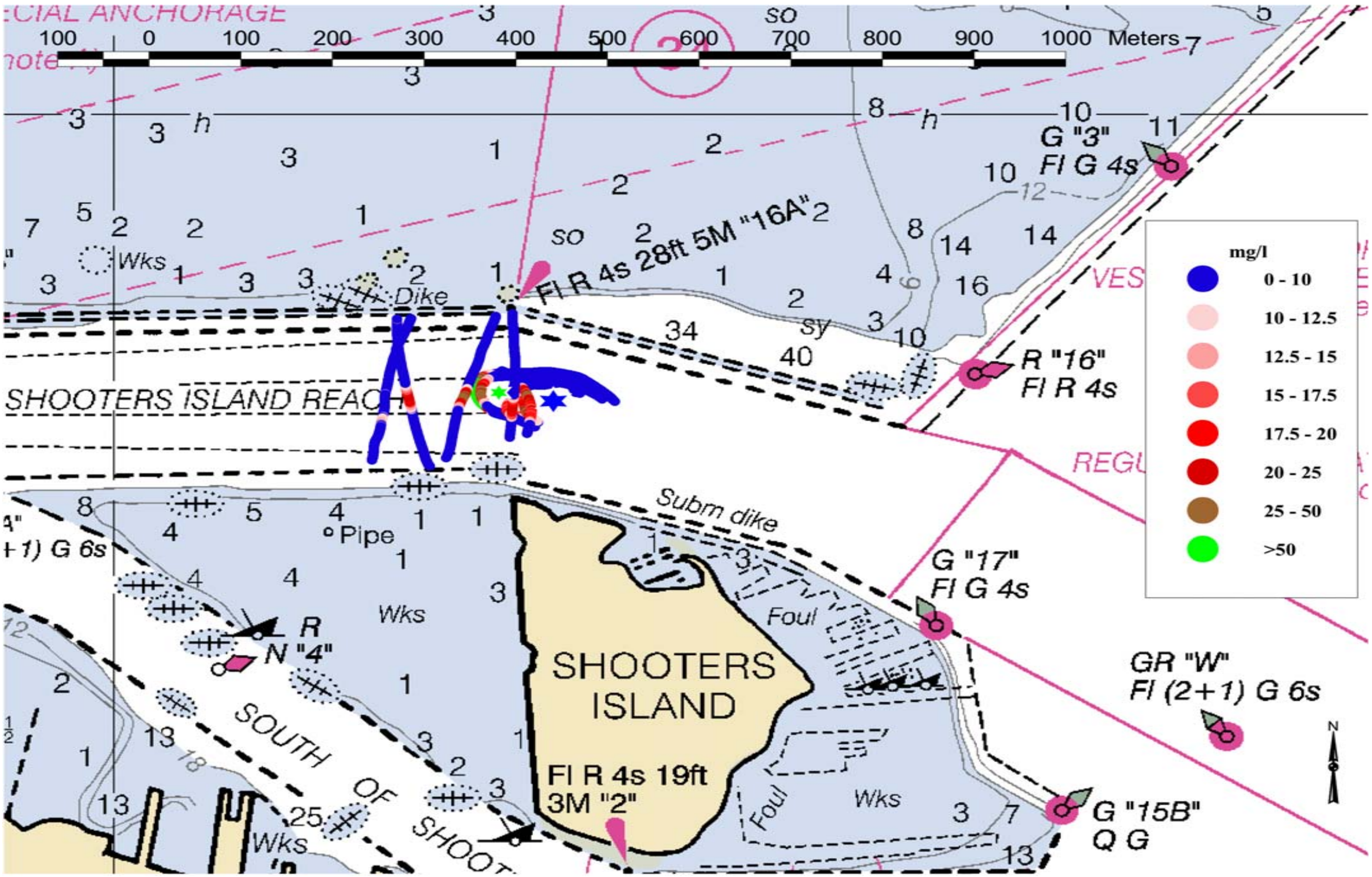


Figure 41. Plan view of detected plume spatial coverage and TSS concentrations at a depth of 12 meters for Survey NJAB, completed during a flooding tide on 22 June 2006.

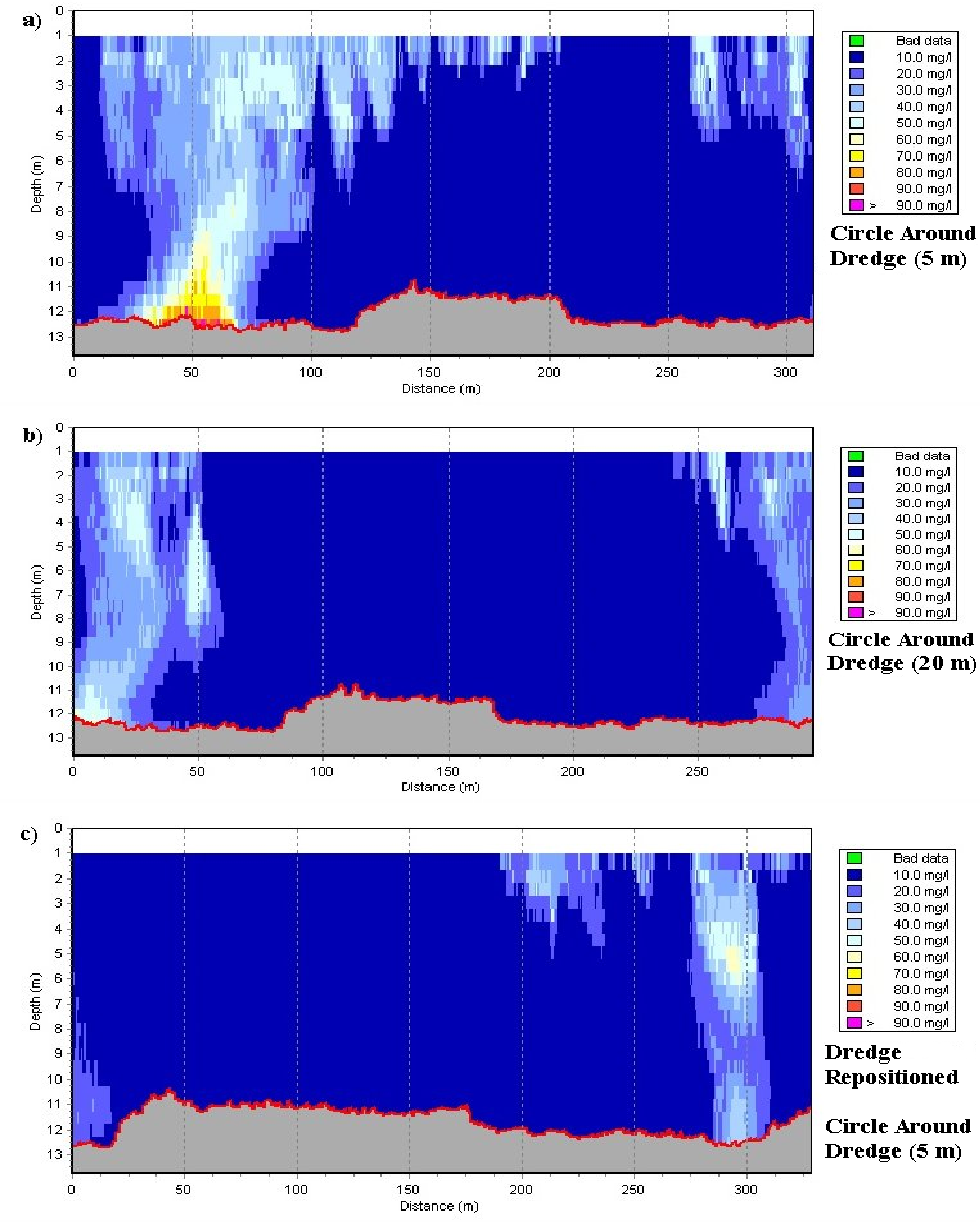


Figure 42. Vertical profiles (Survey NJAB) of TSS concentration across Shooters Island Reach during a flooding tide, 22 June 2006.

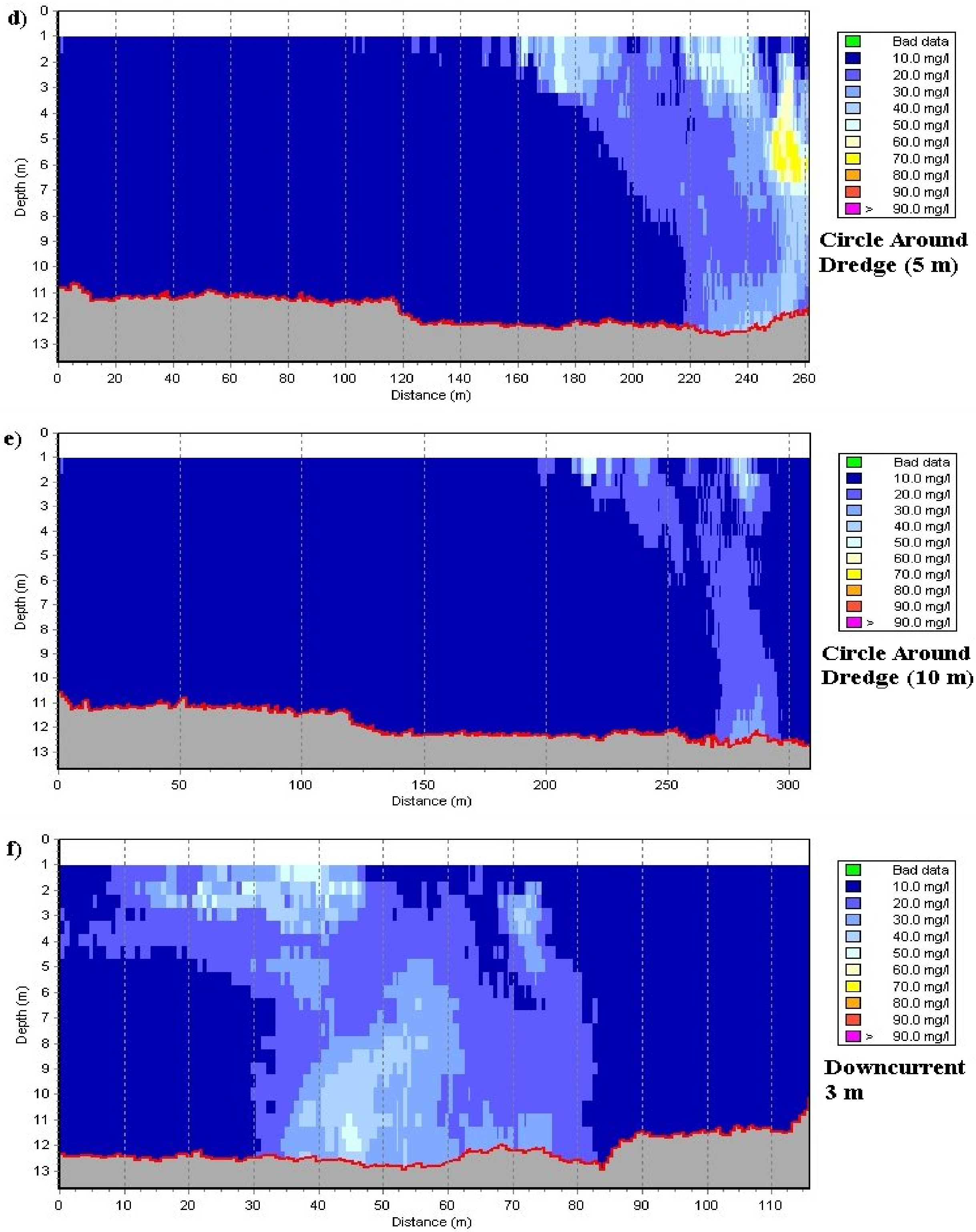


Figure 42 (cont.). Vertical profiles (Survey NJAB) of TSS concentration across Shooters Island Reach during a flooding tide, 22 June 2006.

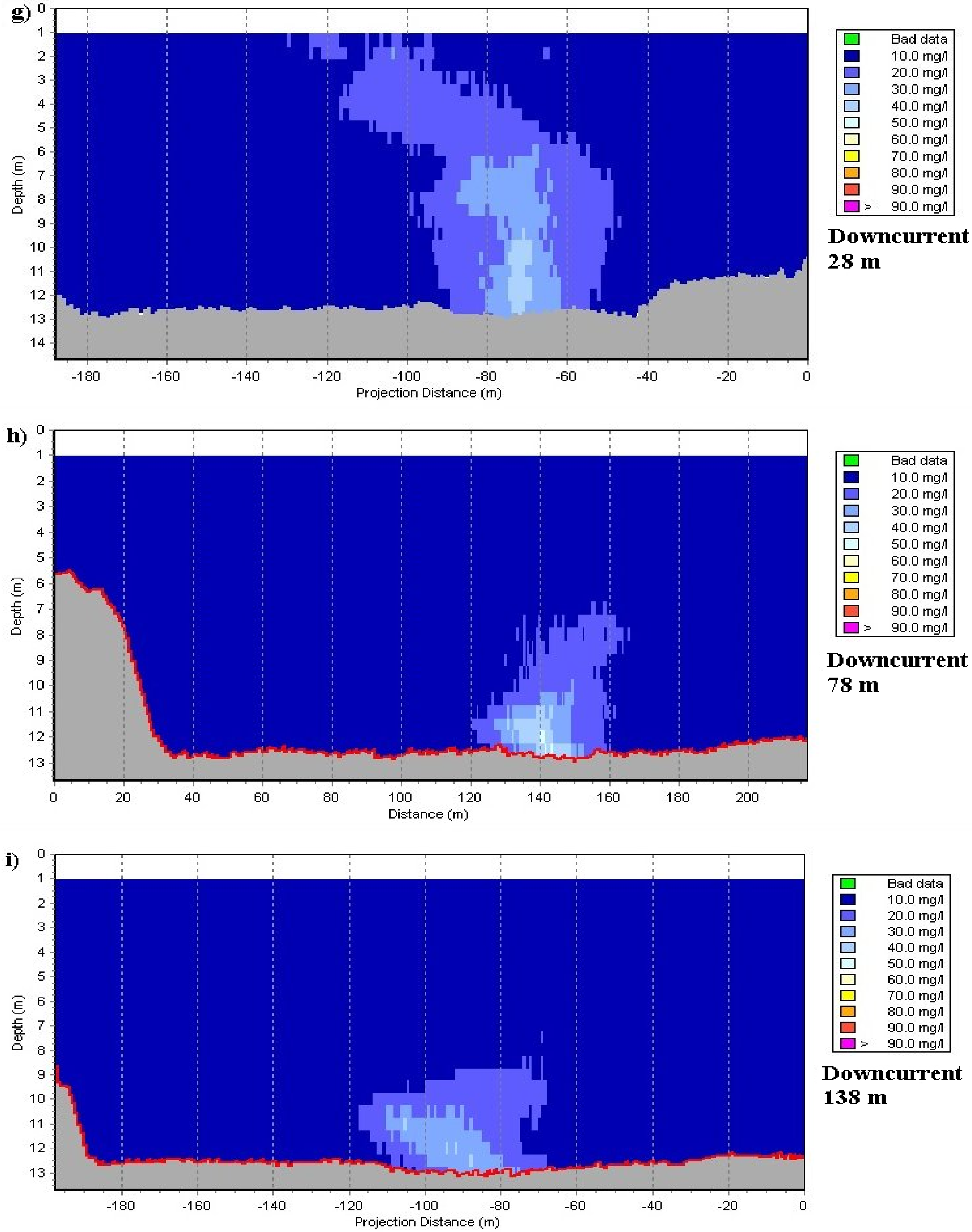


Figure 42 (cont.). Vertical profiles (Survey NJAB) of TSS concentration across Shooters Island Reach during a flooding tide, 22 June 2006.

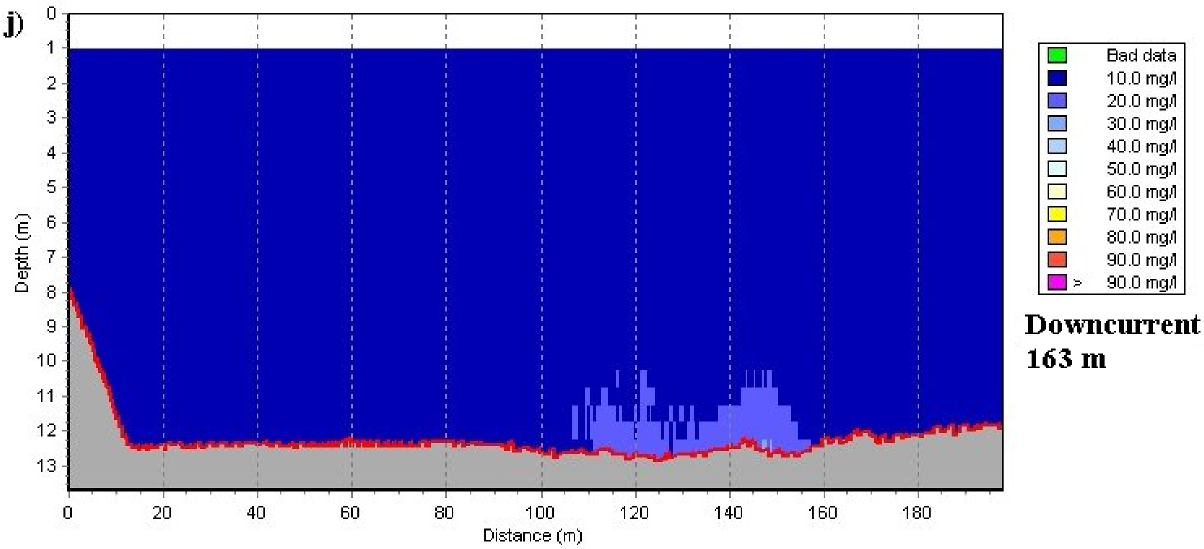


Figure 42 (cont.). Vertical profiles (Survey NJAB) of TSS concentration across Shooters Island Reach during a flooding tide, 22 June 2006.

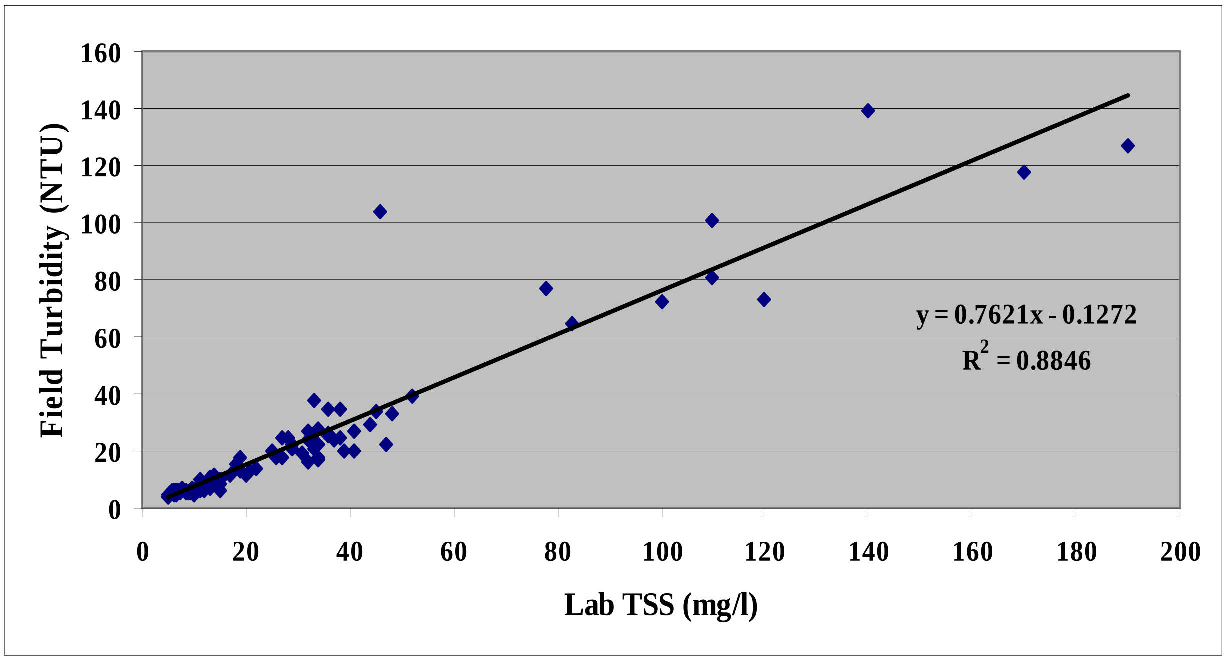


Figure 43. Regression of field turbidity values on TSS concentrations for corresponding samples.

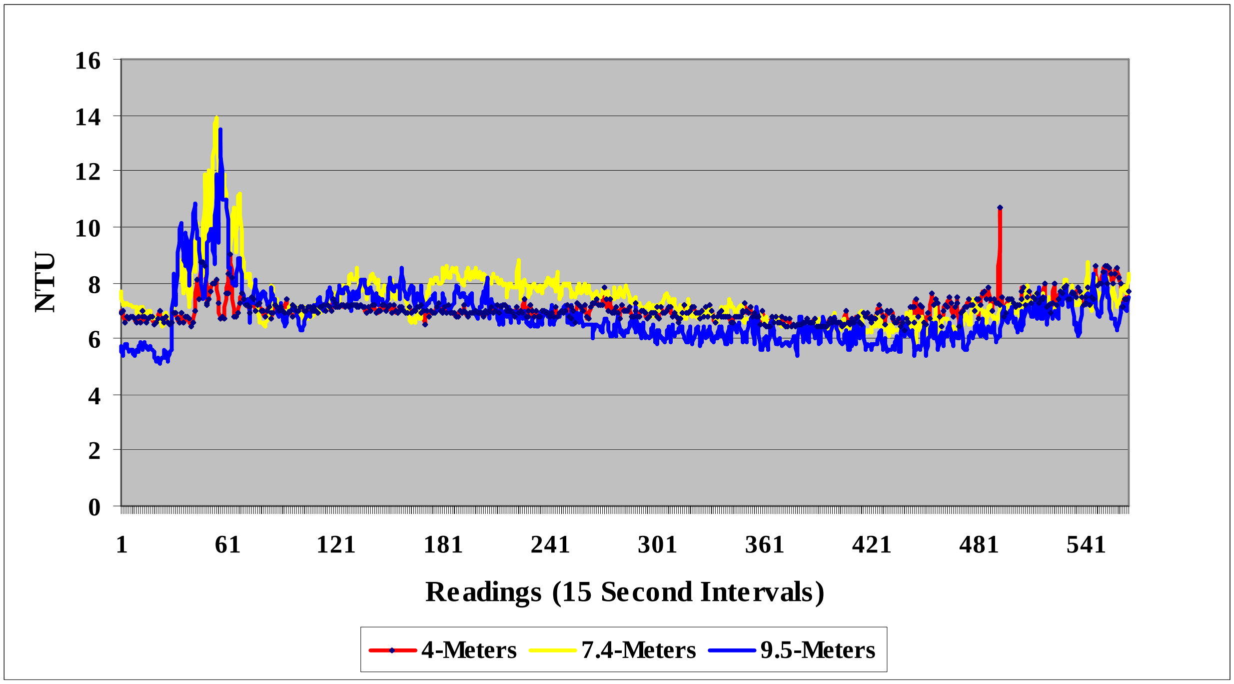


Figure 44. Ambient turbidity measured at depths of 4, 7.4 and 9.5 meters at a distance of 150 meters up-current from the dredging operation during a flooding tide on 20 June 2006.

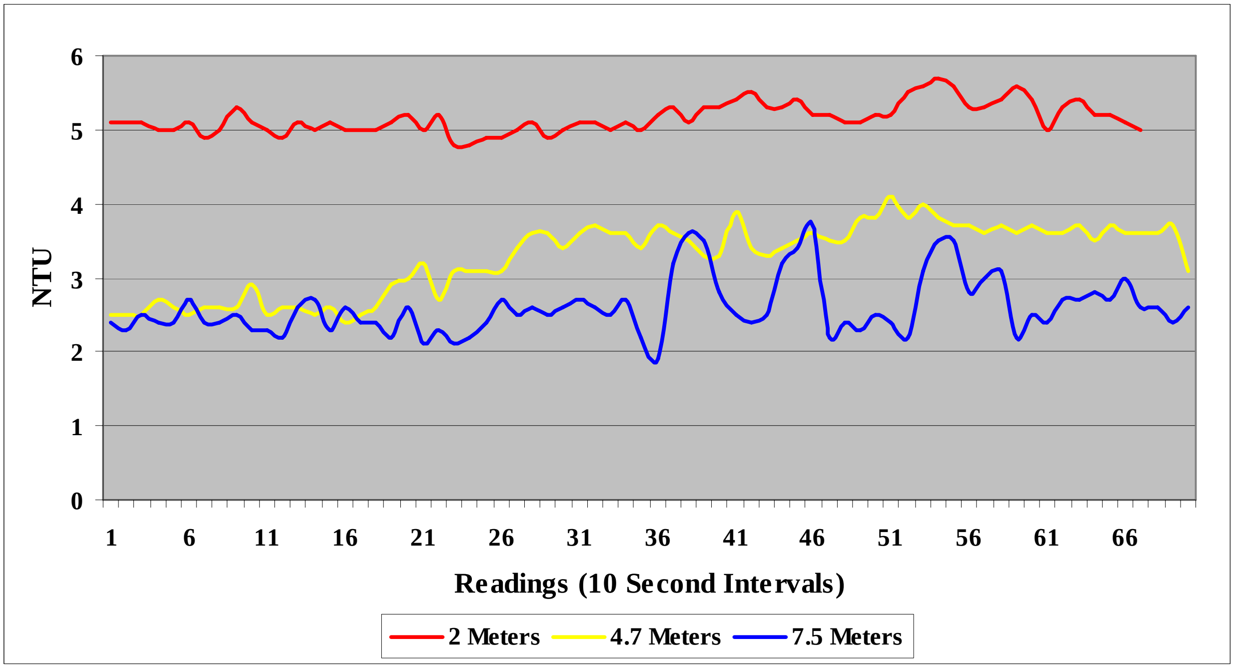


Figure 45. Ambient turbidity measured at depths of 2, 4.7 and 7.5 meters at a distance of 350 meters up-current from the dredging operation during an ebbing tide on 22 June 2006.

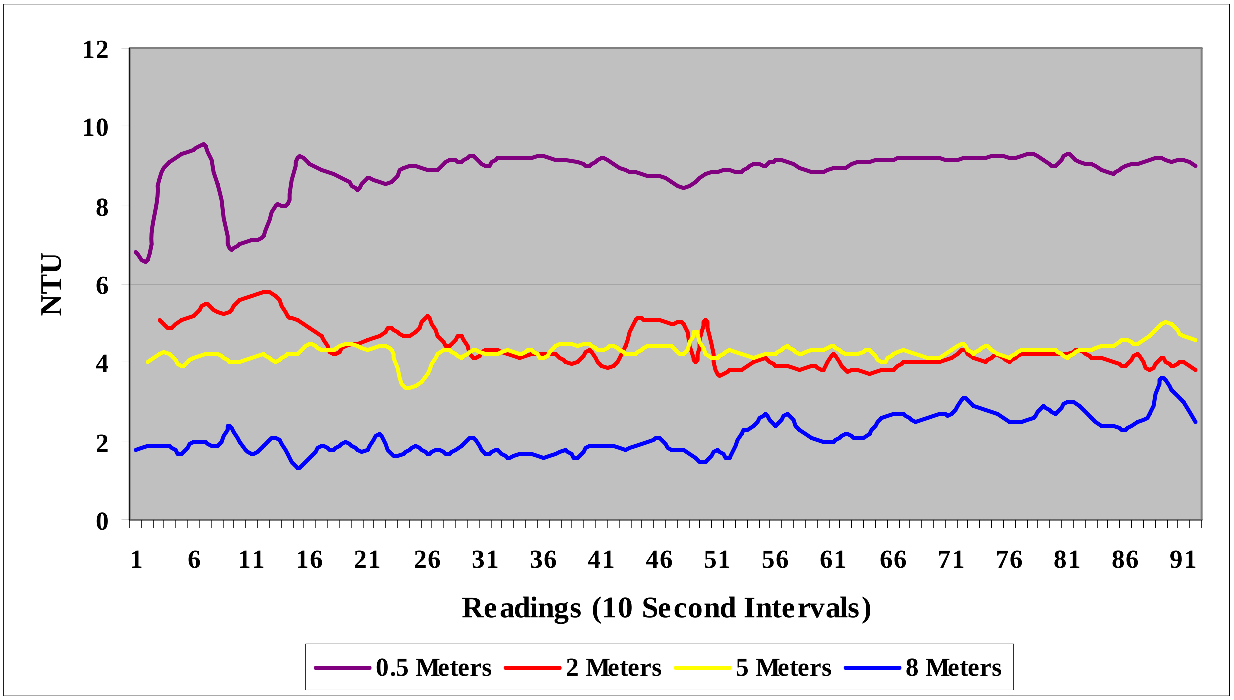


Figure 46. Ambient turbidity measured at depths of 0.5, 2, 5 and 8 meters at a distance of 540 meters up-current from the dredging operation during an ebbing tide on 23 June 2006.

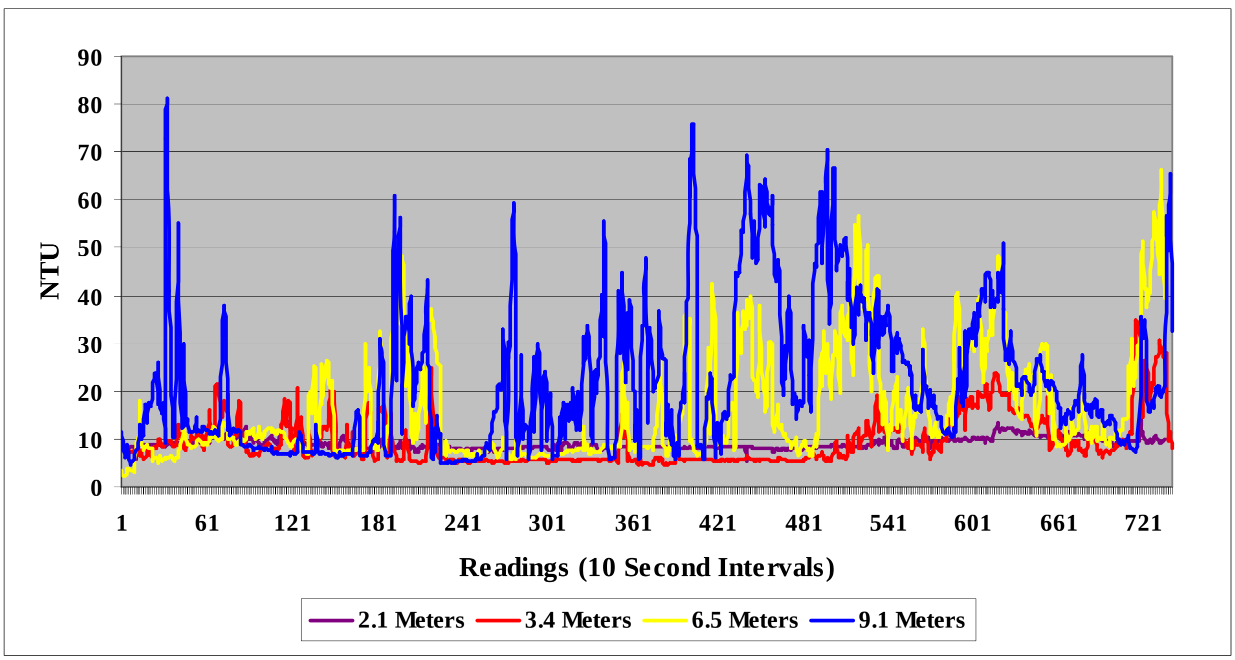


Figure 47. Near-field turbidity measured at depths of 2.1, 3.4, 6.5 and 9.1 meters at a distance of 60 meters down-current from the dredging operation during a flooding tide on 20 June 2006.

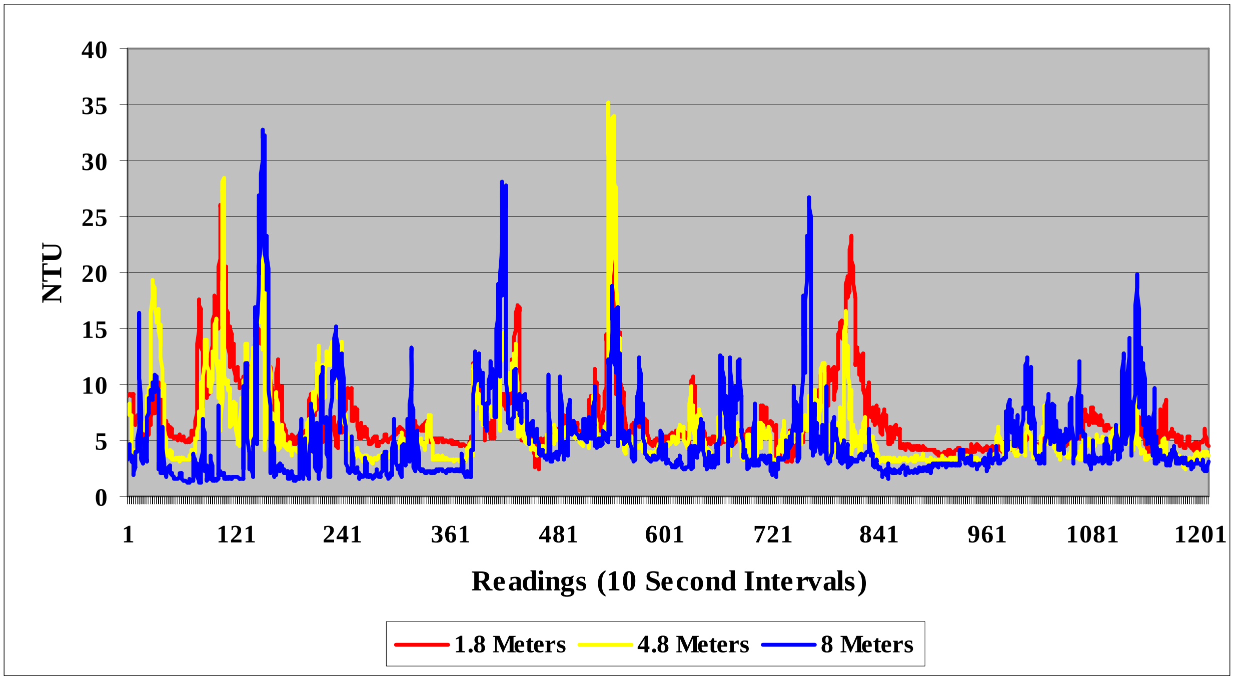


Figure 48. Near-field turbidity measured at depths of 2, 4.8 and 8 meters at a distance of 60 meters down-current of the dredging operation during an ebbing tide on 22 June 2006.

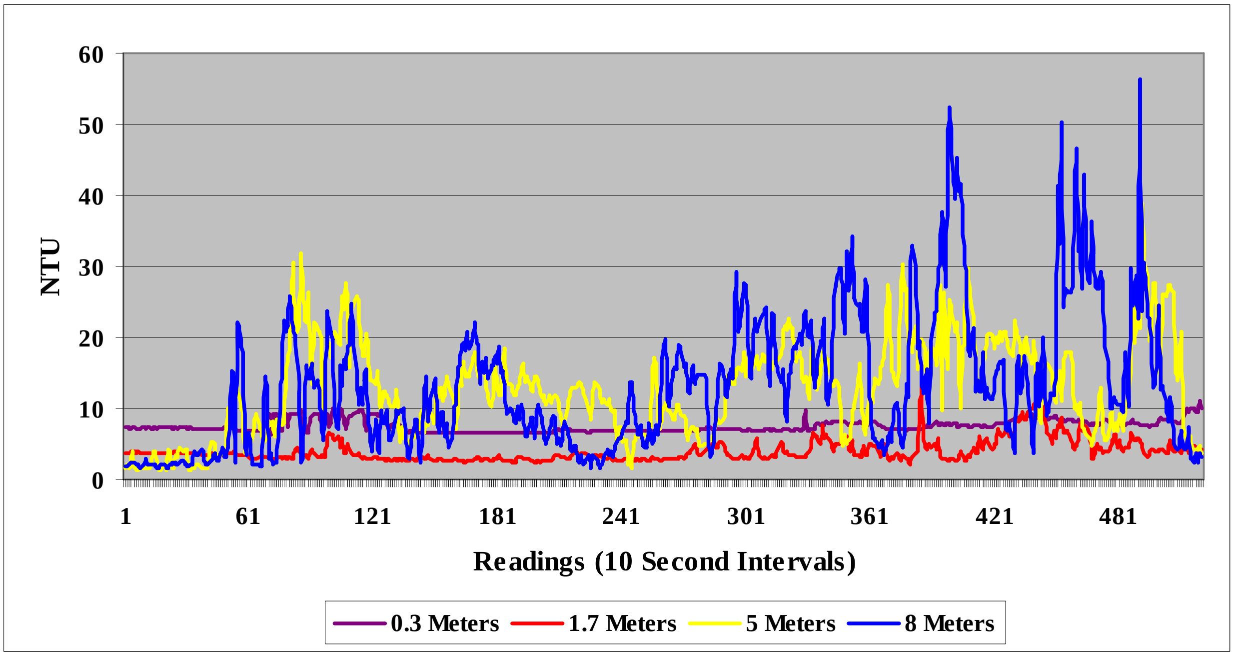


Figure 49. Near-field turbidity measured at depths of 0.3, 1.7, 5 and 8 meters at a distance of 60 meters down-current from the dredging operation during an ebbing tide on 23 June 2006.

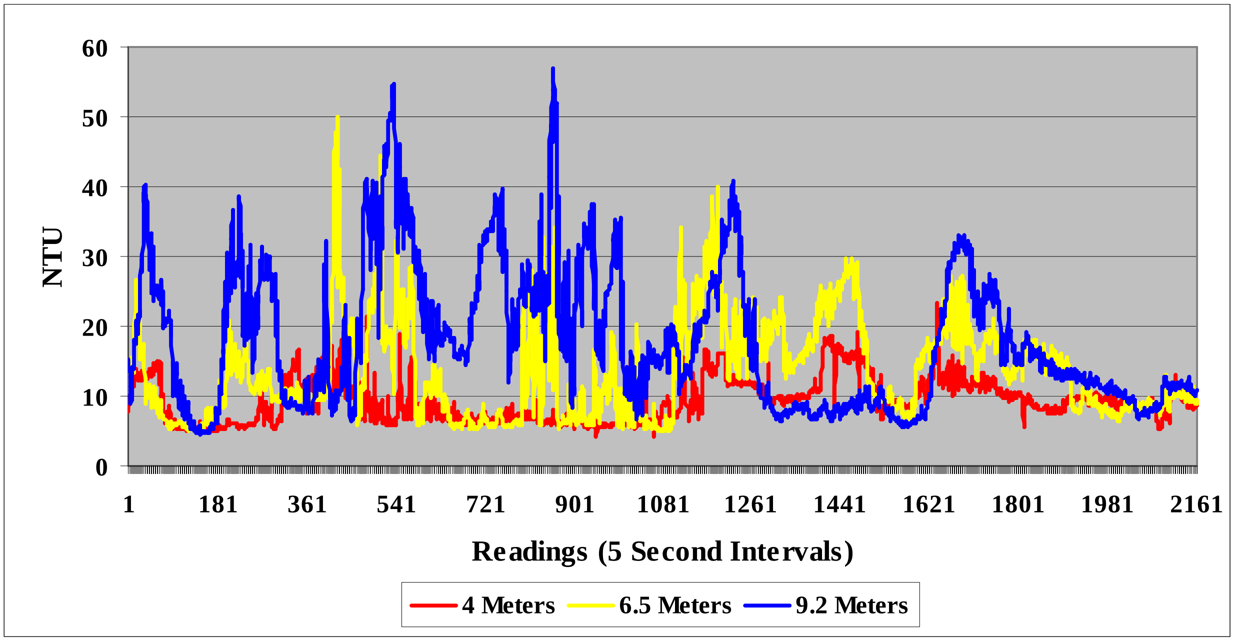


Figure 50. Far-field turbidity measured at depths of 4, 6.5 and 9.2 meters at a distance of 160 meters down-current from the dredging operation during a flooding tide on 20 June 2006.

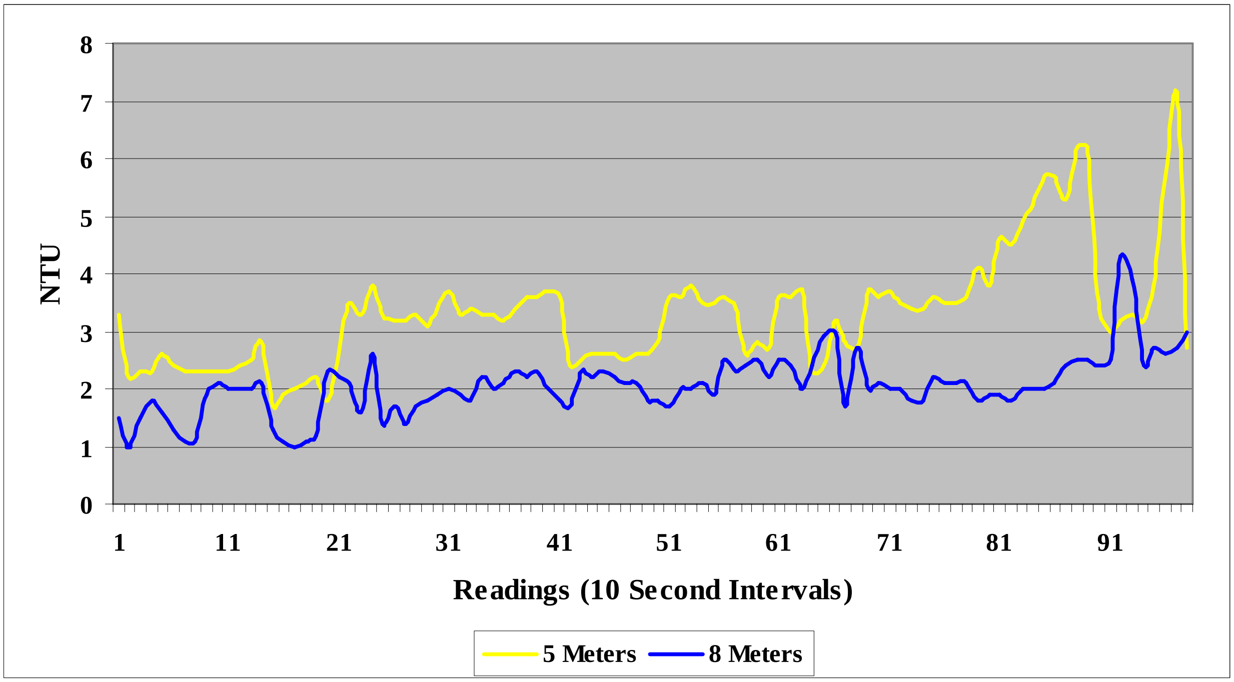


Figure 51. Far-field turbidity measured at depths of 5 and 8 meters at a distance of 150 meters down-current from the dredging operation during an ebbing tide on 22 June 2006. Two OBS units shut down prematurely and recorded no data during this monitoring event.

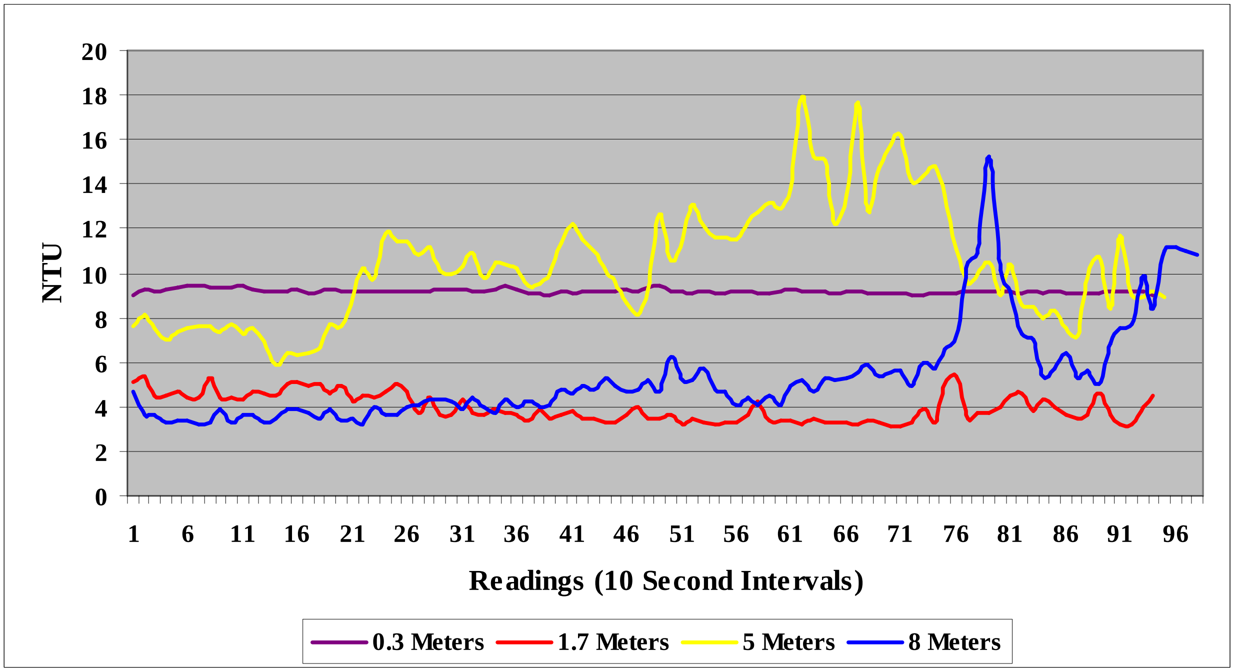


Figure 52. Far-field turbidity measured at depths of 0.3, 1.7, 5 and 8 meters at a distance of 145 meters down-current from the dredging operation during an ebbing tide on 23 June 2006.

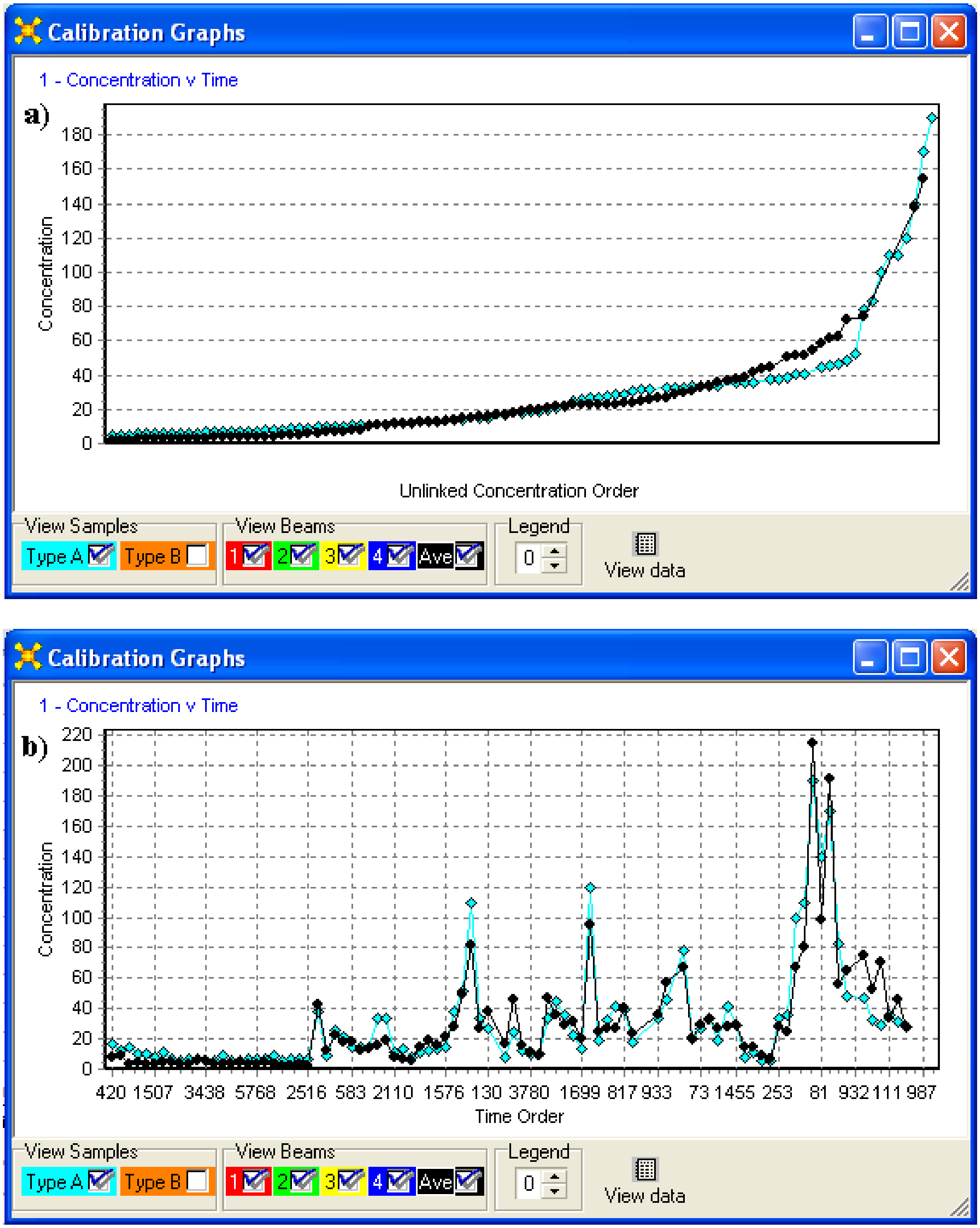


Figure 53. Comparison of gravimetric and acoustic estimates of TSS concentration for the entire population of samples in a) rank and b) paired order. Results of gravimetric analysis (TSS) of water samples are represented in blue, whereas TSS estimates derived from ADCP data are in black.