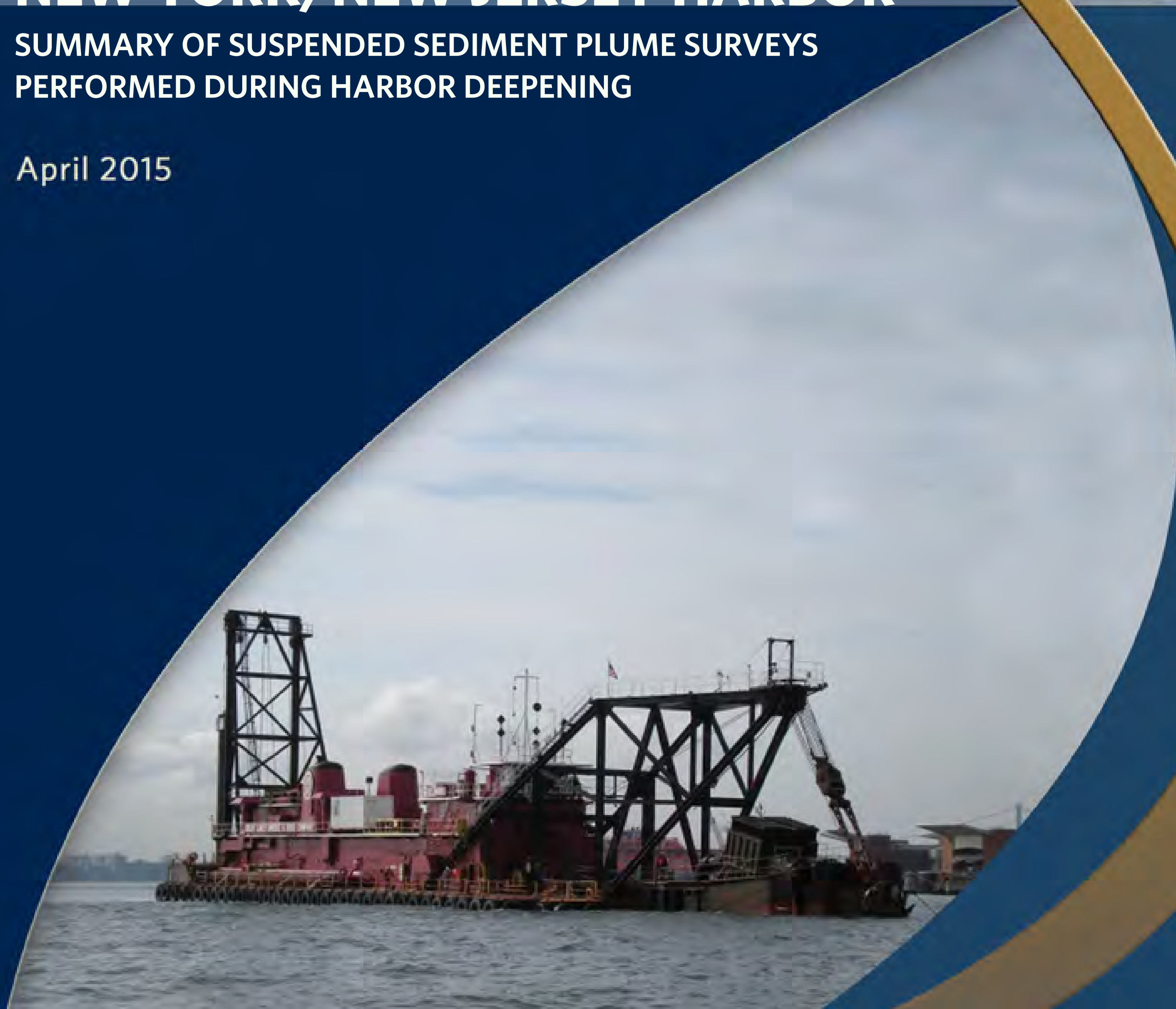
US Army Corps of Engineers®

New York and New Jersey Harbor Deepening Project

DREDGE PLUME DYNAMICS IN NEW YORK/NEW JERSEY HARBOR

SUMMARY OF SUSPENDED SEDIMENT PLUME SURVEYS PERFORMED DURING HARBOR DEEPENING

April 2015



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New York District
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Executive Summary

As part of an extensive, long-term monitoring effort conducted in conjunction with the NY/NJ Harbor Deepening Project, multiple characterizations of dredge plumes were performed. This component of the overall monitoring effort was designated as the total suspended sediment, or TSS component. Plume characterizations included several types of dredging equipment operating in different locations. Collectively the resultant data represent a comprehensive examination of the temporal and spatial dynamics of dredge plumes within the harbor complex. Knowledge of the spatial extents and suspended sediment concentration gradients comprising dredge plumes greatly increases the capability of regulators to assess potential exposures of species of concern and to determine the need, if any, for dredging project management practices to minimize problematic exposures. The primary objective of this report is to assemble the results of the plume characterizations into one resource document in order that future management decisions can be based on factual evidence of probable exposures both within NY/NJ Harbor and New York Bight complex as well as in areas where similar hydrodynamic, sediment and environmental conditions may exist. A summary of the existing state of knowledge regarding dredge plume dynamics is provided to place these newly gained data into context with observations of plumes elsewhere.

In brief, a total of 15 dredging project characterizations were completed within 9 different contract areas between June 2006 and February 2014. Each characterization consisted of multiple surveys utilizing a combination of acoustically measured suspended sediment concentrations and optically measured turbidities. Acoustic surveys involved transect designs that captured the entire spatial extent of plumes generated during both flood and ebb tidal stages. Each survey produced a composite picture of plume structure. Optical measurements of turbidity involved deployment of sensors at different water depths to collect time series data within the central portion of the plume. The majority of characterizations (12) involved mechanical bucket dredges, which are routinely used in NY/NJ Harbor for both deepening and maintenance dredging projects. Bucket capacities ranged from 8 to 30 cubic yards. Additional opportunities (3) were taken to characterize plumes produced by hydraulic cutterhead dredges engaged in either deepening-related (2) or maintenance (1) activities.

Prominent findings of the TSS monitoring effort include: 1) plumes were very predictable in terms of trajectory and suspended sediment concentration structure, and 2) TSS concentrations decayed rapidly with distance down-current from the source. A consistent pattern observed in all surveys was the entrainment of suspended sediment into tidal flows forming a plume that initially widened as suspended particles diffused laterally, but that never formed a plume that extended across the entire channel basin or upper rim to rim cross-section. In addition, significant plume excursion outside of navigation channel boundaries was rarely seen.

Regardless of variation in dredging equipment, even when dredging *in situ* sediments with a high percentage of fine fractions, plumes dissipated rapidly to levels not detectable against background conditions. Plumes generally decayed to background conditions within approximately 200 meters from the dredge in the upper water column and 600 meters in the lower water column. Plume signatures at the bottom rarely extended beyond 800 meters. Consequently, exposures of probable durations for actively swimming or passively drifting organisms at TSS concentrations above their tolerance limits will be limited to passage within a very short distance from the source. Plume avoidance by active swimmers should be easily attainable in all waterways within the harbor. Exposures of passive drifters would be limited to that portion of the population entrained in waters flowing directly under the dredge, and the duration of their exposure would be limited by settlement of sediment particles out of the parcel of water carrying the drifters. Exposures of sessile organisms could potentially be longer, but primarily for organisms occupying the basins or lower side slopes of the channel.

The NY/NJ Harbor plume characterizations, considered in tandem with knowledge gained in studies of dredge plumes in other coastal environments, provide a basis for making informed decisions on the relative risks posed by dredging as commonly conducted within the harbor.

With respect to dredge plume dynamics, NY/NJ Harbor now represents one of the most extensively studied urban, industrialized harbors. These results comprise a valuable contribution toward sustaining navigation infrastructure while protecting fishery resources.

Table of Contents

List of Tables

List of Figures

Introduction

In terms of shipping tonnage, the Port of New York/New Jersey ranks among the busiest in the nation. In 2011 the port handled over 132 million short tons of combined domestic and foreign cargo (AAPA 2012). Consequently, port activities are of tremendous importance to local, state, and regional economies. Access to port facilities requires an extensive navigation infrastructure, which in turn requires dredging for both construction and maintenance. Navigation dredging, since passage of the National Environmental Protection Act (NEPA) in 1969, has been subject to mandatory regulatory oversight to ensure that potential impacts on aquatic resources, especially vertebrate and invertebrate species, are minimized or avoided whenever practical.

One of the primary concerns of regulatory agencies for prudent conduct of navigation dredging is the release of suspended sediment to the water column. Effects of suspended sediments and associated turbidity on aquatic organisms remain one of the most-cited concerns for the imposition of restrictions and protective management practices on dredging operations. Wilber and Clarke (2001) reviewed the state of knowledge pertaining to impacts of suspended sediment on estuarine organisms with an emphasis on navigation dredging. They pointed out that impact predictions should be based upon robust risk assessments, including characterizations of both exposure and response. The level of uncertainty inherent in an impact prediction is linked directly to the degree of knowledge of exposure, i.e. the duration and intensity of immersion within a dredge plume on the part of an organism. Likewise, uncertainty is also dependent upon the degree of knowledge with respect to the response, i.e. the tolerance of the organism to the dose resulting from an encounter with and exposure to a dredge plume. Quantifying the former, the extent of potential exposure to dredge plumes in New York/New Jersey (NY/NJ) Harbor, is a primary objective of this report.

The NY/NJ Harbor complex is comprised of numerous environmental settings, extending from oceanic waters encompassing the Ambrose Channel which provides deep-draft access to the interior port facilities, to the broad open-water channel reaches within the Hudson River portion of the estuary, to the more confined waterways that lead to berthing areas in Newark Bay and the Arthur Kill and Kill van Kull. Monitoring requirements associated with the congressionally authorized deepening of the navigation infrastructure (herein referred to the Harbor Deepening Project, or HDP) within the harbor complex provided an opportunity to collect dredge plume characterization data at a variety of locations. As a consequence of the long-term effort dedicated to characterizing dredge plumes, NY/NJ Harbor now represents one of the most studied harbors in the nation with regard to knowledge of plume dynamics. This report summarizes those data in a manner intended to facilitate future dredging project management decisions both within NY/NJ Harbor as well as in areas where similar hydrodynamic, sediment and environmental conditions may exist. Used in tandem with other reports and source documents that examine responses of key organisms (e.g., winter flounder and other managed species for which Essential Fish Habitat [EFH] has been designated), better informed decisions can be made.

A basic understanding of dredge plume structure and dynamics is a necessity in support of dredging project management decisions. Therefore this report also technically reviews the existing scientific literature pertaining to dredge plumes. Although extensive literature relevant to dredge plumes exists, much of that body of knowledge is found in the gray literature, including conference proceedings (e.g., Aardoom 2006), contracted monitoring reports (e.g., TLA 1991) and state and federal agency research documents (e.g., Collins 1995). Unfortunately, these references can be difficult to locate and obtain. Because assimilation of this information can contribute to a better understanding of the plume dynamics associated with a given dredging project, this report examines appropriate references in the gray as well as peer-reviewed literature with an emphasis on those relevant to dredging as generally conducted in the NY/NJ Harbor. An extensive literature base also exists for dredged material placement and plumes emanating from hopper placements and pipeline discharges. However, the scope of this report places emphasis on plumes generated at the point of dredging rather than at dredged material placement sites. References pertaining to dredged material placement plumes are treated herein only if they contain useful information concerning plume dynamics in general.

Study Area

The New York and New Jersey Harbor complex is located at the apex of the New York Bight. It serves as the port for the greater metropolitan New York area, providing maritime access to shipping terminals via a network of dredged and maintained channels and anchorages (Figure 1). The Harbor exists within the larger confines of the Hudson-Raritan estuary, a diverse and significant habitat complex strongly influenced by tidal action and the mixing of seawater and freshwater inflows (USFWS 1997). The Harbor portion of the estuary covers approximately 298 square miles of surface water (USACE 1999) and includes as part of the HDP the bi-state waters of Newark Bay, Lower New York Bay, Upper New York Bay and the Arthur Kill and Kill Van Kull waterways.

The Harbor complex consists of a network of interconnected navigation channels with a maximum authorized depth of 50 feet, containing scattered small to extensive shoals that would require maintenance dredging to insure safe navigation, and shallow flats that may be adjacent to the deep-water Federal channels. The Lower Bay portion of the Harbor complex is comprised of extensive shallow flats with scattered areas of deeper waters, including borrow areas and pits. The predominant sediment type in the Lower Bay based upon previous sampling and jurisdictional states) mapping surveys is sand, although areas of sandy silt and silty sand are found in Raritan Bay, New Jersey. Pockets of gravelly sand exist near the Verrazano Narrows and off the shorelines of both Staten Island and Coney Island, Brooklyn (Figure 2). The relatively shallow bottoms of the Lower Bay, exclusive of the navigation channels, cover approximately 77% of the total area (38 % is <15 feet deep and 39% is 15 – 25 feet deep), whereas the Upper Bay is comprised predominantly of somewhat deeper water (67% is >25 feet deep). Outside of the navigation channels Newark Bay is dominated by shallow flats (67% is <15 feet deep). In general, the shallow waters of the Lower Bay are more expansive and unfragmented in comparison to other Harbor areas. The predominate sediment type along the shorelines and flats of the Upper Bay is silt, although the main body of the Upper Bay is predominately silty sand to the north which grades to sand approaching the Narrows between

Staten Island and Brooklyn (Figure 3). The Kill Van Kull and Arthur Kill are relatively narrow waterways dominated by major shipping channels. East of Constable Hook, the predominant sediment type of the Kill Van Kull based upon the studies prior to the HDP is silt compared to its western reach which is predominately silty sand, and the Arthur Kill and Newark Bay which are predominately sandy silt and silty sand (Figure 4).

Report Objective and Scope

The United States Army Corps of Engineers – New York District's (USACE-NYD) congressionally authorized Harbor Deepening Project (HDP) is under construction and nearing completion. The HDP is a multi-year Federal channel deepening program focused on improving Harbor navigation and safety while minimizing impacts to existing habitats and natural resources. As part of the HDP, an extensive, multi-year biological sampling program, the Aquatic Biological Survey (ABS), was completed in tandem with multiple Water Quality/Total Suspended Sediment (WQ/TSS) monitoring events. The latter were conducted in various harbor areas to document the extent of suspended sediment plumes generated not only by harbor deepening operations using various bucket scenarios but also following the passage of ocean-going container ships within NY/NJ Harbor. Surveys were conducted down-current of active dredging activities and up-current to establish ambient conditions. These WQ/TSS monitoring events were allocated among specific HDP contract areas in order to support state water quality certifications.

The basic objectives of this report are to:

1) Summarize the results of multiple dredge plume monitoring events within NY/NJ Harbor,
2) Place the results of these harbor-wide plume characterizations into context with the current state of knowledge regarding plume dynamics, and
3) Provide a single reference document to assist in science-based management decisions for future harbor dredging requirements.

Survey Methods

Suspended sediment plumes were characterized using a combination of methods including vessel-mounted Acoustic Doppler Current Profiler (ADCP) mobile surveys, "fixed" station turbidity profiling using optical backscatter sensors deployed at multiple water depths from an anchored array, and water samples collected to directly measure optical turbidity and gravimetric TSS in the laboratory.

Mobile ADCP Survey Design

In the field, a 1200-kHz Workhorse Monitor Series ADCP was typically used and RD Instruments WinRiver software was used to display plume acoustic signatures and to record the ADCP data. The ADCP operates by emitting acoustic pulses into the water column at set time intervals. Each group of pulses, referred to as an "ensemble," is vertically stratified into discrete, fixed-depth increments, or "bins." After the instrument emits a pulse, the ADCP then "listens" for the return of any sound (i.e. backscatter) that has been reflected from particles in the water column (in this case, a "particle" is any acoustic reflector, including sediment, plankton, fish, air bubbles etc.). Once the instrument receives the reflected signals, the WinRiver software can calculate the three-dimensional movement of particles in the water column and thus determine water velocity in each bin.

Water samples were collected concurrently with mobile surveys for laboratory analysis of TSS and calibration of the ADCP (see *Water Sample Collection* and *ADCP Calibration* below). Similarly, navigation data (i.e. GPS positions of the dredge) collected throughout the monitoring period by the dredge contractor were integrated during post-processing of the ADCP data to determine the distance of each transect from the dredge.

Prior to initiating the mobile plume surveys, circular transects using the ADCP were conducted around the actively operating dredge to ascertain the prevailing trajectory of the plume and strength of the acoustic signal of the plume. Subsequent ADCP transects were then conducted across the plume, generally oriented in a direction perpendicular to the channel and extending down-current until the plume's acoustic signatures could no longer be detected against background conditions. Background conditions on the days of the surveys were determined by conducting ambient transects up-current of the plume and outside the active dredging area. 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. The number, and consequently the spacing, of cross-plume transects were maximized within each designated tidal phase in order to provide complete spatial coverage of the detectable plumes and optimal resolution of internal plume structure. To cover a range of tidal conditions, ADCP backscatter data were collected during various stages of ebb (receding or outgoing tide) and flood (incoming or rising tide) tides during the survey periods.

Results for the mobile ADCP plume transects are presented graphically in three ways:

- **Vertical Profile Plots** – Vertical cross-section profiles representing individual transects are examined in detail for TSS concentration gradient structure of the plume at known, increasing distances from the source.

- **Plan-View Plots** – TSS concentrations are presented as composite horizontal "slices" through the plume signature at varying depth intervals.

- **Isometric Plots** – Selected transects are plotted three dimensionally and superimposed on the existing bathymetry to show the spatial extent of the plume within the channel (note: the depth (Z) axis is exaggerated to show detail better since the X,Y spatial extents are much larger than the Z extents). Channel bathymetry is generated using NOAA sounding data.

Fixed Station Turbidity Surveys

In addition to the mobile ADCP surveys, turbidity measurements were recorded at fixed locations and at various water depths using optical backscatter sensors (OBSs) which project a beam of near-infrared light into the water, and measure the amount of light reflected back from suspended particles. The OBS units used in these surveys were Campbell Scientific, Inc.'s OBS-3A units that were pre-calibrated by the manufacturer and programmed to measure turbidities in the 0-1,000 Nephelometric Turbidity Unit (NTU) range.

Typically, the OBS units deployed during the fixed station surveys would be tethered to a taut line and anchored at predetermined depths using a fixed anchor and buoy array. In some instances, arrays were deployed directly from the survey vessel and held in place. This was done in situations where a stationary buoy could not be safely tended. Depending on the survey, the arrays would be deployed for extended periods of time ranging from a few hours to the duration of an entire tidal cycle. The OBS units were configured to record depth (meters), turbidity (NTU), temperature (°C), salinity (ppt), conductivity (mS/cm) and battery level (V). OBS readings were typically logged internally every 10 seconds at a rate of 25 samples per second for duration of 5 seconds. That is, every 10 seconds the OBS recorded 125 samples (25 samples/sec x 5 sec). The internally recorded data were downloaded from the units following instrument retrieval at the end of the survey period.

Water Sample Collection

Water samples were also collected in the field and processed in the laboratory for optical turbidity (NTU) and gravimetric measurement of TSS concentration (mg/l). These data were used to convert the ADCP backscatter data into estimates of TSS as described below. The water samples were collected using a custom made pump sampler or carousel water sampler equipped with an OBS-3A unit to measure and record depth, temperature, salinity, and turbidity values throughout the entire water column profile. The OBS unit was connected via RS-232 serial link to an onboard computer which logged these data using custom software designed to time-stamp the water sample collections with one second accuracy, and to cross-reference these samples with simultaneously logged OBS and ADCP data for use in the ADCP backscatter conversion to TSS concentrations.

ADCP Calibration

Following the field data collection effort, the raw acoustic backscatter measurements collected by the ADCP were converted to estimates of suspended sediment concentration 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 and concurrently recorded ADCP acoustic backscatter data. The degree of confidence that can be placed in the estimates of TSS is directly proportional to the quality 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 conditions.

Water samples were collected at known locations within the water column, so that individual gravimetric results could be directly correlated with ADCP acoustic backscatter data for a "bin" of water as close to the water sample as possible. Following the Sediview calibration, the results were then applied to all of the ADCP files recorded during each of the far-field surveys, resulting in an ADCP-derived estimate of TSS concentration for each recorded ADCP bin. Figure 5 plots the water samples used for ADCP calibration against the calibration derived TSS value for the corresponding bin of water. In Figure 5a, samples are plotted in a time series, with earlier surveys at the beginning of the figure. Figure 5b is a scatter plot of all water samples, along with a linear regression and corresponding coefficient of determination.

Because air is injected into the water column as the dredge bucket breaks the air-water interface, and air bubbles are acoustic reflectors, care was exercised in converting acoustic data derived very close to the operating bucket to TSS estimates. Air 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. Previous experiments were conducted for the U.S. Army Corps of Engineers – New England District during the monitoring of a closed bucket during maintenance dredging operations in the Providence River, in which the bucket was intentionally plunged through the air-water interface without removing sediment from the bottom (Reine *et al.* 2006). These experiments were conducted under slow to moderate current flow conditions, and determined that the "bubble signature" pattern dissipated within approximately 50 meters of the source.

In addition, acoustic "echoes" reflected from the seabed may interfere with the ADCP signal. The ADCP emits most of its acoustic energy in a very narrowly confined beam; however, a small amount of energy is emitted at angles far greater than that of the main lobe. These "side lobes", despite their low power, can contaminate the echo from the main lobe, typically in the area directly above the seabed. The net effect of this side lobe interference is to show artificially high backscatter from the near-seabed areas. This effect is exacerbated in vessel-mounted surveys when the seabed elevation changes rapidly (e.g., during the transition from the shallows to the channel areas or vice-versa). In general, the side lobe distance above the seafloor is equal to approximately 6% of the water depth at that point.

Summary of Harbor-wide Results

Table 1 and Table 2 summarize the results of suspended sediment plume surveys in the various HDP contract areas. Between June 2006 and February 2014, a total of 15 distinct water quality/TSS surveys were conducted as part of the program. A majority of the surveys (11 of 15) were conducted within the Newark Bay Study Area as defined by the Environmental Protection Agency's Remedial Investigation and Feasibility Study, which includes the Arthur Kill north of the Goethals Bridge. Additional surveys were conducted in the Kill Van Kull and Anchorage

Channel associated with harbor deepening and one survey was conducted at Jones Inlet on the south shore of Long Island in association with maintenance dredging operations for a federal navigation project as part of an effort to fill an identified data gap for this TSS Summary Report (Figure 6). Except where noted, the surveys involved monitoring of plumes associated with mechanical bucket dredging of fine-grained sediments. Appendix A includes a photographic record (when available) of the working dredges from each survey.

Newark Bay Study Area

Arthur Kill 2/3 (June 2006)

Ambient conditions and the spatial structure and temporal dynamics of suspended plumes associated with fine-grained sediment dredging using an 18-cubic yard Cable Arm© environmental bucket on the Dredge *Michigan* in the Arthur Kill Channel directly north and east of Shooter's Island were characterized in June 2006 (USACE 2007 and Clarke *et al.* 2007). Observed plumes in this study were largely confined to the lower portion of the water column within short distances down-current from the bucket as depicted in Figures 7 and 8. Average turbidities exceeded background by 15 NTU at approximately 30 meters down-current, and 11 NTU at 50 meters. Maximum TSS concentrations at 10 meters from the source were approximately 300 mg/l, and generally did not exceed 120 mg/l at 100 meters, 50 mg/l at 150 meters, and 20 mg/l at 350 meters.

S-NB-1: Survey #1 (February 2008)

The plume structure and dimensions observed during far-field surveys of the Dredge *#53* configured with a 26-cubic yard capacity Cable Arm© environmental bucket operating in the B-3 Acceptance Area of S-NB-1 Contract Area (USACE 2008) were consistent with the results of the previous mechanical dredge plume monitoring effort (USACE 2007). Maximum TSS concentrations approached 300 mg/l near the surface, although air entrainment likely inflated these measurements to some degree. The core of the plumes typically ranged between 80 and 200 mg/l within the first 75 meters down-current from the source. For plumes surveyed in

February 2008, a consistent pattern was observed of relatively rapid decay and settlement in the water column. TSS concentrations 150 meters down-current from the source generally did not exceed 100 mg/l. Moreover, the suspended sediment plumes exhibited minimal lateral diffusion with distance traveled down-current, seldom measuring more than 75 meters wide at detectable concentrations above background. Figure 9 (ebb survey) and Figure 10 (flood survey) provide evidence that the spatial extent of the plumes were confined to relatively small segments of the cross-sectional profiles of the channel, and that the movements of plumes were generally confined to the bottom of the navigation channel with no evidence of plume excursion beyond the channel side slopes.

S-NB-1: Survey #2 (November 2008)

Plume far-field surveys were conducted during the operation of the Dredge *#55* configured with a 26-cubic yard capacity Cable Arm© environmental bucket in the B-1 Acceptance Area of S-NB-1 Contract Area in November 2008 (USACE 2009b). Maximum TSS concentrations were again found in concentrations above 300 mg/l in small pockets near the surface. TSS concentrations in the central portion of the plume within the first 150 meters down-current from the dredge typically ranged between 100 and 200 mg/l, and decayed rapidly with concentrations less than 70 mg/l at distances beyond 150 meters as depicted during the late flood survey on 18 November (Figure 11a-c).

One of the prominent geomorphological features of Newark Bay is the extensive area of shallow water flats located along the eastern perimeter of the Bay across from the Port Elizabeth and Port Newark Marine Terminals. The location of the dredging operation adjacent to these flats during the November 2008 sampling provided an opportunity to assess the extent, if any, of suspended sediment plume excursion outside the channel and above the channel side slopes. Mobile ADCP transects encompassed the entire spatial extent of the plume and clearly showed that the suspended sediment plumes at this location did not diffuse laterally to any great extent. Plumes seldom measured more than 75 to 100 meters wide. Figure 12 (early flood survey), Figure 13 (late flood survey) and Figure 14 (ebb survey) show selected ADCP transects superimposed over existing channel bathymetry and provide further evidence that the spatial extent of the plumes were consistently very small features within the expanses of deep channel waters. Plume trajectories were generally confined to the navigation channel with no evidence of plume excursion beyond the channel side slopes.

S-E-1: Survey #1 & #2 (March and April 2009)

Plumes observed during the operation of the Dredge *Delaware Bay* configured with an 8-cubic yard capacity Cable Arm© environmental bucket in the S-E-1 Contract Area in March and April 2009 were variable depending on the tide and the location of the dredge operating in the eastern end of Elizabeth Channel (USACE 2010a). Due to the configuration of Elizabeth Channel, connecting with Newark Bay Middle Reach and the Port Newark Pierhead Channel, prevailing current velocities and directions differed greatly across short distances within the surveyed area. Surveys conducted during the ebb tide (Figure 15) were particularly challenging due to the complex bathymetry and hydrodynamics of the area, as was the flood tide survey on 28 April (Figure 16) in which the plume appeared to be concentrated beneath the dredge platform and confined between the platform and the northeast bulkhead of the Port Elizabeth Marine Terminal.

In this flood tide survey transects conducted both to the west and north of the dredge revealed no evidence of a distinct plume outside of the uppermost four meters of the water column immediately adjacent to the dredge. This signal was likely attributable to air entrainment caused by vessel traffic in the area. A plan-view profile of the lower water column at 14-16 meters shows a highly localized plume signature with maximum estimates of TSS less than 100 mg/l confined between the dredge platform and the Elizabeth Terminal bulkhead (Figure 17).

During the ebb tide surveys conducted on 27 April, the prevailing hydrodynamics within the channels and the constricted nature of the sampling area dictated that transects were conducted parallel to the plume instead of perpendicular as illustrated in a plan-view profile taken for the lower mid-water column at a depth of 10-12 meters (Figure 18). In this survey, the dredge was situated on the south side of the Elizabeth Channel near the northeast corner of the Port Elizabeth Marine Terminal and the prevailing ebb tide essentially carried the plume east out of the Elizabeth Channel and then south around the corner of the Elizabeth Terminal and into the Newark Bay Channel, necessitating that the down-current transects be conducted parallel to the Newark Bay Channel and parallel to the plume.

Maximum TSS concentration observed during the S-E-1 surveys were recorded in the upper half of the water column, as high as 500 mg/l on occasion, but likely reflected the confined sampling area. This necessitated that initial down-current ADCP transects often be conducted within 50 meters of the dredge platform. Also, the Elizabeth Channel is a laterally constricted feature that experiences a high volume of deep-draft vessel traffic. Consequently, several ADCP transects were affected to some degree by the acoustic backscatter created by prop wash and sediment resuspension created by the passage of deep-draft container ships and their attending tugs.

S-NB-2: Survey #1 (July 2011) & #2 (October 2011)

Plume far-field surveys were conducted during the operation of the Dredge *Delaware Bay* configured with an 8-cubic yard capacity Cable Arm bucket in Acceptance Area 1 of the S-NB-2 Contract Area during July and October 2011 (USACE 2013b). Observed plumes varied depending on the tide and the exact location of the dredge operating in South Elizabeth Channel. In nearly all mobile ADCP surveys conducted, however, the suspended sediment plumes were confined to the lower half of the water column and did not extend outside of the navigation channel. As influenced by prevailing current patterns and the position of the dredge during July 2011, the plume was observed to remain within the channel boundaries on the same side of the dredge (eastern side) during both a flood (Figure 19) and ebb tide (Figure 20).

Plume surveys conducted during October 2011 were also affected by the position of the dredge. During this survey, the dredge was positioned over the channel side slopes and over shallow flats along the southern edge of the South Elizabeth Channel such that transects were established both perpendicular to the channel in up and down-current directions and parallel to the channel in order to give the most complete picture possible of the suspended sediment plume (Figure 21). In these surveys, the water column was shallower than in previous events but the plume still descended to the bottom half of the water column within 100 meters of the dredge. Peak suspended sediment concentrations were typically less than 300 mg/l within approximately 100 meters of the dredge platform and quickly dissipated to background conditions (Figure 22a-c). Even at the plume's greatest observed distance from the dredge, the plume remained primarily within the South Elizabeth Channel or along the channel-bordering edge of the adjacent flats. Rapid plume dissipation was also evident in turbidity time-series data collected during deployment of the OBS arrays in which down-current readings at 85 and 300 meters from the dredge were equivalent to ambient turbidities within the channel or over the flats (Figure 23).

S-AK-2: Survey #1 & Survey #2 (March 2012)

Plume far-field surveys were conducted during the operation of the Dredge *Delaware Bay* configured with a 15-cubic yard capacity Cable Arm© environmental bucket in Acceptance Area F of the S-AK-2 Contract Area of the HDP in the North of Shooters Island Reach of the Arthur Kill in March 2012 (USACE 2013c). Sediments in S-AK-2, as confirmed by grain size analysis of grab samples, were predominantly composed of silt with smaller fractions of clay and sand. During both S-AK-2 sampling events, ambient suspended sediment conditions in the survey area were stratified within the water column, with concentrations of 0 to 30 mg/l near the surface and increasing with depth. Maximum observed ambient TSS concentrations near the bottom ranged from 40 to 200 mg/l. In some locations, the maximum ambient suspended sediment concentrations were similar to those observed in the plume down-current from the dredge *Delaware Bay*. A TSS plume generated by the excavator dredge *J. P. Boisseau* was also detected in some ADCP surveys, as this dredge was often operating in proximity to the *Delaware Bay*.

Maximum TSS concentrations in the plume created by the *Delaware Bay* ranged from approximately 250 mg/l to approximately 700 mg/l in one ebb tide survey. These peak concentrations were detected in very small areas near the bottom of the channel no further than

200 meters down-current from the dredge (Figure 24a-c). In both survey events, TSS concentrations remained below 200 mg/l for most of the plume's extent.

With one exception, the sediment plume dissipated to background conditions within 660 meters down-current. During an ebb tide survey conducted on 16 March (Figure 25), the plume was detected above background conditions as far as 1,070 meters down-current from the dredge (T20). Current velocities as high as approximately 1.0 m/s were measured during this survey, and the fact that the *J.P. Boisseau* was operating approximately 175 meters to the north and west of the *Delaware Bay* may have contributed to the down-current extent of the observed plume during this survey.

Maximum plume width varied between 50 and 200 meters, and averaged approximately 100 meters across all S-AK-2 surveys. In all surveys, the widest portions of the plume were detected in the bottom two-thirds of the water column. In several surveys, for example the 15 March flood tide survey (Figure 26) and the 16 March ebb tide survey (Figure 25), where the plume was observed to extend throughout the water column in transects close to the dredge, concentrations in the upper portion of the water column tended to be less than 100 mg/l in a band narrower (less than 50 meters) than portions near the bottom. The plumes descended rapidly within the water column and widened along the bottom of the channel as distance from the source increased, as illustrated in the ebb tide survey on 12 March (Figure 27). In this survey the plume spread along the bottom of the Arthur Kill Channel, but remained confined within the channel side slopes (Figure 28a-c). None of the plumes surveyed on these dates were observed to extend beyond the slopes of the channel.

S-AK-3: Survey #1 & Survey #2 (November 2013)

Two far-field WQ/TSS surveys were conducted between 18 and 20 November (Survey Period #1), and 25 and 26 November 2013 (Survey Period #2) in the vicinity of an active dredging operation in Acceptance Area B and C of the S-AK-3 Contract Area. During both survey periods, the mechanical *Dredge 54* configured with a 30-cubic yard capacity Cable Arm©

environmental bucket was located in the Elizabethport Reach of the Arthur Kill Channel to the north and east of the Arthur Kill Railroad Bridge (AK Bridge). Water depths in this area ranged from approximately 5 to 15 meters. Throughout both survey periods, the drillboat *Apache* was conducting blasting operations in the navigation channel, but at a distance from the dredge sufficient to minimize any influence on the surveys, and plumes produced by the *Dredge 54* remained separable and distinct from any influence of the drilling operations.

During both survey periods, ambient suspended sediment concentrations in the survey area were consistently less than 25 mg/l throughout the water column. However, background suspended sediment concentrations as high as 50 mg/l were occasionally observed during parts of the ebb tide surveys on 18 and 19 November 2013, when a layer of higher ambient suspended sediment concentrations was present in the bottom portion of the water column (Figure 29a-c). During flood tide far field surveys on 20 and 25 November, similar high ambient concentrations were present near the surface and in the middle of the water column.

Maximum TSS concentrations in plumes created by the *Dredge 54* ranged from approximately 75 mg/l to 300 mg/l. These peak concentrations were detected only in small areas, generally near the surface within 137 meters down-current from the dredge (T05 and closer). During all surveys TSS concentrations were observed to decay with increasing distance from the bucket, rarely exceeding 200 mg/l beyond 458 meters from the bucket (T15 and further), and never detectable above background conditions beyond 690 meters (T21) down-current from the source (Figure 30).

Other HDP Contract Areas

S-KVK-1: Acceptance Area A: (June 2009)

Far-field surveys were conducted during June 2009 within Acceptance Area A of the S-KVK-1 Contract Area in the Constable Hook Reach of the Kill Van Kull to characterize suspended sediment plumes associated with the cutterhead *Illinois* dredge operation (USACE 2013a). The methodologies employed for this survey were similar to those used to survey bucket dredging operations of fine-grained sediment in other HDP contract areas. During typical cutterhead operations, the rotating cutter dislodges sediments that are then entrained as a sediment-water slurry and pumped through a pipeline to a designed placement site. In this specific case the cutter was being used to dislodge rocky bottom materials, which were temporally relocated to an adjacent area on the channel bottom through an installed downspout before final removal using a mechanical excavator dredge.

Maximum TSS concentrations attributable to the cutterhead dredging operation in the Kill Van Kull reached 600 mg/l in the lower third of the water column during a flood tide survey on 19 June 2009, but remained confined within the channel boundaries (Figure 31a-c). Peak concentrations of 200 to 400 mg/l were more typical during the other surveys, including an ebb tide survey on 22 June 2009 (Figure 32a-c). These peak concentrations were somewhat higher than those observed in other surveys monitoring cutterhead dredge operations (approximately 200 mg/l), including a subsequent survey in the same S-KVK-1 Contract Area (USACE 2012). Although the objective of the dredging during this survey was removal of the underlying Serpentinite bedrock, sampling locations in the survey area may have been overlain with a thin layer of finer grained silt and clay. Grain size analysis of the sediment sample collected during this survey from the cutterhead field of operation consisted of a 13.7% silt-clay fraction. These finer grained sediments may have accounted for the higher observed TSS concentrations.

During these surveys plumes were confined to the lower third of the water column, and because the prevailing currents within the Kill Van Kull were strongly oriented parallel to the long axis of the channel, did not extend into adjacent shallow water areas. In instances where a portion of the plume occurred in the upper water column, relatively low TSS concentrations (approximately 100 mg/l or less) were observed, with higher TSS concentrations confined to the bottom of the water column.

During these surveys the plume generated by cutterhead operations extended further down-current from the source during a flood tide than an ebb tide, as exemplified in the plan-view plots for the lower water column during the 19 June (Figure 33) and 22 June (Figure 34) surveys, respectively. On average, plumes dissipated to ambient conditions within approximately 500 meters during an ebb tide (T07), but extended as far as 800 meters down-current during a flood tide (T13). Higher TSS concentrations also persisted to a greater distance down-current from the dredge during a flood tide than during an ebb tide. Suspended sediment concentrations dissipated to 100 mg/l or less within approximately 300 meters during an ebb tide (T03 and closer). During flood tides concentrations of approximately 250 to 300 mg/l were seen up to approximately 600 to 800 meters from the cutterhead (T11 to T13). These differences may be attributed to the position of the dredge in proximity to the Kill Van Kull which contributed differences in current velocities across the S-KVK-1 Contract Area. Throughout the survey and across both tide cycles, current velocities were observed to be much faster within the narrower channel of the Kill Van Kull than in the portion of the channel which extended into the Upper Bay. The dredge *Illinois* was positioned near the transition between these two areas, and thus current velocities to the west of the dredge were likely higher than to the east during both tide cycles. Thus during a flood tide, the velocities would have been stronger in the down-current direction, accounting for the greater down-current extent of the plume during a flood tide in this area.

S-AN-2: Anchorage Channel Survey (January 2011)

Far-field surveys of an 8-cubic yard capacity Cable Arm© environmental bucket operating in Acceptance Area 4 of the S-AN-2 Contract Area of the Anchorage Channel in Upper Bay, New York were conducted in January 2011 around the Dredge *Michigan* (USACE 2011). Sediments in S-AN-2 were predominantly sand and silt. Prevailing currents in the Anchorage Channel were strongly oriented parallel to the long axis of the channel, which tended to confine the plume within the navigation channel and away from the surrounding shallow water areas. Suspended sediment plumes were confined primarily to the lower half of the water column and did not extend outside of the navigation channel (Figure 35).

Maximum TSS concentrations in excess of 500 mg/l were recorded during the 04 January ebb tide survey, extending as far as approximately 200 meters down-current from the dredge (Figure 36a-c). Plumes descended to the lower half of the water column at concentrations of less than 150 mg/l within 800 meters from the dredge (Figure 37a-c).

Ambient conditions during the 04 January surveys showed an atypically high TSS concentration approaching 150 mg/l through out the water column (Figure 38a-c), which may have been due to a variety of factors including nearby ship/tug traffic and/or high discharges from tributaries. In the week prior to these surveys there were snowfall events followed by several consecutive days of above-freezing temperatures, possibly causing additional runoff discharges into the estuary. In addition, the Anchorage Channel is a high volume vessel traffic area experiencing frequent passages of deep-draft container ships and their attending tugs. Surveys may also have been influenced by proximity to repeated transits by the Staten Island Ferry.

Mobile ADCP plume surveys conducted during both a flood and an ebb tide on 06 January showed ambient conditions that were more typical of those expected in the Upper Bay. Down-current transects during these surveys showed plumes that were entirely confined within the channel and did not extend more than 200 meters from the dredge at concentrations above 80 mg/l (Figure 39a-c and Figure 40a-c, respectively).

S-KVK-1: Acceptance Area H (March 2011)

Far-field plume surveys were conducted between 21 and 25 March 2011 within Acceptance Area H of the S-KVK-1 Contract Area of the HDP in the Constable Hook Reach of the Kill Van Kull to characterize plumes associated with the cutterhead *Florida* dredge operation (USACE 2012). As in the previous cutterhead surveys, the cutterhead dredge was in engaged in breaking apart the underlying Serpentinite bedrock. Once fractured, the material was moved by pipeline from below the cutterhead to an adjacent area on the channel bottom through an installed downspout. The fractured rock was later removed by a mechanical excavator dredge.

Maximum TSS concentrations attributable to the cutterhead dredging operation during this survey did not exceed 200 mg/l. Plumes dissipated to concentrations of less than 120 mg/l within approximately 375 meters of the source (Figure 41) and were not detectable above background conditions at a distance of 500 meters down-current before another source of backscatter was recorded at 600 meters down-current (Figure 42). The plume from the cutterhead operation was entirely confined to the lower quarter of the water column, and the prevailing currents within the Kill Van Kull carried the plume parallel to the channel side slopes such that plumes did not extend into adjacent shallow water areas (Figure 43).

Maintenance Dredging Contract Areas

Jones Inlet Survey (January and February 2014)

Previously described characterizations of dredging-induced plumes in NY/NJ Harbor largely focused on mechanical bucket dredging operations associated with deepening and maintenance of deep-draft vessel navigation channels. During coordination efforts with both state and Federal resource agencies a knowledge gap relevant to other common dredging practices in the area was identified; in particular as related to sediment plumes generated by hydraulic cutterhead pipeline operations in shallow-draft channels. These operations frequently occur in coastal inlets, which are critical links for fishery resources in movements between open coastal waters and embayments. A series of WQ/TSS surveys was conducted between 16 January and 11 February 2014 in Jones Inlet on the south shore of Long Island, New York. Monitoring occurred during maintenance dredging operations of the cutterhead Dredge *CR McCaskill* equipped with a 34-inch intake suction diameter cutter and involving shoreline placement authorized as a Federal Navigation Project. The objective of these surveys was to assess the spatial extent and temporal dynamics of suspended sediment plumes associated with cutterhead dredging of predominantly medium grain-size sandy sediments from shoals that had accumulated within the navigation channel.

The methodologies employed were generally similar to those used to survey multiple dredging projects in NY/NJ Harbor. However, because the nature of the sediments being dredged and the geomorphology of the Jones Inlet contract area were substantially different than those represented by the prior surveys, field and data analysis methodologies were modified. Under the typical survey design, the results of the gravimetric analysis of water samples are used to calibrate the ADCP-derived acoustic backscatter values for conversion to estimates of total suspended solids concentration. However, because of the coarse grained nature of the sediments encountered in this survey area, the compact size of the plume prevented collection of water samples that would allow an accurate conversion of ADCP backscatter to TSS concentration. Instead, raw acoustic backscatter values were used to assess the extent, intensity and dynamics of the dredge plume. Results from gravimetric TSS analysis of collected water samples were used to provide secondary data on the extent and intensity of the plume.

In this series of surveys, ADCP backscatter data indicated that ambient (background) suspended sediment concentrations in the survey area were generally low throughout the water column. In one survey (27 January flood tide), a naturally occurring layer of slightly higher suspended sediment concentrations was present near the surface, possibly representing air bubbles due to surface chop. Results of gravimetric TSS analysis of water samples indicated that ambient TSS concentrations ranged from 11 to 37 mg/l during the survey period compared to a range of 20 to 48 mg/l for the in-plume water samples collected within 110 meters down-current of the active dredge.

Suspended sediment plumes attributable to operations of the cutterhead dredge *CR McCaskill* were detected as ADCP backscatter. Using the intensity of acoustic backscatter as an index of TSS concentration, the areas of highest plume concentrations were typically found to be within 110 meters down-current from the source (Figure 44). Unlike previous cutterhead monitoring conducted in the Kill Van Kull (described above) in which the plume tended to remain in the bottom third of the water column, during the Jones Inlet surveys in the zone immediately down-current from the dredge, the highest TSS concentrations extended throughout the water column, but were more intense and more widely dispersed in the upper portion of the water column. This observation is interesting in that sediment disturbance by a cutter occurs at the seabed/water interface and does not involve "pulling upward" and release of sediments in the water column in the manner of a mechanical bucket. However, this operation did involve a relatively large cutterhead working in relatively shallow water. Applying a relatively high rate of cutter rotations per minute to "cut" the coarse sand bed could have resulted in throwing sediment into the upper water column, resulting in the observed plume pattern. The dredge plume had a maximum width of approximately 350 meters at a distance of 20 meters down-current from the source. Width of the plume in the case of a cutterhead includes the lateral distance swept by the cutter as well as the influence of currents dispersing the plume. The plume narrowed as it progressed further from the source, to a width of approximately 50-80 meters before becoming undetectable. The bottom-oriented component of the dredge plume was detected with an acoustic signature above ambient at a maximum distance of 360 meters down-current from the source (Figure 45).

Results of this study suggest that dredge plumes produced by hydraulic cutterhead dredges in coastal inlets similar to Jones Inlet will have very small spatial extents and be characterized by relatively low TSS concentrations. Multiple factors contributed to the observed plume dynamics including the existing hydrodynamic conditions at the time of the surveys which ranged between approximately 0 and 0.8 m/s during these surveys. Even in the presence of low to moderate tidal current velocities, however, resuspended sand particles descended rapidly back to the seabed.

In addition, the results of this study clearly demonstrated the distinct differences in plume dynamics of hydraulic cutterhead operations in shallow versus deep draft channels, and in coarse sand versus higher silt content sediments. In contrast to deep draft, fine-grained sediment dredging, plumes in Jones Inlet were generally smaller in spatial extent and comprised of low TSS concentrations. Although the plumes in Jones Inlet sometimes extended throughout the entire water column (unlike the plumes from the Kill Van Kull which tended to remain in the bottom third of the water column), their comparatively small, diffuse, and compact nature posed very little risk of dispersing fine sediments to habitats outside of existing navigation channel boundaries.

Discussion

Factors governing the dynamics of dredge plumes, including the physics of dredge plumes, dredging-induced sediment resuspension as compared to other sediment sources, and characteristics of dredge plumes studied elsewhere are discussed in the following paragraphs. Findings and conclusions of the various NY/NJ Harbor navigation dredging plume surveys were presented in the individual survey reports. The intent of this summary report is to put the cumulative results of the NY/NJ Harbor TSS monitoring into context with the broader base of knowledge pertaining to sediment plumes. A primary goal of this study was to develop an understanding of plume dynamics to aid in future assessments of water quality impacts from dredging and associated impacts on aquatic resources.

Factors Governing Dredge Plumes

Dredge plumes have a number of attributes that are relevant to impact assessments, among which are trajectory, depth profile, horizontal and vertical dimensions, and suspended sediment concentration gradient structure (Bridges *et al.* 2008). The trajectory of a plume from the point of release is driven by water currents as affected by tide stage, river discharge and wind-wave interactions. The plume's depth profile with increasing distance from the dredge source is influenced by forces, which are briefly described below, that act upon the sediment particles in suspension. The same forces operate at various temporal and spatial scales to determine the down-current dimensions of the plume and the TSS concentration at any given location within the plume. Because prevailing current velocities and directional vectors vary at different sites within the harbor, a generic plume description cannot be made with a high degree of detail. However, the cumulative plume characterizations can be used to conservatively describe a "typical" plume for the dredging scenarios that are common in NY/NJ Harbor, or any other harbor, including surrounding inlets and embayments, that might have similar hydrodynamic, sediment and environmental conditions.

Historically, by volume, most of the navigation dredging in NY/NJ Harbor has been accomplished by mechanical dredges. Hydraulic dredging by hopper dredges (also known as trailer-suction hopper dredges) has largely been limited to the Ambrose Channel. Hopper dredges also are used for mining sand offshore for beach nourishment projects. Within the greater study area hydraulic cutterhead dredges have primarily been used for channel maintenance at coastal inlets. However, a cutterhead dredge was used on a limited basis for harbor deepening to break apart the underlying Serpentinite bedrock in the Kill Van Kull (see WQ/TSS survey events in June 2009 and March 2011 described above). During typical cutterhead operations, the rotating cutter dislodges sediments that are then entrained as a sediment-water slurry and pumped through a pipeline to a designed placement site. In this specific case the cutter was being used to remove rocky bottom materials, which were temporally relocated to an adjacent area on the channel bottom through an installed downspout before final removal using a mechanical excavator dredge. The prominence of mechanical dredges for navigation dredging in NY/NJ Harbor is due in part to the requirement for maneuverability in tight berthing areas and for the sometimes problematic need to process large volumes of water entrained by hydraulic dredges. Hence, this report emphasizes plumes generated by mechanical dredges as used in NY/NJ Harbor.

Mechanical dredges have many variations in design that can influence the amount of sediment released and the manner in which the sediment is released. For example, mechanical dredge buckets have widely varying capacities, in general ranging from just a few cubic yards (or cubic meters) up to 50 cubic yards or larger. In common practice buckets used for navigation dredging tend to be larger, which reflects the need to excavate relatively large volumes of sediment in an economical manner for navigation purposes. The majority of navigation dredging projects in NY/NJ Harbor employ buckets of between 15 and 35 cubic yards (11.5 and 26.8 cubic meters) working capacity.

Bucket Types

Although an industry-wide terminology of bucket designs does not exist, several basic types can be identified. A fundamental difference is demonstrated by open versus closed bucket designs. An open bucket consists simply of two opposing, hinged "clamshells" or scoops, which take a semi-circular "bite" of sediment from the bottom substrate during each bucket cycle. In the closed position an "open bucket" is open in the sense that the upper surface of the sediment is exposed and water is allowed to freely drain as the bucket transitions through the water/air interface. In contrast, a "closed bucket" in the closed position has a cover that encloses the excavated sediment. Closed buckets are available in numerous configurations, but generally include vents in the canopy shields that reduce the pressure wave in advance of the descending bucket, allow water to escape as the opposing scoops are closed, and serve to retain sediment as the bucket ascends by minimizing water movement over the sediment surface.

Many closed buckets are custom fabricated for individual dredging contractors, but Cable Arm© buckets are widely used, including in NY/NJ Harbor. Cable Arm buckets are available in various sizes, and include "level-cut" versions, which are able to produce a relatively uniform, flat post-dredging sediment surface. The Cable Arm© environmental bucket is a variation of an environmental "closed" clamshell bucket designed to minimize release of sediment to the water column. 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. In addition to the use of a closed clamshell bucket, operational measures including restriction of hoist speed to no more than two feet/second and the use of dredging instrumentation ensuring full bucket closure were collectively used as management practices to reduce overall sediment re-suspension.

Different bucket designs can release sediments in different amounts and different ways. Depending on the geotechnical properties of the sediment being dredged, erosion from the sediment surfaces, the amount of metal surface area of the bucket, and the degree of sediment adhesion to these metal surfaces can affect the rate of sediment release and where in the water column the release occurs (Bergeron *et al.* 2000, Borrowman 2001, Hayes *et al.* 2007).

Operational Measures

In addition to physical properties of the sediment being dredged and the type of bucket, operational measures can affect sediment release. Among these are bucket ascent and descent speeds, and skill of the dredge operator. Dredging generally does not produce plumes that are homogeneous, uniform "clouds" of suspended sediment. Although the dredging schedule may call for twenty-four hour/seven days per week operations, many interruptions in the dredging process are normal. These occur as the dredge finishes an individual "cut" or the limit of reach of the bucket while the dredge barge remains stationary. As this point is reached the bucket is usually placed on deck, suspended above the attending barge, or placed on the bottom as an anchor while the dredge barge is advanced. Stoppages also occur frequently to perform routine maintenance, such as repainting lift marks on the bucket hoist and open-close cables. Routine bucket dredging practices also involve different methods to achieve project authorized depths. For example, the dredger may perform a sweep through a cut using maximum effective penetration of the bucket followed by a second "clean up" sweep to the final depth. Sediment releases during the initial sweep can be very different than during the follow-up sweep, in which the bucket contains less sediment and more water. It is commonly assumed that bucket capacity as stated in design specifications determines production rates, whereas in reality every bucket has a fill factor which can change depending on the aggressiveness of the dredge operator (Adair and Randall 2006). Thus plumes produced by bucket dredges are heterogeneous in structure and intermittent rather than continuous within the overall duration of a project.

A distinction should be made between dredging processes integral to navigation dredging as opposed to environmental or remedial dredging (e.g., Randall 2001, Palermo *et al.* 2004, Lane *et al.* 2005, Thompson *et al.* 2008). The latter involves handling of sediments that have been classified as contaminated through testing procedures required by regulators. Dredging of highly contaminated sediments necessarily involves precision in technologies for sediment removal and treatment or controlled placement. In contrast to navigation dredging, most environmental dredging projects involve relatively small volumes of dredged material. The need for precision and minimal release of contaminated sediments constrains production rates during remedial dredging and necessitates the use of specialized equipment and management practices that tend to slow the rate of sediment removal. On the other hand, navigation dredging often involves very large volumes of dredged material and consequently bucket capacities for navigation dredging projects tend to be substantially larger than those used for environmental dredging projects.

Physics of Dredge Plumes

Although different types of dredges release sediment to the water column in different ways, physical forces acting upon the sediment particles in suspension are identical for all dredge plumes, regardless of actual geographic location. A basic understanding of these forces and how they influence plume structure and behavior can provide useful insights into assessments of environmental impacts associated with a given dredging project.

Two phases of plume development and decay are recognized: a dynamic phase in which properties of the sediment comprising the plume are dominant in determining plume behavior, and a passive phase in which hydrodynamic forces and gravity dominate. Both are described below, again with an emphasis on bucket dredge operations.

In most cases dredges release sediment into the water column in the form of a high density mixture of sediment and water. Having a greater density than the surrounding waters, the plume tends to descend toward the bottom immediately. In the case of bucket dredges the release has several components linked to the stages of the bucket cycle. The actions of bucket impact with the bottom, bucket closure, and subsequent bucket withdrawal from the bottom tend to create a pulse of resuspended sediment just above the sediment bed. Sediment is then released as the bucket ascends through the water column and is washed off the bucket's external surfaces or from the sediment contained within the bucket depending on the design of the bucket in use.

Another pulse of sediment release generally occurs as the bucket is lifted above the water/air interface as a hydraulic head is formed and the supernatant water drains out of the bucket. Some spillage may occur as the bucket is swung above the tending barge's gunnels and the material placed into the hopper. Additional spillage may occur as the bucket is maneuvered back to the entry point at the water's surface, and some residual sediment adhering to the bucket may be released as the bucket descends and the next cycle begins. The bucket dredging process does include other sources of resuspension, notably during spud maneuvering during periodic advances of the dredge platform and during activities of tending vessels, such as tugs moving full or empty barges into position which may create prop wash disturbances of the sediment. Thus sediment is released unevenly throughout the water column during each bucket cycle, and non-uniformly as time elapses during each cycle. Methods to estimate losses during each component of the bucket cycle have been refined repeatedly (Hayes and Wu 2001, Hayes *et al.* 2007).

Releases from other types of dredge plant can vary considerably from that of bucket dredges (Hayes *et al.* 1984, Raymond 1984, Blokland 1988, Pennekamp and Quaak 1990, Herbich and Brahme 1991, Collins 1995, Pennekamp *et al.* 1996, SAIC 2001a, Anchor Environmental 2003, Palermo *et al.* 2004, PIANC 2009). An excavator or backhoe dredge would have some similarities, depending on the manner in which the bucket penetrates into and is withdrawn from the substrate. Releases from cutterhead dredges are almost entirely limited to just above the bottom. Sediment resuspension rates of operating cutterheads depend on cutter rotation velocities, speed of cutter lateral movement while either overcutting or undercutting into the sediment face, pump intake rates, and the specific design of the cutterhead's blades. Releases from hopper dredges are usually only of concern if overflow practices are used. Major differences in overflow plume structure and behavior are imparted by the continuous movement of the point at which sediment is discharged from the hopper into the water column, as opposed to the relatively stationary bucket or cutterhead releases. Overflows from most modern hopper dredges occur by means of weirs or standpipes in the hopper and discharge occurs through the bottom of the hull. This provides the released sediment with some downward momentum, which tends to enhance plume descent. One complicating factor is injection of air into the hopper discharge, which can have a buoyant effect on the plume in the hopper dredge's wake. Reviews of hopper dredging equipment in relation to plumes can be found in John *et al.* (2000) and Jones *et al.* (2010), which summarize experience in the European sand mining industry.

Returning to the example of release by an operating bucket dredge, the descent and ascent movements of the bucket generate strong turbulent currents in the water column that serve to disperse released sediments within the dynamic plume. As noted for plumes produced by hopper dredge overflows, movements of the bucket can introduce a large amount of air into the water column, which can cause a buoyant effect as bubbles rise. Particularly at the periphery of the high density plume, turbulent mixing tends to strip sediment particles by entrainment into the contiguous water mass, forming what is termed the passive plume. Spatially, the volume of water immediately adjacent to the dredge subject to very turbulent mixing is known as the "dredging zone." Immediately down-current from the dredging zone is the "near field", in which suspended sediment concentrations may remain elevated, but dredge-induced current flows are much less turbulent. Dimensions of the near field are generally small, not usually extending beyond 200 meters from the dredge. However, the distance at which a given plume transitions from the dynamic, near field phase to the passive, "far field" phase varies among dredging project scenarios. Other terminologies have been used to describe essentially the same plume spatial structure (e.g., Bohlen 1978, Borrowman 2001, Burt and Land 2003). The age of a plume can be a more important consideration than distance from the source, as air bubbles in the plume dissipate over a span of several minutes. During slack current flows the near field-to-far field transition may begin within 50 meters of the dredge. During peak tidal velocities the transition may extend outward to 200 meters or further. Invariably, the concentrations of suspended sediment particles entering the far field portion of a plume are orders of magnitude less than those at the source. Much of the originally released sediment mass quickly settles out of the plume, including coarse fractions and fines that are not disaggregated. Even substantial amounts of silt- and clay-sized particles rapidly decay from a plume as cohesive clumps.

Although relatively high concentrations of sediments of all particle sizes present in the *in situ* sediments can occur immediately adjacent to the bucket, draghead or cutterhead, concentrations of coarse sediment particles (fine sand and above) decreases exponentially with time and distance in the down-current direction from the point of release. Unless the dredging occurs in the presence of very high current velocities, coarser sediment particles, once outside of the zone of turbulence created by the dredging equipment, settle under the influence of gravity. Rates of settlement can generally be predicted based on Stokes Law, which yields settling velocities of spherical particles of known specific gravities. Importantly, a large proportion of sediment released will be in the form of clumps or aggregates of even very fine particles, which therefore behave as larger, denser particles with comparatively rapid settling rates. Also, in saline waters many fine particles will form flocs, which similarly behave as larger particles than their disaggregated form. These processes dominate in the near field.

The far field plume consists entirely of fine sediments in suspension. As the plume ages with increasing distance down-current from the dredge, constituents of the plume continue to descend through the water column. In estuarine waters disaggregated fines form flocs which behave as large, dense particles with relatively high settling velocities. Re-aggregation of the disaggregated material results in larger, lower density particles. However, the larger particle size results in faster settling rates due to the R-squared component of Stokes Law. Whereas the near field plume has a longevity on the order of minutes, the far field plume can persist for hours or even days, albeit at extremely low concentrations just above background and sometimes indistinguishable from the ambient condition with existing technologies, until currents are sufficiently slow to allow complete settlement. The remaining fine particles drift within the passive plume's trajectory as determined by water currents and bathymetric features down-current from the dredging site. Dimensions of the resultant far field passive plume are the result of both horizontal movements, termed advection, and lateral and vertical movements, termed diffusion. As settlement proceeds within the passive plume, sediment particles are deposited on the sediment bed. The footprint of deposition will reflect site-specific conditions. It is important to note that due to their relatively low critical shear stresses of erosion newly deposited flocs and disaggregated particles can be resuspended by the resumption of tidal flows. Therefore plume dynamics are not terminated by initial deposition of sediment particles from suspension.

In order to assess the potential for dredge plumes to impact a given aquatic organism, one must consider the probability of that organism encountering a plume, the response of the organism to the encounter (i.e. avoidance, attraction, or neutral behavior), and the consequences of exposure to the plume, if any. Far field plume surveys as documented and described herein allow an informed assessment of the likelihood of an encounter. For example, does the plume occur within a harbor area known to be occupied by one or more life history stages of that organism? Does the plume occur during a season in which the life stage is present? If so, does the plume represent a feature that based upon areal extent could not be avoided, thereby potentially forming a migratory impediment? Using technologies demonstrated in the present studies, plume dimensions can be characterized in great detail. For example, would a dredge operating in a particular reach of channel produce a plume that extended from bank to opposing bank in that waterway? What maximum portion of the channel's cross-sectional profile would fall within the plume's boundaries? Plume surveys provide accurate depictions of plume dimensions such that these questions can be addressed.

In a worst case scenario a dredge plume would encompass a sufficiently large portion of the channel's cross-sectional profile such that an assumption could be made that the organism would be exposed to suspended sediment concentrations above ambient conditions. In tandem with supplemental information on where in the water column an organism is likely to be found and at what speed the organism tends to move, plume surveys provide adequate characterizations of TSS concentrations within the plumes to estimate exposures and doses. As suggested by Wilber and Clarke (2001), knowledge of the dredging process, plume dynamics, and organism behavior can be combined to estimate dose. A dose experienced by a sessile organism residing on the bottom adjacent to a navigation channel being dredged would obviously be quite different than that experienced by a highly mobile organism transient to the area.

Dredging in Perspective with Other Sources of Sediment Resuspension

Placing potential exposures to dredge plumes into context with exposures to other natural and anthropogenic sources of suspended sediments is also a necessary step in evaluating impacts. Surprisingly few dedicated studies have attempted to place dredging-induced resuspension and sedimentation into context with these other sources. Bohlen (1978, 1980), Bohlen *et al.* (1979), and Bohlen *et al.* (1996) described dredging-related resuspension events as minor in comparison to the combined effects of wind and wave-induced resuspension. Whereas dredging caused short-term spikes in TSS concentration of up to 100 mg/l at water quality sampling stations adjacent to the navigation channel, elevations as high as 700 mg/l for up to 3 days were observed that were not caused by the dredging operation. Bohlen (1980) observed that a typical bucket dredging operation in the Thames River, Connecticut, increased suspended sediment load by 25% over an area that equated to 2.5% of the estuary, whereas a storm event increased the suspended sediment load by as much as 300% throughout the entire estuary. Bohlen (1980) concluded that given the comparative magnitudes of resuspension and the higher frequency of storm events that dredging appeared to represent a minor influence. Bohlen *et al.* (1979) stated that "dredge-induced resuspension is primarily a near field phenomenon producing relatively minor variations as compared to those caused by naturally occurring storm events." These findings were consistent with those of Sosnowski (1984), who reported that sediments resuspended by storms and dredges obey the same physical laws, but that the two sources differ with respect to spatial and temporal scales.

Resuspension by storms and associated waves and currents have been the subject of numerous studies (e.g., Oviatt and Nixon 1975, Brydsten 1992, Schoellhamer 1995), but relatively few studies have directly compared storms, dredging, and other sources of resuspension. For example, Brydsten (1992) noted that a major storm event could maintain suspended particulate loads within an estuary for at least four days, and retain significant amounts of particles in suspension for at least nine days. Maa *et al.* (1998) noted that sediments in the inner portions of Baltimore Harbor, Maryland had much lower critical shear stress values than sediments in the outer reaches, and were therefore much more subject to resuspension. Studies by Schoellhamer

(1996, 2002) are among the few to place dredging into context with storms as sources of sediment resuspension. Schoellhamer (1996) demonstrated that large vessel passage through navigation channels in a shallow estuary created solitary long waves that had a major effect on sediment resuspension throughout Hillsborough Bay, Florida, and that trawling could produce plumes that held particles in suspension for up to eight hours. In that shallow estuary, anthropogenic sources of sediment resuspension accounted for a larger portion of the annual resuspension budget than natural sources. In contrast, Schoellhamer (2002) determined that wind-wave resuspension was a primary factor affecting suspended sediment loads in San Pablo Bay, California, and that dredging played a minor role.

Recreational and commercial shrimp trawling activities have been shown to be significant sources of sediment resuspension (Schubel *et al.* 1979, Dellapenna *et al.* 2006), especially in shallow estuaries. TSS concentrations were approximately 250 mg/l in the wake of shrimp trawls in Galveston Bay, Texas, equivalent to those concentrations generated by frequent wind events at the study site (Dellapenna *et al.* 2006). Offshore trawling activities have been shown to similarly affect turbidity and suspended sediment regimes on large spatial scales (Churchill 1989, Palanques *et al.* 2001). Other forms of commercial fishery activities have been observed to be significant sources of sediment resuspension in estuaries, such as scallop and clam dredging (Peterson *et al.* 1987, Ruffin 1998). Tarnowski (2001) reviewed studies that characterized suspended sediment plumes associated with escalator dredging of shellfish. Kyte and Chew (1975) measured TSS concentrations as high as 584 mg/l near an escalator dredge in shallow water with silt/clay sediments. The plume rapidly dissipated within 61 meters (200 feet) from the dredge, with TSS concentrations falling to 89 mg/l. They noted that background levels at the site occasionally reached 441 mg/l. Black and Parry (1999) measured TSS concentrations as high as 5,000 mg/l in the immediate vicinity of a scallop dredge. Concentrations dropped to several hundred mg/l within minutes, and to background levels within 30 minutes.

The potential for ships to resuspend substantial quantities of sediment has been recognized for some time (e.g., Liou and Herbich 1976, Sly 1977, Munawar *et al.* 1991). However, sediment resuspension by ship traffic has received limited attention, although evidence exists that both long waves (Schoellhamer 1996) and propeller wash (Hayes *et al.* 2012) can represent significant sources. Hayes *et al.* (2012) used models of propeller-induced bottom shear stresses and erosion rates to estimate resuspension rates for vessels of a range of horsepower ratings, vessel speeds, and water depths. A conclusion was reached that vessel traffic could represent a source of sediment resuspension equal to or greater than marine construction projects. Clearance under the hull appeared to be a major determinant of the degree of scour, with a water depth equivalent to ten prop diameters needed to eliminate scour. Hayes *et al.* (2012) suggested that limiting vessel speed was the most effective management practice that could be applied to ship traffic to reduce resuspension. Stortz and Sydor (1980) and Erdmann *et al.* (1994) measured wind and ship-induced resuspension events in Duluth-Superior Harbor. Results of these two studies indicated that TSS concentrations reached 185 mg/l in the immediate wake of passing ships. Ship-induced plumes decayed rapidly, with estimates of complete settling time of between 1.0 and 3.5 hours, whereas wind-induced sediments persisted in the water column for 6 to 12 hours.

Dynamics of ship-induced suspended sediment plumes in Newark Bay, New Jersey were investigated by Clarke *et al.* (2015). Spatial scales, TSS concentration gradients, and dispersion patterns were monitored following the passage of a range of vessel types by ADCP surveys supplemented by collection of water samples. Plumes varied in structure depending on vessel type (deep versus shallow draft) and movement pattern (e.g., container ship under power, maneuvering with assistance of tugs, berthing with bow-thrusters). Very large plumes encompassing the entire water column were created by deep draft vessels during turning maneuvers. Plumes rapidly dissipated in the upper water column, but persisted at depth for long periods. TSS concentrations above 90 mg/l were found over broad expanses, with detectable plumes present for at least 50 minutes in open waters at depth and indefinitely in berthing area secondary channels where dispersive currents were minimal. Plumes persisted in the lower 2 meters of the water column for at least 65 minutes following deep draft vessel passage, whereas no evidence of bottom disturbance was noted for shallow draft vessels. They concluded that deep draft vessel traffic represented a significant source of sediment resuspension in Newark Bay, acting in tandem with dredging and natural sources to affect temporal and spatial distributions of suspended sediments. Ship traffic has a definite effect on redistribution of sediments within Newark Bay, with likely consequences on sedimentation patterns that influence maintenance dredging needs (e.g., Wakeman *et al.* 2007).

Previous Dredge Plume Characterizations

Water quality alterations induced by dredging activities have been the subject of both concern and interest for decades. In particular, one water quality concern that arose in conjunction with dredging projects in New York and New Jersey waters involved potential depletion of dissolved oxygen concentrations. In the 1980s regulators frequently expressed concern that disturbance and resuspension of sediments with high oxygen demands could significantly reduce dissolved oxygen concentrations in the water column. Potential exacerbation of already chronically low dissolved oxygen concentrations in areas with poor water quality was a priority concern. As early as 1968, Brown and Clark (1968) reported that maintenance bucket dredging in the Arthur Kill during 1963 and 1964 involving accumulations of "waste discharges" consisting of "black, soft, oily silt" with "odors of chemicals, oils, and hydrogen sulfide" resulted in depressions of water column dissolved oxygen concentrations on the order of 4 mg/l or parts per million (ppm). Unfortunately, Brown and Clark (1968) did not provide sufficient details of their methods to verify their findings. It is highly probable that the composition of the sediments in this highly industrialized waterway contributed to the observed dissolved oxygen depression.

Fishery resource managers later cited similar concerns when a proposal was made to dredge the Haverstraw Bay reach of the Hudson River navigation channel, which was viewed as a critical nursery area for striped bass (*Morone saxatilis*) and other species. NYD conducted both field monitoring and modeling studies of bucket dredging at the Haverstraw Bay site to estimate dissolved oxygen depletion (Lunz *et al.* 1988, Houston *et al.* 1989, Houston *et al.* 1994). Sediments to be dredged consisted of 88% fines with high total organic content, which heightened concerns. Houston *et al.* (1994) reported minimal adverse effect on dissolved oxygen concentrations as plume dissolved oxygen concentrations deviated below ambient concentrations generally by less than 0.2 mg/l and never by more than 1.0 mg/l. In a more recent study Wilber and Clarke (2010) examined long-term water quality monitoring data for hydraulic cutterhead dredging operations in the Savannah River, Georgia. During planning of the Savannah River dredging concerns were raised that dredging during periods of chronically low dissolved oxygen concentration in Savannah Harbor would exacerbate already stressful conditions for fish and shellfish. Wilber and Clarke (2010) concluded that dredging operations had no demonstrable effect on dissolved oxygen concentrations, and recommended as a viable management practice that dredging be conducted during periods of hypoxia when most organisms avoided the affected waters. A general conclusion from the above studies is that dissolved oxygen concentrations are minimally, if at all, reduced in plumes at dredging sites.

Nutrient and trace metal constituents of dredge plumes have also received limited attention. Tramontano and Bohlen (1984) studied the nutrient and trace metal geochemistry of plumes produced by a bucket dredge operating in the lower Thames River estuary, Connecticut. They reported substantial increases in concentrations of dissolved phosphate, ammonia, silica, manganese, and copper adjacent to the dredge, but observed exponential decreases in these concentrations with distance down-current from the dredge. Tramontano and Bohlen (1984) concluded that dredge plume alterations of dissolved and particulate concentrations were essentially near field phenomena on a minor scale when compared to resuspensions caused by natural storm events. For New York/New Jersey waters Tavolaro and Mansky (1985) measured dissolved nutrient concentrations, including nitrates, nitrites, ammonia, total phosphate, orthophosphate, and total Kjeldahl nitrogen (TKN) in hopper dredge overflow plumes in Raritan Bay. Of these parameters, only nitrites appeared to be elevated as a direct consequence of the dredging activity.

In contrast to the small number of studies directed at dredging-induced dissolved oxygen depletion, turbidity and TSS conditions have been the subject of numerous investigations. An extensive review is given in Anchor Environmental (2003), which examines biological effects as well as resuspension characteristics of various dredge types with an emphasis on contaminated sediment issues.

As environmental protection became an issue of international attention in the 1960s and 1970s, a need for dredge plume predictive tools was recognized. Early effort focused on quantifying the loss of sediment by various types of dredges and developing numerical models of the loss processes of hydraulic (e.g., Kuo *et al.* 1985) and mechanical dredges (e.g., Kuo and Hayes 1991). The development of sophisticated dredge plume models continues to the present (e.g., Wilson 1979, Cundy and Bohlen 1980, Herbich and Brahme 1984, Bowen and Hartman 1991, Kuo and Hayes 1991, Arts and Kok 1994, Bonetto 1995, Black and Parry 1999, Zhang and Adams 1999, Borrowman 2000, Johnson *et al.* 2000, Swanson *et al.* 2000, Wu and Hayes 2000, Andersen *et al.* 2001, Borrowman 2001, Borrowman 2002, Germano *et al.* 2002, Nieuwaal *et al.* 2002, Je and Hayes 2004, Je and Kim 2004, Davies *et al.* 2005, Babcock *et al.* 2007, Gailani *et al.* 2007, Hayes *et al.* 2007, Je *et al.* 2007, Lackey and MacDonald 2007, Mastbergen and Arentz 2007, Bilimoria *et al.* 2008, Kang *et al.* 2008, Lackey and Smith 2008, Swanson and Isaji 2008, Fitzpatrick *et al.* 2009, Lackey and Kim 2010, Bell and Reeve 2010, Poon *et al.* 2010). Partly due to the intense interest in predictive models, the need for field data to support model validation, verification, and calibration efforts was recognized. Field data provided important insights into dredge plume dynamics. For example, Je and Hayes (2004) noted that Stokes' Law, which describes settling rates of particles of known dimensions in water, underestimated settling rates of particles in near-field plumes and overestimated settling rates in far-field plumes. Based upon similar findings elsewhere, recent research has focused on internal plume processes including flocculation (e.g., Smith and Friedrichs 2007). Likewise, research continues on the means to measure and calculate loss rates by various dredges, as these serve as critical inputs for predictive models (Collins 1995, Wu and Hayes 2000, Borrowman 2001, Land *et al.* 2007).

Interest in characterizing resuspension by different dredge types coincided with growing awareness of the need to control releases at both dredging and placement sites (O'Neal and Sceva 1971, Barnard 1976). Just as numerical models of dredge plumes have become more robust over time, so have methodologies and technologies for collecting plume characterization data. Early studies such as Tavolaro and Mansky (1985) relied heavily on taking water samples at predetermined distances from a dredge and at various water depths to describe plume structure. Water samples were analyzed gravimetrically in the laboratory and often results were unavailable for several days after sample collection. Also, logistical constraints of sample collection in the field greatly limited the spatial resolution of plume characterizations. The need for rapid plume characterizations led to wide use of turbidity, an optical property of suspensions, as a surrogate for TSS measurements (Telesnicki and Goldberg 1995, Thackston and Palermo 2000, Clarke and Wilber 2008). Although having the advantage of real-time data collection, optical measurements of turbidity could not be directly converted to suspended sediment concentration without undergoing a calibration procedure involving suspensions of *in situ* sediments (Pfannkuche and Schmidt 2003, Hawley 2004, Minella *et al.* 2007). This requirement was often overlooked by investigators engaged in early characterizations of dredge plumes. Considerable research was motivated by the need to overcome the limitations of water sampling for gravimetric analysis and optical measurements, including the use of continuously pumped water samples (e.g., Puleo *et al.* 2006, Albro *et al.* 2008, Curtis *et al.* 2010). Another approach led to the development of robust acoustical techniques, which could survey large areas in short periods of time. Acoustic Doppler current profilers (ADCP), which originally were designed to measure the echo return from sound scattered by particulates moving in the water column to determine current velocities and directional vectors, were adapted to measure quantities of sediment in the ensonified water (Thorne *et al.* 1991, Ogushwitz 1994, John *et al.* 2000, Land and Bray 2000, HR Wallingford 2003, Palmer 2003, Land *et al.* 2004, Aardoom 2006). In Europe research continues into measurement and prediction of suspended sediment plumes by various types of dredges. For example, Dutch and United Kingdom researchers have invested substantial effort into development of the Turbidity Assessment Software System (TASS), which specifies standard protocols for plume characterizations (Land *et al.* 2004, Aarninkhof *et al.* 2007). Flocculation processes and effects on settling rates of particles within plumes have recently received attention (Mikkelsen and Pejrup 2000, Smith and Friedrichs 2007).

Pipeline Cutterhead Dredge Plume Characterizations

Smith *et al.* (1976) observed short-term increases in turbidity measured as Jackson Turbidity Units (JTUs) and other water quality parameters associated with cutterhead dredging in Grays Harbor, Washington. They did not specify the magnitude of change with respect to either temporal or spatial scales.

Nakai (1978) used field measurements of TSS concentrations near operating cutterheads to develop a Turbidity Generation Unit (TGU) method to predict releases based on sediment properties and dredging operational parameters. Spatial dimensions of the plumes, however, were not reported.

Results of suspended sediment plume monitoring at three cutterhead dredging projects in Japan were reported by Koba (1985). The three projects represented a range in terms of dredging depth (5 to 18 m), cut thickness (0.5 to 2.6 m), production rate (4,500 to 9,100 cubic meters/hour), cutter rotation speed (12 to 17.6 rpm), and swing speed (4 to 18 m/min). TSS concentrations near the bottom were approximately 6 mg/l above ambient at a distance of 50 meters from the cutterhead and 2 mg/l at a distance of 200 meters.

Hayes *et al.* (1984) and McClellan *et al.* (1989) examined resuspension by hydraulic pipeline cutterhead dredges of various designs at three locations: Calumet Harbor, Illinois, Savannah River, Georgia, and James River, Virginia. Sediments were predominantly fine silts and clays at all three sites. Maximum plume TSS concentrations above background levels were 10, 120, and 200 mg/l respectively. McClellan *et al.* (1989) concluded that cutterhead resuspension was influenced primarily by swing speed, depth of burial of the cutterhead, and cutter rotation speed. They also stated that cutterhead dredges consistently exhibited lower resuspension rates than other types of conventional dredges. Data derived from McClellan *et al.*'s (1989) study were analyzed by Andrassy and Herbich (1988a, 1988b), who reported relationships between resuspension by cutterheads and operating parameters of the dredge, including rotational speed, suction velocity, swing rate, thickness of cut, ladder angle, sediment properties, and cutter size.

They concluded that resuspension by cutterheads could be minimized by optimizing cutter rotational velocity in combination with swing rate and suction velocity. These principles are in line with current knowledge on means to maximize production rates of cutterhead dredges. Hayes *et al.* (2000) also used the same data to derive loss rates for cutterhead dredges operating under a range of operating conditions as a step in development of predictive regression models.

Hydraulic Hopper Dredge Plume Characterizations

In Europe and the Far East, much attention has been given to overflow plumes emanating from hopper dredges extracting sand and gravel (e. g., Whiteside *et al.* 1995), whereas in the United States emphasis has been placed on overflow plumes produced during navigation dredging. Sustar (1976, 1979) examined the effects of different sediment types on the composition of plumes produced during hopper dredging in San Francisco Bay. Based on turbidity measurements (light transmission), Sustar demonstrated that salinity had a substantial effect on plume structure due to water column stratification and flocculation in the saline portion of the water column.

Goodwin and Michaelis (1984) used a combination of aerial photography and water samples to examine hopper dredge plumes in Tampa Bay, Florida. They observed plumes of "moderate to high" turbidity levels associated with various dredging operations, but did not specifically state plume characteristics. They did conclude that during dredging projects average turbidities appeared to increase by about 2 NTU at long-term monitoring stations.

McLellan *et al.* (1989) investigated plume dynamics of hopper dredges fitted with various types of dragheads at Grays Harbor, Washington. In their study water samples were collected either at a fixed location in the wake of the U. S. Army Corps of Engineers Hopper Dredge *Essayons*, or by following the dredge at a constant distance. During overflow plumes with TSS concentrations of 100 mg/l above background extended up to 7,000 feet (2,134 meters) behind the dredge, although most of the sediment in the plume settled to the bottom within 4,000 feet (1,219 meters) of the dredge. Maximum TSS concentrations of 800 mg/l occurred only near the source of overflow. Elevated concentrations were observed up to one hour after cessation of overflow. Plumes produced by dragheads during periods of no overflow were found only in the lower water column at TSS concentrations below 50 mg/l and at distances of up to 3,000 feet (914 meters) behind the dredge.

Results of monitoring of plumes produced by hopper dredge operations in the Chesapeake Bay were reported by Nichols *et al.* (1990). They described two separate plumes: a surface plume produced by overflow discharge, and a near-bottom plume produced by contact of the draghead with the bottom and rapid settling of the surface plume. The surface plume was detected out to a distance of 5,200 meters. Maximum near-field TSS concentrations, defined as within 300 meters of the source, were as high as 7.2 g/l, but decayed exponentially with increasing distance from the source. Detectable plumes persisted for at least 90 minutes following discharge. In terms of release, Nichols *et al.* (1990) estimated that 12 % of the total volume of dredged material was returned to the water column and subsequently re-deposited, but that only 1 % of this amount departed the channel.

Plumes produced by a hopper dredge using overflow practices in the Port of Townsville, Australia, were monitored by Wolanski and Gibbs (1992). Bottom TSS concentrations ranged above 1,000 mg/l immediately following passage of the hopper dredge. They did observe movement of the plume outside of the navigation channel, but did not examine spatial or temporal scales of far field distribution.

Whiteside *et al.* (1995) used aerial photographic surveillance to guide the collection of water samples within overflow plumes of hopper dredges in Hong Kong Harbor as part of a program to support development of models of both the dynamic and passive phases of plume development and decay. They observed well-defined plumes resulting from discharges as a density current which persisted for as long as ten minutes, followed by passive plume decay to background levels over the course of up to three hours. In addition to tidal currents, dispersion of the plumes was driven by air entrained in the discharge and somewhat by propeller wash from the dredge itself.

Overflow plumes from hopper dredges mining sand and aggregate in the United Kingdom were monitored extensively by a joint US/UK investigation. Results have been reported by Hitchcock, Newell and Seiderer (1999). Measurements were able to discern a relatively minor plume associated with interaction of the draghead with the sediment bed, whereas prominent "surface" plumes were produced by overflow practices. Plume dispersion was dependent on the mass of sediment in the overflow, particle size distribution of the sediments, and prevailing water currents. As seen in other plume studies, Hitchcock, Newell and Seiderer (1999) stated that rates of plume decay and settlement were much faster than would have been predicted by Gaussian diffusion models. Plumes generally decayed to background conditions within a few hundred meters of the point of release.

Miller *et al.* (2001, 2002) studied overflow plumes at both coarse and fine-grained sediment sites from the USACE Hopper Dredge *McFarland* in the Delaware Bay and Delaware River respectively. Based on data derived from ADCP acoustic backscatter surveys, OBS sensors, and automated water samplers, they reported that plumes produced during loading of coarse sediments settled rapidly entirely within the navigation channel and decayed to background levels within one hour. At the fine sediment site the plume again rapidly became a bottom feature, with TSS concentrations of several hundred mg/l persisting for at least 30 minutes, but returned to background levels within one hour.

Cheung and Ho (2004) reported that overflow plumes from hopper dredges engaged in sand mining for a large land reclamation project in Hong Kong decayed to background conditions within one km of the borrow area. TSS concentrations within the plume decreased to less than 50 mg/l within 15 minutes of release.

Dickerson *et al.* (2005) described overflow plumes from the U. S. Army Corps of Engineers Hopper Dredge *Yaquina* conducting maintenance dredging in Humboldt Bay, California, using a combination of acoustic and optical measurements. They reported that plumes produced by discharges through the bottom of the hull in a relatively linear reach of the navigation channel descended rapidly through the water column to the channel basin. Passive plumes in the wake of the dredge could be detected out to a distance of 1,500 meters and for up to 25 minutes. Little evidence was seen of plume excursion out of the navigation to adjacent flats. When dredging in a turning basin at the terminus of the navigation channel, plumes did migrate over a portion of the adjacent flats, possibly as a consequence of the dredge's need to turn and maneuver against the side slope. Plumes persisted in the turning basin for approximately 55 minutes, entailing 40 minutes of active loading and up to 15 minutes of decay following departure of the dredge for the placement site. Although acoustic backscatter from the ADCP used was not converted to TSS concentration, turbidities measured with optical backscatter sensors deployed in the dynamic phase of the overflow plumes ranged as high as 150 to 200 NTU in the central core of the plume.

Mechanical Bucket Dredge Plume Characterizations

Bohlen (1978) provided one of the earliest characterizations of bucket dredge plumes. Plumes produced by open bucket operations in the Lower Thames River Estuary, Connecticut, were described by Bohlen to be "relatively small scale features having maximum longstream dimensions of 700 meters." He estimated losses from the buckets to be on the order of 2 to 4% of each bucket cycle, which resulted in plumes of up to 400 mg/l near the bucket with rapid decay with increasing distance downstream. Bohlen observed that settling rates in the plumes significantly exceeded those based on theoretical assumptions of particle size characteristics, and was one of the first to suggest that plume dynamics could be modeled effectively. These results were also reported in Bohlen *et al*. (1979).

Sediment resuspension by open and closed buckets were first compared by Yagi *et al.* (1976). Tests involved eleven bucket cycles for separate treatments involving depth of penetration, hoist speed, and overall cycle time. Based on spillage rates from the two buckets, they concluded that the closed bucket performed better in terms of reduced resuspension.

Sediment resuspension characteristics of a conventional open bucket and a modified "watertight" bucket were compared by Raymond (1983). The "watertight" bucket consisted of a conventional bucket modified with seals and plates to enclose the upper portion of the bucket. Depth averaged TSS concentrations along transects extending radially from the dredge indicated that the modified bucket reduced levels of suspended sediments in the upper portion of the water column.

Vertical profiles of TSS concentration in plumes produced by a bucket dredge in Mamaroneck Harbor, New York, were used by Tavolaro (1984) to calculate the sediment mass released to the water column. TSS concentrations were generally around 63 mg/l except when the dredging rate was accelerated, at which time concentrations ranged as high as 790 mg/l. Plumes were largely confined to the lower half of the water column and decayed to background conditions within 125 meters from the source.

Tavolaro and Mansky (1985) monitored plumes associated with conventional bucket dredging operations near Red Hook and Bay Ridge in Upper NY/NJ Harbor. Near the surface plumes decayed to background levels at between 300 and 480 meters down-current from the dredge, and near the bottom at distances between 280 and 570 meters. Beyond 210 to 300 meters from the dredge TSS concentrations seldom exceeded 20 to 30 mg/l.

McLellan *et al.* (1989) expanded on the results of Raymond (1983). They monitored plumes produced by conventional (i.e. open) bucket dredges at the Calumet River, Illinois, Duwamish Waterway, Washington, Black Rock Harbor, Connecticut, and the St. Johns River, Florida. At the latter site they also monitored a closed bucket for comparison. The closed bucket had a capacity of approximately 15 cubic yards (11.5 cubic meters). Sediments consisted primarily of silts and clays at all four sites. Maximum TSS concentrations produced by the four open buckets were 140, 1,100, 160, and 480 mg/l. All maximum TSS concentrations occurred in bottom samples. Detected plume lengths, although not reported other than in graphs, were generally less than 800 feet (244 meters) in all cases. In the open versus closed bucket comparison, the closed bucket tended to have reduced TSS concentrations in near-surface samples, but higher TSS concentrations in bottom samples.

TLA (1991) monitored plumes produced by bucket dredging operations removing maintenance material in the Delaware River along the Philadelphia, Pennsylvania waterfront. Only minor elevations in TSS concentration of approximately 10 mg/l above ambient were observed as far as 1,500 feet downstream from the dredge. Their results may have reflected difficulties in taking samples within the central portions of the plume.

Burton (1993) provided the results of water quality monitoring of nine separate bucket dredging operations in the Delaware River. Based on statistical comparisons of pre-, during, and post-dredging average turbidity measurements at distances of 500, 1,000, 2,000, and 3,300 feet (or approximately 150, 300, 600 and 1,000 meters, respectively) downstream from the point of dredging, turbidities increased by 7 NTU during dredging. Occasional exceedances of the 150 NTU critical threshold established by the Delaware Basin River Commission for the projects were recorded, to as high as 318 NTU. However, exceedances represented only 13 out of 10,500 measurements. Seven exceedances were associated with one of the nine dredging operations.

Bohlen *et al.* (1996) reported results of monitoring plumes produced by a mechanical dredge using a 19.9 cubic meter open bucket in New Haven Harbor, Connecticut. Plumes tended to remain within the confines of the navigation channel except when the dredge was in the immediate vicinity of the adjacent flats and during peak tidal flows when excursions over adjacent flats did occur. TSS concentration gradients within the plumes dissipated rapidly, generally back to background levels within several hundred meters downstream. Based on acoustic data, they observed that the plumes became progressively more patchy and asymmetric with distance from the source.

Comparisons of sediment releases by a conventional 26 cubic yard open bucket, a 39 cubic yard closed bucket, and a 39 cubic yard Cable Arm© bucket were conducted in Boston Harbor, Massachusetts, by Hayes *et al.* (2000). Results of the study are also given in Welp *et al.* (2001). Continuous turbidity measurements were taken at four depths within 25 feet of the point of dredging, and supplemented by water samples analyzed gravimetrically. The conventional open bucket produced the highest depth averaged turbidities (57 Formazin Turbidity Units [FTUs[1]]) and TSS concentrations (210 mg/l). A maximum TSS concentration of 445 mg/l was measured at the bottom. In contrast, the closed bucket produced a depth-averaged turbidity of 12 FTU and TSS concentration of 210 mg/l, whereas the Cable Arm© bucket produced comparable turbidity value of 31 NTU.

Wang *et al.* (2000, 2002) monitored water quality during evaluation of open and closed buckets for application in a deepening dredging project in Seattle, Washington. Their findings indicated that the closed bucket actually caused a greater number of turbidity criterion exceedances than did the open bucket. However, the test was deemed inconclusive due to variability in operational factors and insufficient spatial resolution of samples.

Clarke *et al.* (2005) characterized plumes associated with mechanical dredging of fine maintenance materials with a 12 cubic yard closed bucket at the Port of Oakland, California. They used an ADCP calibrated to in situ sediments to examine TSS concentration gradients within plumes driven by relatively weak tidal currents. During both ebb and flood conditions plumes rapidly became bottom features not extending beyond 400 m from the dredge. Outside of the dynamic plume zone concentrations above 275 mg/l were found only in immediate proximity to the bucket, and concentrations above 100 mg/l were confined with few exceptions to small parcels of water just above the bottom.

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[1] Note that FTU is similar to NTU in that both measure scattered light at 90 degrees from the incident light beam, but the FTU is measured with an infrared light source whereas the NTU is measured with a white light.

Acoustic determinations of sediment flux from a large (22.9 cubic meters) closed bucket removing maintenance material from the Providence River, Rhode Island were made by Land *et al.* (2007) to estimate loss rates. Acoustic signatures of plumes produced at two locations in the river were detected to distances of 1.1 km from the dredge. Although estimated losses at the bucket locations were relatively high (5.4 and 9.6%), TSS concentrations decayed rapidly, from over 1,000 mg/l at a distance of 29 meters from the bucket, to approximately 300 mg/l at 79 meters, and 100 mg/l at 429 meters. Loss rates were among the highest reported in the literature, which was attributed to extremely high water content of the in situ sediments, bucket leakage, and aggressive bucket cycles.

Plumes produced by a mechanical dredge using a conventional 15 cubic yard open bucket in Maumee Bay, Ohio, were characterized by Reine *et al.* (2007) to assess potential exposures of early life history stages of walleye (*Sander vitreus*), a valuable fishery resource in the Great Lakes region. OBS sensors were deployed to obtain time series turbidity data in combination with ADCP surveys and collection of water samples for gravimetric analysis. Results indicated a very rapid settling of suspended sediments within a short distance from the source, attributable in part to the prevailing slow water currents. TSS concentrations fell from 800 mg/l at the source to less than 300 mg/l within 25 meters from the source, and to 40 mg/l at 115 meters. Only indistinct plume signatures were observed beyond 125 meters from the dredge, at TSS concentrations no more than 5 to 10 mg/l above background. Turbidities reached 700 NTU at a distance of 15 meters from the bucket and 300 NTU at 46 meters. No evidence was seen of plume excursion over the adjacent shoals, which represented walleye spawning habitat.

Mechanical Backhoe Dredge Characterizations

Science Applications International Corporation (SAIC 2002) used several methods to monitor suspended sediment plumes produced by two backhoe (excavator) dredges operating in the Kill van Kull waterway in NY/NJ Harbor. Methods included both towed and moored OBS and conductivity-temperature-depth sensors, water samples for gravimetric analysis, current drogues, and ADCP surveys. Plumes were more prominent in the lower portion of the water column, assumed to be the consequence of backhoe disturbance of the sediment bed. Plumes were detected along the bottom as far as 1,500 meters downstream from the dredges. The peak measured turbidity was 140 FTU at a distance of 100 meters downstream. The peak measured TSS concentration, also at 100 meters downstream, was 57 mg/l.

Plumes Associated with Other Dredging Scenarios

Findings of several studies of suspended sediment plumes produced by less traditional modes of dredging are consistent with those of studies described above.

Hydraulic shell dredging operations have been the subject of numerous studies spanning decades (e.g., Wilson 1950, Engle 1962, May 1973, and others), including specific interest in turbidity and suspended sediment plumes. Several studies reported very high TSS concentrations at the location where shell rinse water was returned to the receiving body of water. For example, Wilson (1950) measured concentrations as high as 58 g/l in Copano Bay, Texas, although these measurements may have been taken in fluid mud accumulations below the discharge. Plumes generally extended out to 900 feet from the dredge and as far as 1,800 feet on occasion. For similar shell dredging operations in Mobile Bay, Alabama, May (1973) reported that ambient TSS concentrations were exceeded out to a distance of 2,000 feet from the dredge at mid-depth, and 2,800 feet on the bottom. May (1973) noted that plumes generally increased in spatial extent on windy days, as turbulence delayed settling.

For dredging operations that involved barge overflow at the Port of NY/NJ Passenger Ship Terminal, Tavolaro (1984) described plumes that had average water column TSS concentrations of 89 mg/l, but which ranged above 800 mg/l near the source.

Palermo *et al.* (1990) monitored plumes produced by an 18 cubic yard open bucket filling a barge while allowing overflow into the Cape Fear River, North Carolina. The primary objective was to examine economic loading of the barges, but plumes were measured using a combination of visual and turbidity and TSS samples. Dredging-induced plumes averaged 6.2 NTU above background levels, whereas overflow plumes averaged 21.6 NTU above background. TSS samples in the dredge plume averaged 47 mg/l above background levels, whereas overflow plumes averaged 65 mg/l above background. These results were also reported by Payonk *et al.* 1988, 1989).

Reine *et al.* (2002) characterized plumes produced by overflow from barges filled by a hydraulic pipeline cutterhead dredge in the Cape Fear River, North Carolina. Near the source TSS concentrations ranged as high as 191 mg/l. At a distance of 300 meters downstream the maximum measured TSS concentration was 80 mg/l. ADCP surveys of the plume indicated that the plume became primarily a bottom feature within 300 meters of the barge. One of the objectives of the monitoring was determination of the plumes trajectory in relation to fish spawning habitat outside of the navigation channel. No evidence was seen of plumes leaving the boundaries of the channel.

Battisto and Friedrichs (2003) used both calibrated ADCP and OBS data to characterize plumes produced by an oyster shell excavator dredge in the James River, Virginia. Plumes were produced by removal of shell and sediment from the bed and washing of the dredged shell aboard the receiving barge. Plumes were relatively narrow, bottom-oriented features that under strong prevailing tidal currents extended an estimated 4 km downstream. TSS concentrations beyond 100 to 400 meters from the source generally fell to less than 30 mg/l above ambient.

A process which entails dragging a large bar across the bottom is frequently used to level high spots during the final stages of dredging projects or as an alternative to conventional dredging if the shoals to be dredged can be displaced into deeper waters. This process is known as bed leveling or knockdown, among other terms (e.g. bar dragging). Plumes generated by knockdown operations at Redwood City, California were investigated by Clarke *et al.* (2006). Plumes varied greatly temporally as the tug pulling the bar moved between deposits along the toe of the navigation channel. Based on calibrated ADCP surveys, knockdown plumes were narrow, bottom-oriented features with maximum TSS concentrations of approximately 600 mg/l that decayed to les than 100 mg/l within 7 to 9 minutes. Turbidities measured by drifting through the plumes with OBS sensors deployed at several depths determined that near-bottom turbidities spiked for short duration at up to 210 NTU, but remained below 50 NTU in the upper half of the water column.

USACE (2009a) describes the results of TSS monitoring during the construction of a confinement berm and the placement of clean fill from Port Jersey Federal Navigation Channel as part of a habitat enhancement project near the Military Ocean Terminal Bayonne (MOTBY). During the placement of the beneficial use material, the plume's visibility functioned in approximately the same time scale as it took the scow to unload and move offsite. Plumes that were noted were never expansive and tug boat activity was observed to enhance the localized plume. Overall, there were no instances of elevated TSS concentrations (measured in the laboratory) migrating beyond 500 feet from the placement zone. The study also concluded that TSS concentrations around the enhancement site were directly influenced by many factors including: mechanical disturbances, meteorological and seasonal events, tidal energy, and density gradients.

Conclusions

As a consequence of the multiple plume far-field surveys conducted during the deepening of NY/NJ Harbor, plume dynamics within this estuarine system are as well understood as anywhere in the nation. Cumulatively, these plume characterizations yield an extensive, detailed knowledge base of plume structure and spatial and temporal dimensions that can be applied to future dredging project management decisions.

In most dredging scenarios monitored within the Harbor, plumes were shown to decay rapidly in terms of TSS concentrations within relatively short distances down-current from the dredge. Likewise, the plumes in most cases descended in the water column to form bottom-oriented features. These findings were consistent for the variety of bucket dredging scenarios involved, as well as for the specialized cutterhead operations engaged in fracturing rocky substrate. Importantly, a consistent pattern was shown in which plumes were entrained into tidal flows within the basins of the navigation channels such that delivery of resuspended sediment to shallow flat habitats having fishery resource support functions in the Harbor was extremely unlikely to occur.

This latter point is significant in the context of the 2001 conservation recommendations issued by the National Marine Fisheries Service (NMFS) regarding potential impacts of the HDP on federally managed essential fish habitat (EFH) species and other regional species of concern. Specifically, the conservation recommendations identified the re-deposition of sediment suspended during dredging as a concern for potential impacts on aquatic communities and EFH species, in particular winter flounder. This included short-term and indirect impacts such as potential burial and smothering of early life stages. Based on the results of the TSS/WQ studies, a general conclusion that plumes do not deliver sediment in quantities sufficient to affect shallow water habitats adjacent to channels would be defensible in all but a very small number of potential dredging scenarios depending on existing hydrodynamic, bathymetric and sediment characteristic conditions.

NY/NJ Harbor, as one of the busiest harbors in the nation, undergoes continuous exposure to sources of sediment resuspension other than dredging. Periodically the passage of storms and the occurrence of freshets and high riverine discharges lead to elevated TSS concentrations throughout the harbor complex. As has been documented by extensive studies in the harbor and elsewhere, deep-draft vessel traffic is a significant source of sediment resuspension throughout the network of navigation channels on a daily basis. TSS concentrations typical of dredging-induced plumes fall within the range regularly produced within the Harbor by the transit and maneuvering of large container ships, bulk carriers, and other vessels (Clarke *et al.* 2015) and from natural occurring storm events (Bohlen 1980, Sosnowski 1984, Tramontano and Bohlen 1984).

In all respects, the plume characterizations collected during the HDP were consistent with knowledge in the expanding scientific literature pertaining to suspended sediment plumes of both natural and anthropogenic origin. Collectively, examinations of these sources of relevant characterizations can provide a basis for more refined assessments of potential impacts of dredging operations on a project site-specific basis, or be extrapolated, as justified, to make reliable determinations of risk to resources from dredging operations. For example, if dredging were necessary during a period that coincided with migrations of anadromous fishes through the narrow harbor complex features, characterizations of plume structure could be referred to in order to assess the availability of an adequate corridor for fish migration outside the plume to bypass the dredge. The ADCP-based cross-sectional profiles of plumes provide detailed information on the vertical and lateral extent of plumes that would be encountered in a given channel reach and could be extrapolated to anticipate any potential impacts or assessment of future work in that reach.

The implications for future improvement/deepening or maintenance dredging programs in the deepened NY/NJ Harbor in terms of assessing potential impacts on species of concern, including winter flounder and migratory species, are clear. An adaptive management application of the expansive scientific dataset collected as part of the HDP, in conjunction with a better understanding of EFH functions of habitats in the harbor, should be undertaken to revise existing seasonal dredging restrictions (see also USACE 2010b). In this manner more effective and efficient regulation of dredging activities while adhering to a risk-averse approach to protecting fisheries resources can be achieved. Seasonal dredging constraints based on the 2001 conservation recommendations for the HDP have had adverse cost, schedule, navigation safety, environmental, and construction efficiency implications and could similarly affect future required maintenance or deepening operations. The integration of knowledge gained from both the water quality/TSS monitoring program and the biological surveys can be used to support improved, science-based management practices applied to dredging and other activities in the NY/NJ Harbor, and possibly be used to support similar Federal actions in other similar harbor or bight ecosystems. Early attempts to establish a risk-based approach for evaluating the need for and selection of dredging project management practices (e.g., LaSalle *et al.* 1991) encouraged the application of site-specific data in tandem with knowledge of the dredging process. The feasibility of applying risk-based frameworks has been examined recently by Suedel *et al.* (2008). Sufficient plume exposure data are now available to better assess the degrees of risk posed by various dredging scenarios. Basing dredging impact assessments on factual information rather than perceptions of plume dynamics can lead to better informed dredging management decisions while protecting and sustaining fishery resources. Toward this end the results of the TSS/WQ component of the HDP represent a valuable contribution.

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Tables

Table 1. Summary of Suspended Sediment Plume Surveys Associated with HDP and Maintenance Dredging Contract Areas.

HDP Contract Area	Survey Date	Dredge Monitored	Final Report
Arthur Kill 2/3	June 2006	Dredge *Michigan* with 18-CY environmental cable arm bucket (Donjon Marine Company, Inc.)	USACE 2007
S-NB-1 (Survey #1) Acceptance Area B-3 Newark Bay	February 2008	Dredge #53 with 26-CY environmental cable arm bucket (Great Lakes Dredge & Dock Company)	USACE 2008
S-NB-1 (Survey #2): Acceptance Area B-1 Newark Bay	November 2008	Dredge #55 with 26-CY environmental cable arm bucket (Great Lakes Dredge & Dock Company)	USACE 2009b
S-E-1 (Survey #1 & 2): Eastern End Port Elizabeth Channel	March 2009 & April 2009	Dredge *Delaware Bay* with 8-CY environmental cable arm bucket (Donjon Marine Company, Inc.)	USACE 2010a
S-KVK-1: Acceptance Area A Kill Van Kull	June 2009	Dredge *Illinois* with 8.7-ft diameter cutterhead (Great Lakes Dredge & Dock Company)	USACE 2013a
S-AN-2 Acceptance Area 4 Anchorage Channel	January 2011	Dredge *Michigan* with 8-CY environmental cable arm bucket (Donjon Marine Company, Inc.)	USACE 2011
S-KVK-1: Acceptance Area H Kill Van Kull	March 2011	Dredge *Florida* with 11-ft diameter cutterhead(Great Lakes Dredge & Dock Company)	USACE 2012
S-NB-2 (Survey #1 & 2): Acceptance Area 1 South Elizabeth Channel	July 2011 & October 2011	Dredge *Delaware Bay* with 8-CY environmental cable arm bucket (Donjon Marine Company, Inc.)	USACE 2013b
S-AK-2 (Survey #1 & 2): Acceptance Area F Arthur Kill Channel	March 2012	Dredge *Delaware Bay* with 15-CY environmental cable arm bucket (Donjon Marine Company, Inc.)	USACE 2013c
S-AK-3 (Survey #1 & 2): Acceptance Area B & C Arthur Kill Channel	November 2013	*Dredge 54* with 30-CY environmental Cable Arm bucket (Great Lakes Dredge & Dock Company)	USACE 2014b
Jones Inlet Federal Deposition Basin 1 & 2 Navigation Channel	January 2014	Dredge *CR MCCaskill* with 34-inch intake suction diameter cutter (Weeks Marine)	USACE 2014a

Table 2. Summary of Suspended Sediment Plume Survey Results for HDP and Maintenance Dredging Contract Areas.

Survey	Months	Date	Tide	Distance From Source(m)	Plume Width (m)	Highest ADCP TSS (mg/L) value within plume	Ambient ADCP TSS (mg/L)	Average TSS Ambient Water Samples (mg/l)	Average TSS Plume Water Samples (mg/l)	Highest TSS Plume Water Sample (mg/l)	Dredge Field Grain Size (%Gravel/%Sand/%Silt/%Clay)	Comments
AK 2/3	Jun-06	6/19/2006	Ebb(NJEA)	25	70	>90	10	Water samples not divided into plume/ambient			No sediment sample collected	
			Ebb(NJEB)	63	55	50	10					
		6/20/2006	Flood(NJFD)	100	55	120	10					
		6/22/2006	Flood(NJAB)	28	70	40	10					
S-NB-1 (1)	Feb-08	2/2/2008	Ebb	36	110	300	29	Water samples not divided into plume/ambient			0 / 7.94 / 52.64 / 39.42*	Collected 1/31/08
		2/14/2008	Flood	5	65	150	29					
S-NB-1 (2)	Nov-08	11/18/2008	Flood (Early)	130	60	200-300	22	17.9	63	234	0 / 3.5 / 62.5 / 34	
			Flood (Late)	100	70	>300	22					
		11/19/2008	Ebb	30	120	200-300	22				0 / 3 / 62 / 35	
S-E-1 (1)	Apr-09	3/31/2009	Ebb	34	180	150-200	24	16.7	79.3	421	0 / 5 / 63 / 32	
		4/1/2009	Ebb	32	250	90-100	24				0 / 3 / 59 / 38	
			Flood	51	110	100-150	24					
		4/2/2009	Flood	45	100	100-150	24				0 / 4 / 55 / 41	
S-E-1 (2)		4/27/2009	Ebb	90	225	300-500	37	24	92	628	0 / 3 / 53 / 44	
		4/28/2009	Ebb(1)	57	80	>500	37				0 / 4 / 51 / 45	
			Ebb(2)	80	60	>500	37					
			Flood	68	40	80-90	37					
		4/29/2009	Flood	77	90	300-500	37				0 / 7 / 62 / 31	
S-KVK-1 (Dredge Illinois)	Jun-09	6/19/2009	Flood	78	150	>600	50	17.9	143.2	564	46.4 / 39.9 / 13.7**	Collected 6/15/09, Silt and Clay combined
		6/22/2009	Ebb (1)	168	150	400-600	50					
			Ebb (2)	162	260	>600	50					
			Flood	111	100	400-600	50					
S-AN-2	Jan-11	1/4/2011	Ebb	125	75	>500	30	91.5	89.9	164	0.5 / 33 / 56.6 / 9.9	
		1/5/2011	Flood	80	75	100-150	30				3.5 / 74.3 / 16.6 / 5.6	
		1/6/2011	Ebb	109	75	90-100	30				0.1 / 49.2 / 42.1 / 8.6	
		1/6/2011	Flood	35	60	70-80	30					
S-KVK-1 (Dredge Florida)	Mar-11	3/23/2011	Flood	172	150	160-180	65	48.7	65.2	169	0 / 75.1 / 17.5 / 7.4	
S-NB-2 (1)	Jul-11	7/25/2011	Flood	90	80	250-300	40	45.1	65.7	139	0 / 47.5 / 37 / 15.5	
		7/26/2011	Flood	102	110	200-250	40				20.5 / 18.7 / 37.6 / 23.2	
		7/27/2011	Ebb	113	110	250-300	40				0 / 4.1 / 68.4 / 27.9	
		7/29/2011	Ebb	81	100	100-120	40				0 / 4.1 / 77.9 / 18	
S-NB-2 (2)	Oct-11	10/4/2011	Flood	87	160	70-80	40	29.3	49.4	103	0 / 4.4 / 74.6 / 21	
		10/6/2011	Ebb	46	100	250-300	40				2.4 / 46.1 / 43.5 / 8.1	
		10/7/2011	Ebb	48	170	250-300	40				0 / 42.3 / 46 / 11.7	
S-AK-2 (1)	Mar-12	3/10/2012	Flood(1)	98	70	300-400	30	29.6	63.9	158	0 / 4.5 / 80.4 / 15.1	
			Flood(2)	117	60	300-400	30					
		3/12/2012	Ebb	94	60	200-250	30				0 / 3.7 / 81.8 / 14.5	
		3/13/2012	Flood	141	60	100-150	30				0 / 8.4 / 79.5 / 12.1	
S-AK-2 (2)		3/14/2012	Flood	74	70	300-400	30	31.65	132.9	337	0 / 4.7 / 81.8 / 13.5	
		3/15/2012	Flood	93	50	300-400	30				0 / 6.7 / 78.7 / 14.6	
		3/16/2012	Ebb	142	75	500-700	30				0 / 4.4 / 75 / 20.6	
		3/19/2011	Ebb	118	80	250-300	30				0.4 / 7.7 / 76.5 / 15.4	
S-AK-3 (1)	Nov-13	11/18/2013	Flood	122	100	50-75	25	14.7	69.9	525	0.4 / 12.4 / 74.3 / 12.9	
			Ebb	59	40	150-175	25					
		11/19/2013	Ebb	85	105	250-300	25				0 / 13.3 / 67.8 / 18.9	
		11/20/2013	Flood	125	50	175-200	25				0 / 19.2 / 56.8 / 24	
S-AK-3 (2)		11/25/2013	Ebb	80	60	200-250	25	12.8	116.7	328	0 / 15.1 / 62.6 / 22.3	
			Flood	26	60	>300	25					
Jones Inlet	Jan-14 to Feb-14	1/27/2014	Ebb	200	120	116-120 (dB)	96 (db)	21.9	27.8	48.3	0 / 98.1 / 1 / 1	
		2/11/2014	Flood	20	175	116-120 (dB)	96 (db)				No sediment sample collected	

Figures

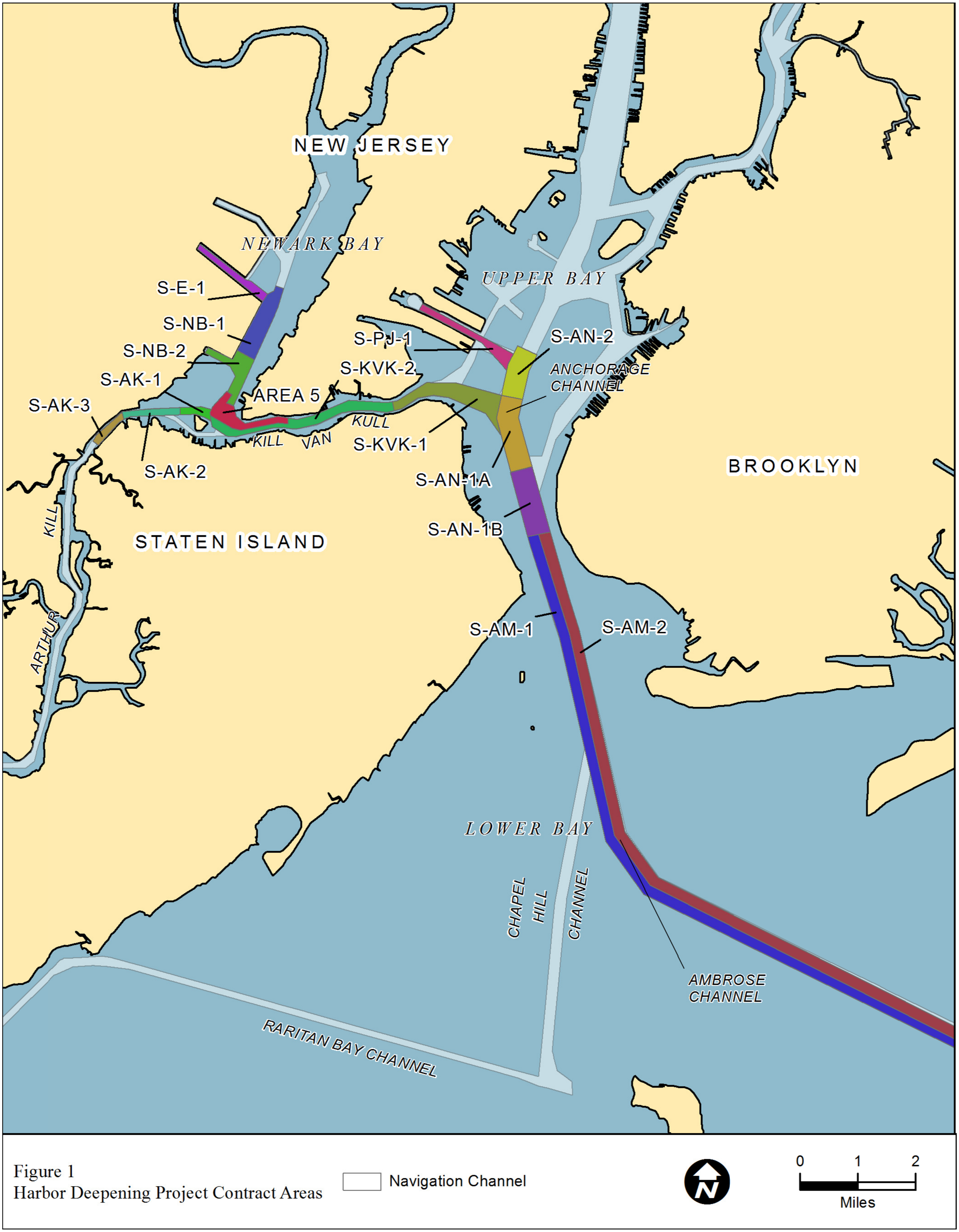


Figure 1
Harbor Deepening Project Contract Areas

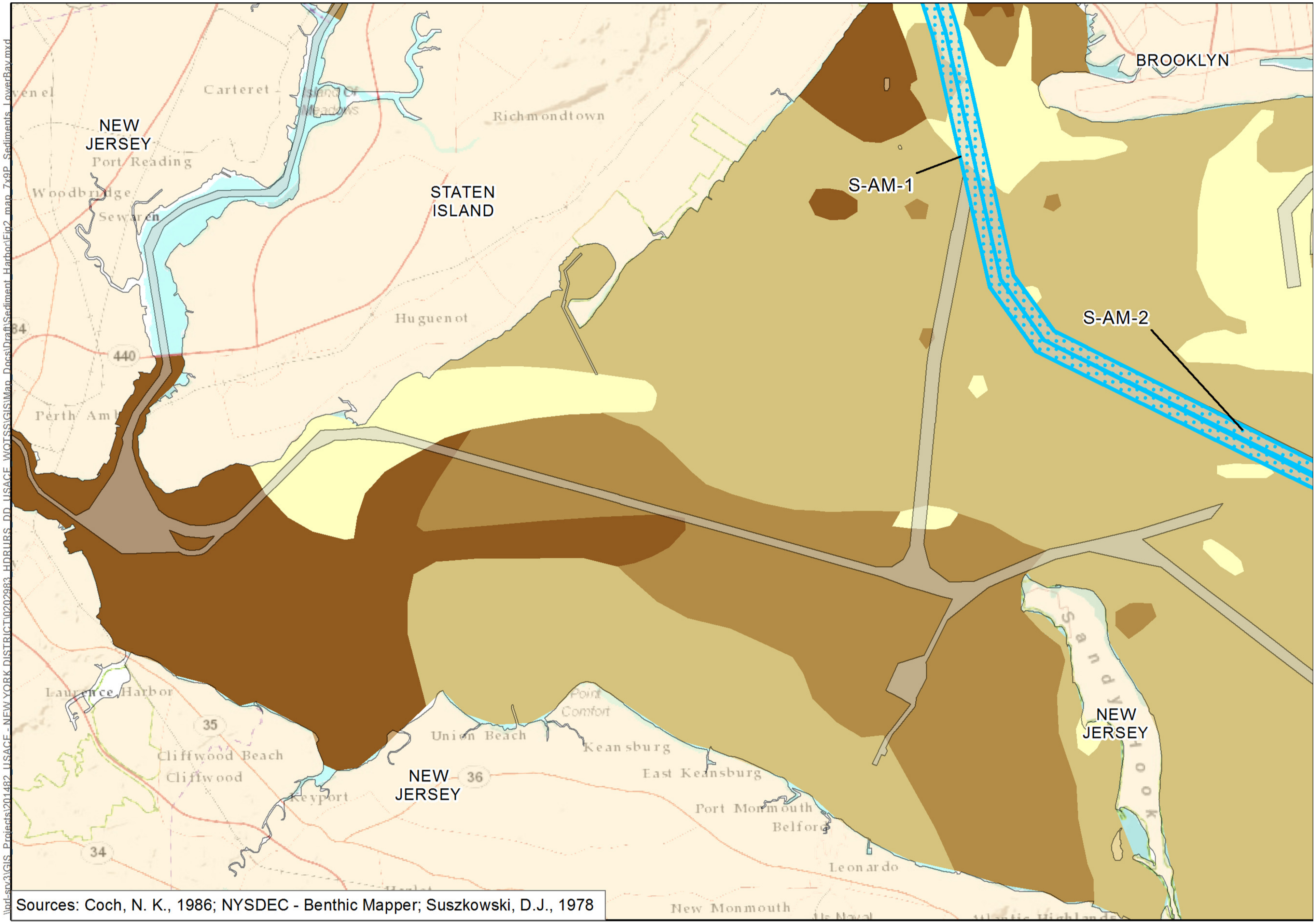


Figure 2 - Lower Bay
Major Sediment Classification Types with
Harbor Deepening Contract Areas

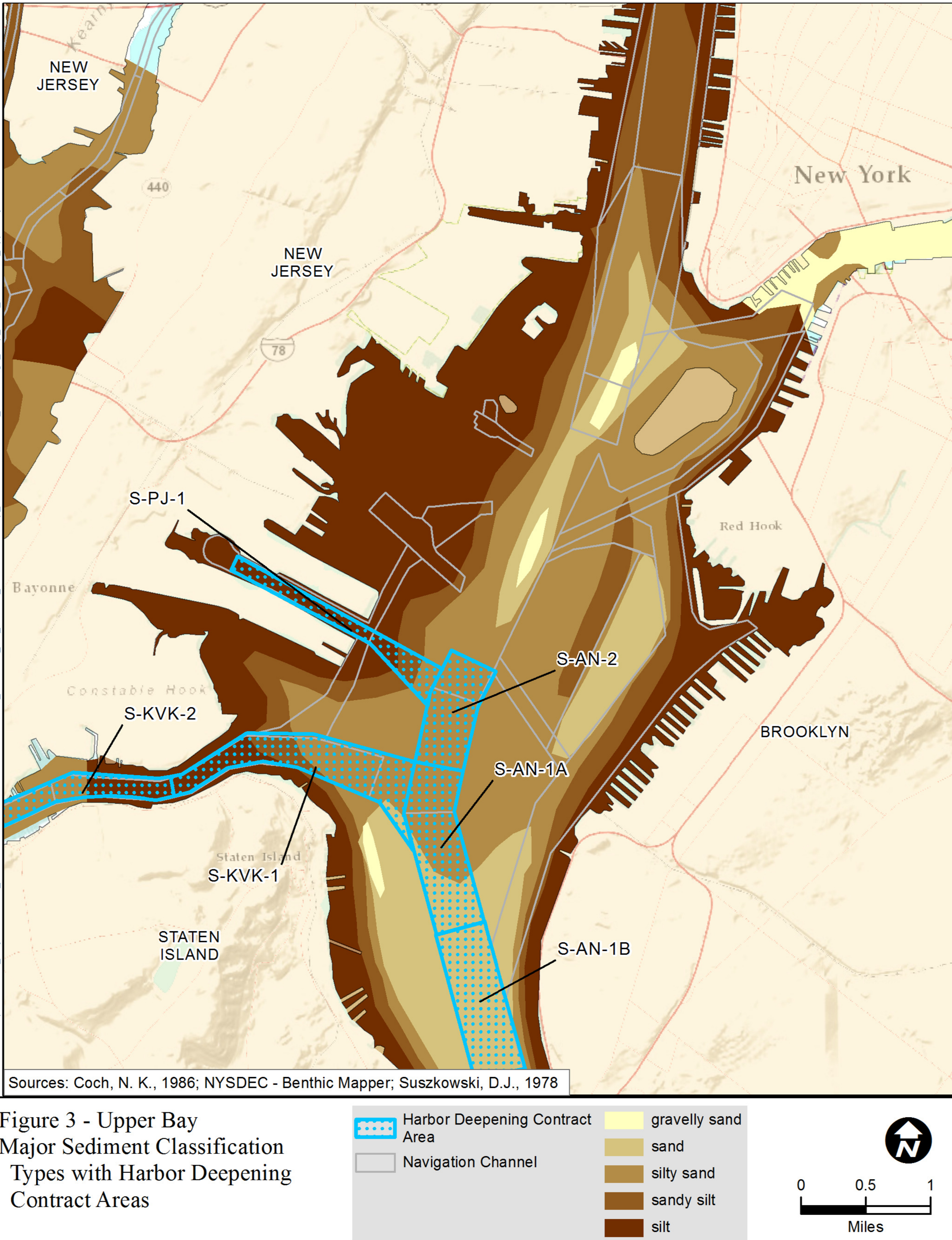


Figure 3 - Upper Bay
Major Sediment Classification Types with Harbor Deepening Contract Areas

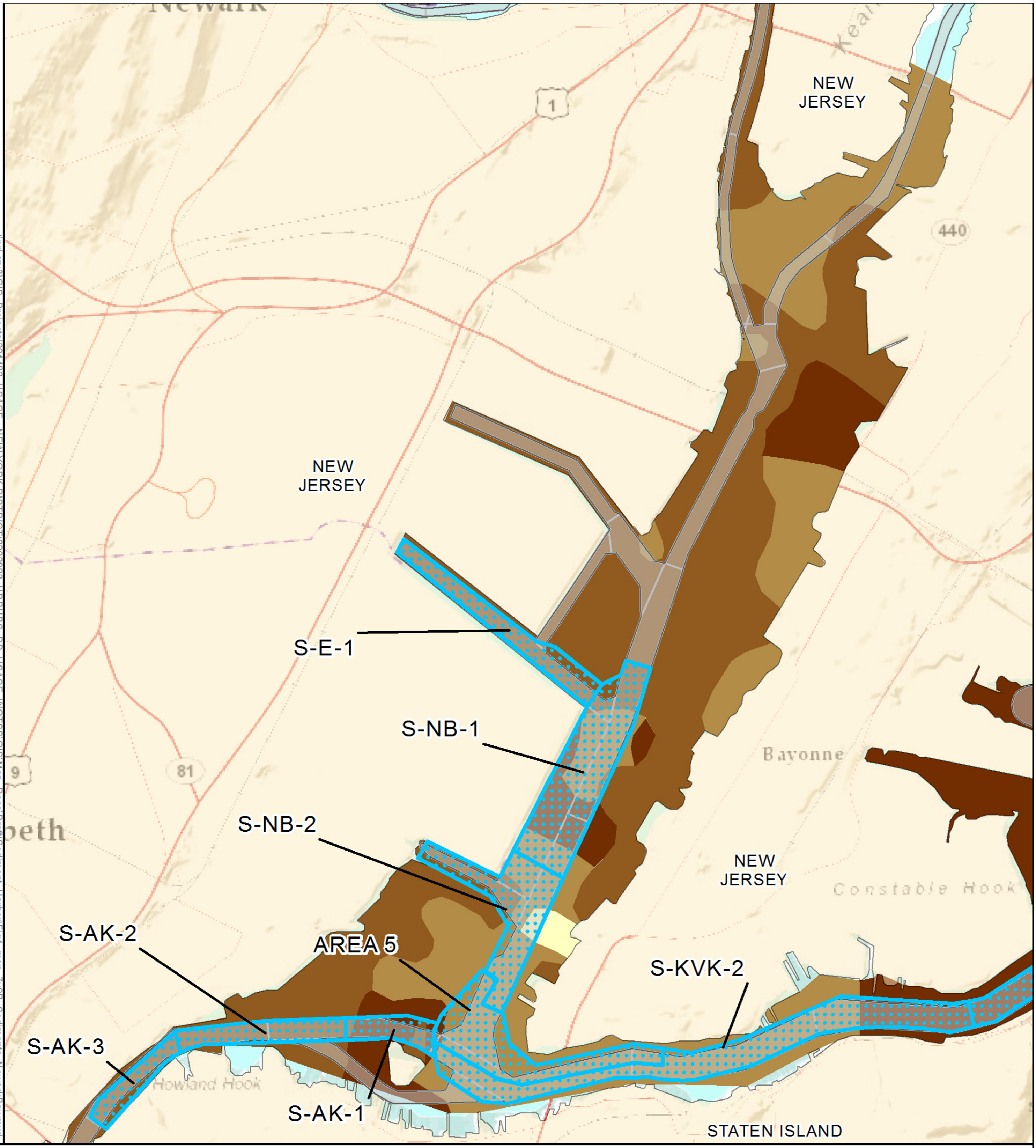


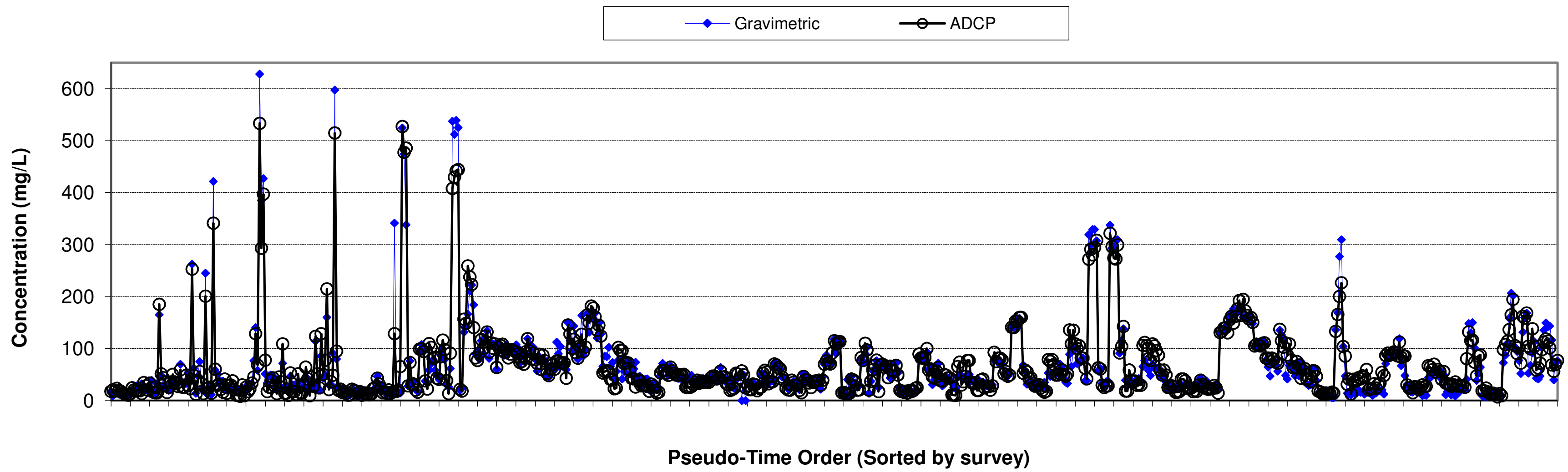
Figure 4 - Newark Bay/Arthur Kill Major Sediment Classification Types with Harbor Deepening Contract Areas

Sources: Coch, N. K, 1986.; NYSDEC - Benthic Mapper; Suszkowski, D.J., 1978

- Harbor Deepening Contract Area
- Navigation Channel
- gravelly sand
- sand
- silty sand
- sandy silt
- silt

0 0.5 1
Miles

a)



b)

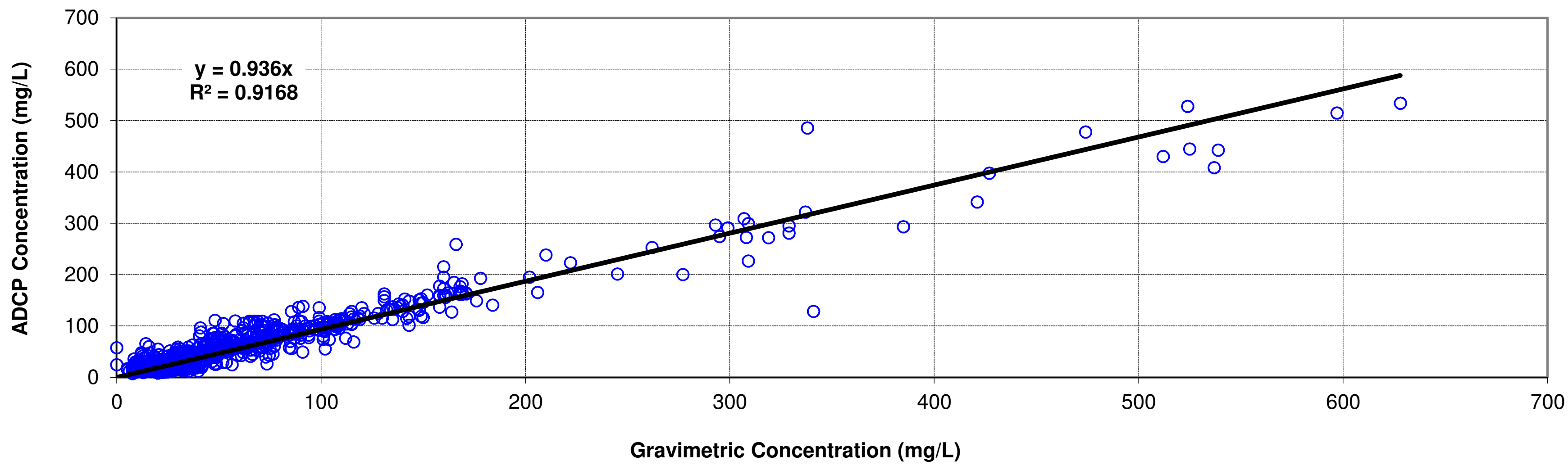
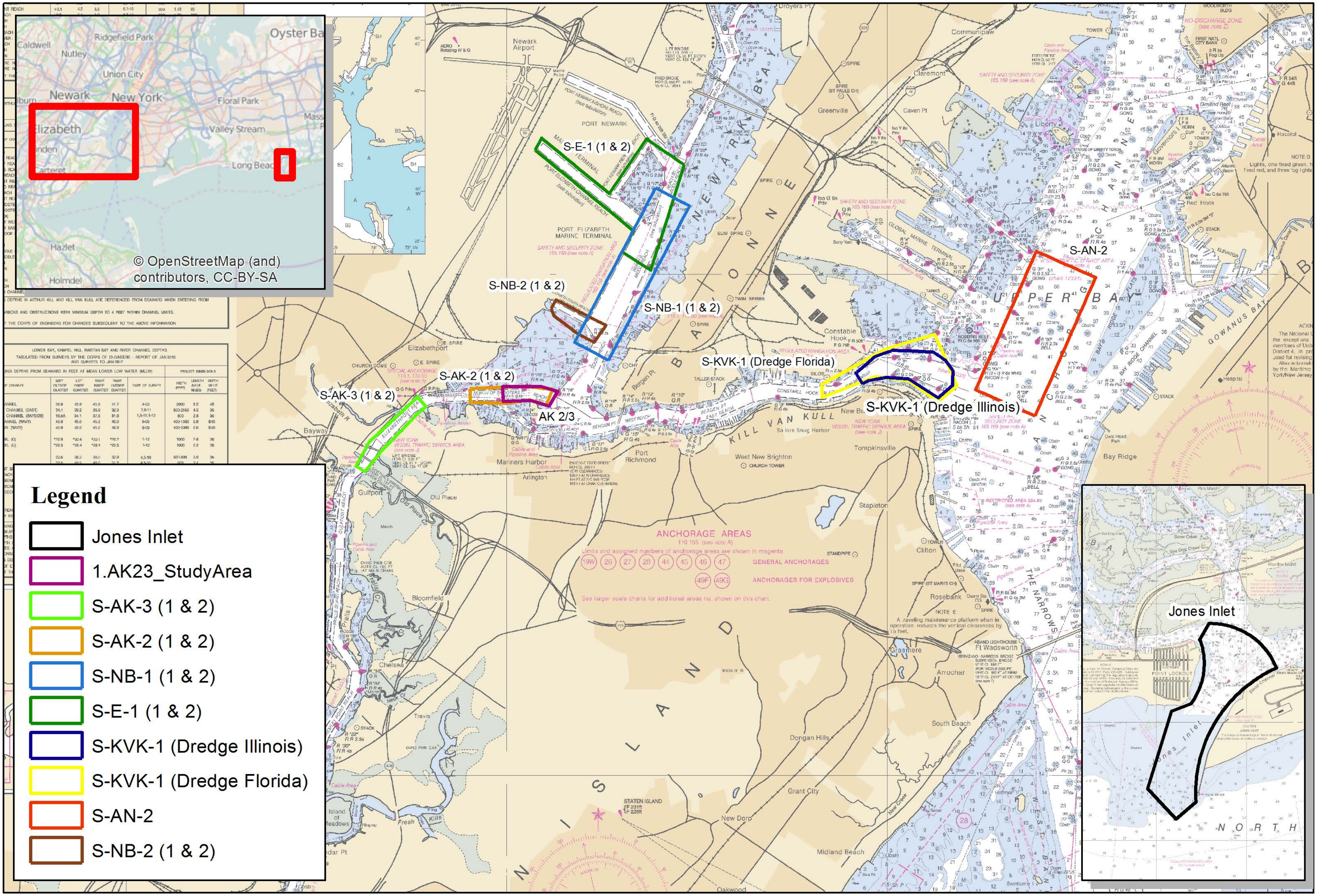


Figure		
5	*USACE Harborwide TSS Far Field Survey*	**Comparison of gravimetric and ADCP estimates of TSS concentration** **a) Concentration vs. Time b) ADCP Concentration vs. Gravimetric Concentration**

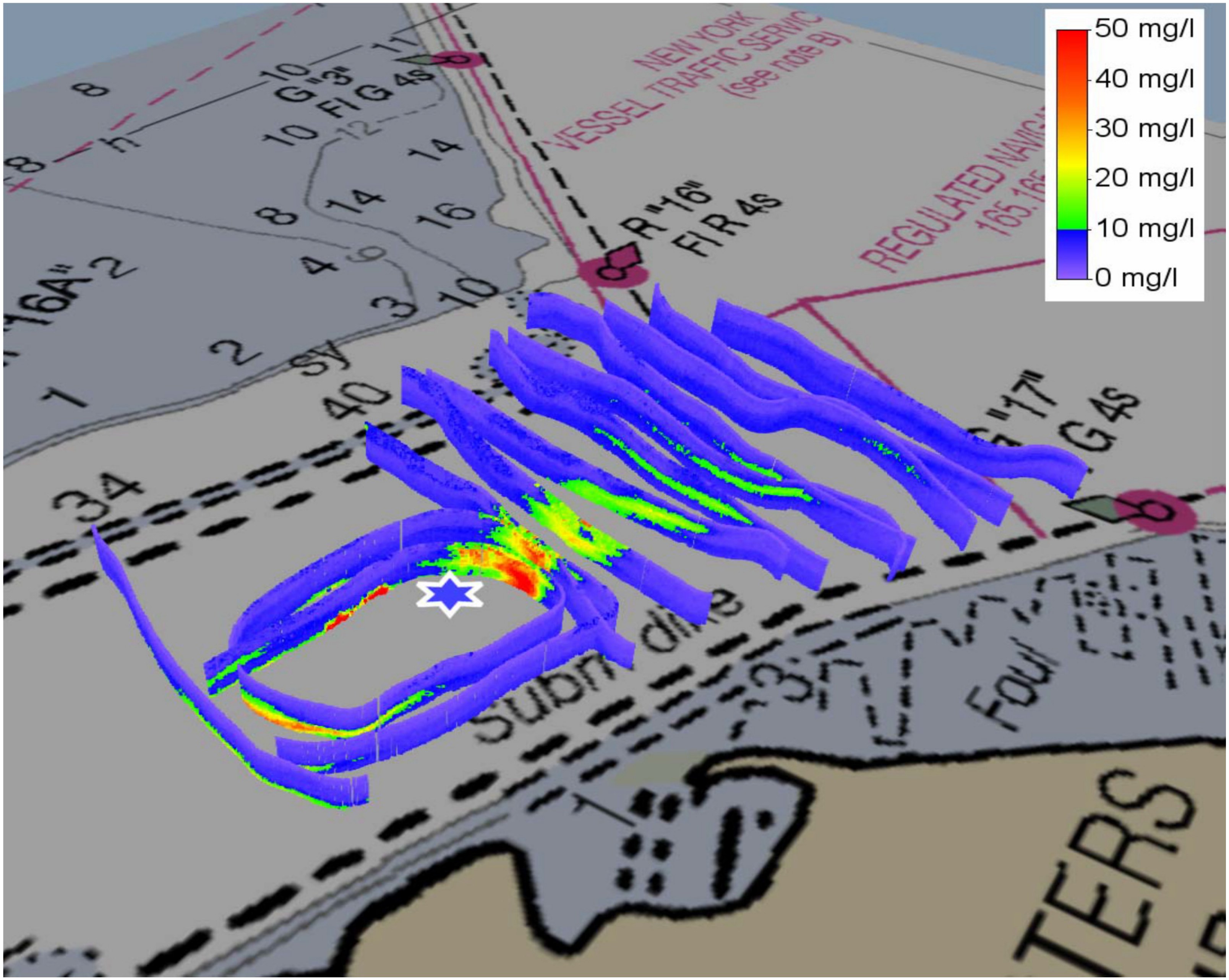


United States Army Corp of Engineers

Figure 6: New York Harbor and Jones Inlet TSS Study Areas

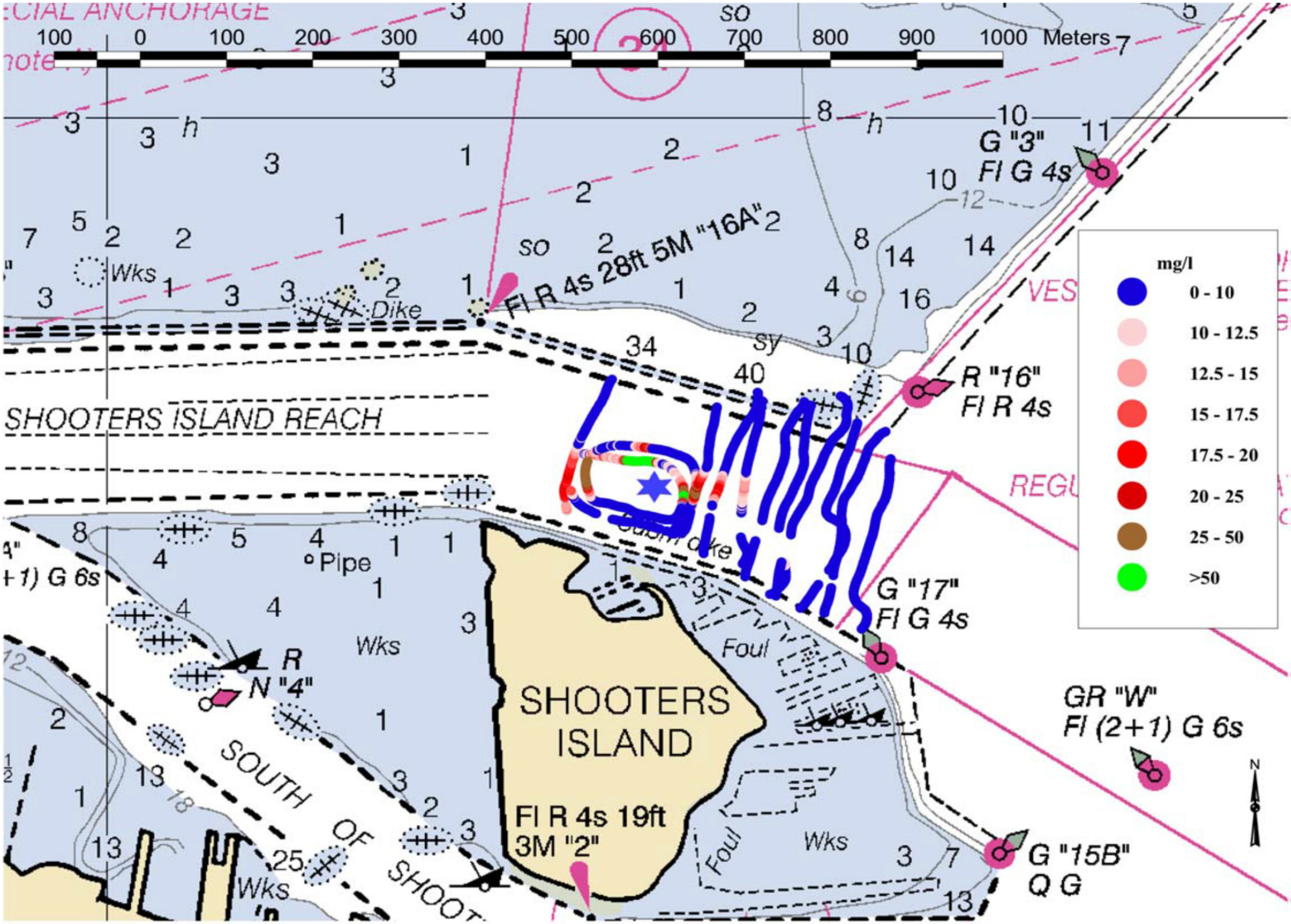
0 1 2 4 6 8 Miles

N



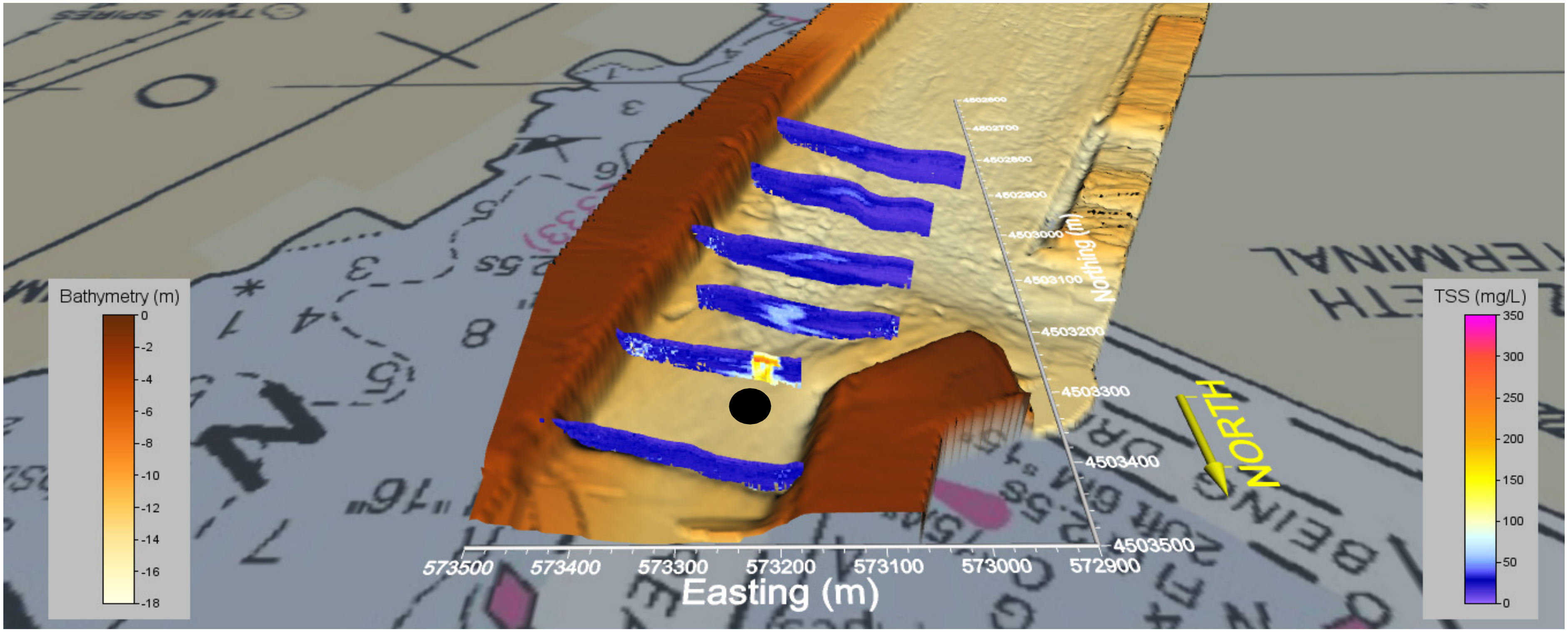
Dredge position indicated by star

Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: Arthur Kill 2/3	ADCP Average TSS Values with Respect to their x, y, and z Coordinates 19 June 2006	Tide
7			Flood



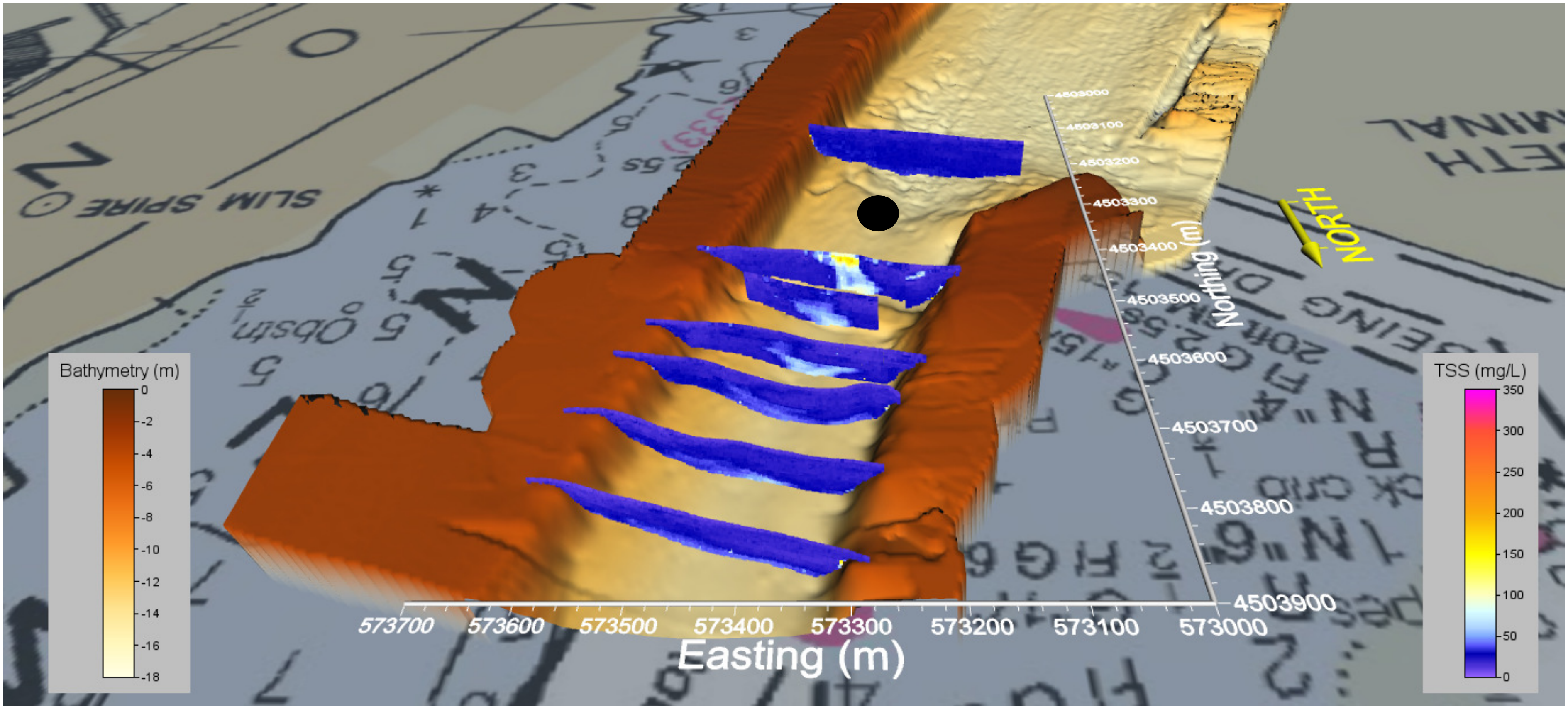
Dredge position indicated by star

Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: Arthur Kill 2/3	Plan view of detected plume spatial coverage and TSS concentrations at a depth of 12m 19 June 2006	Tide
8			Flood



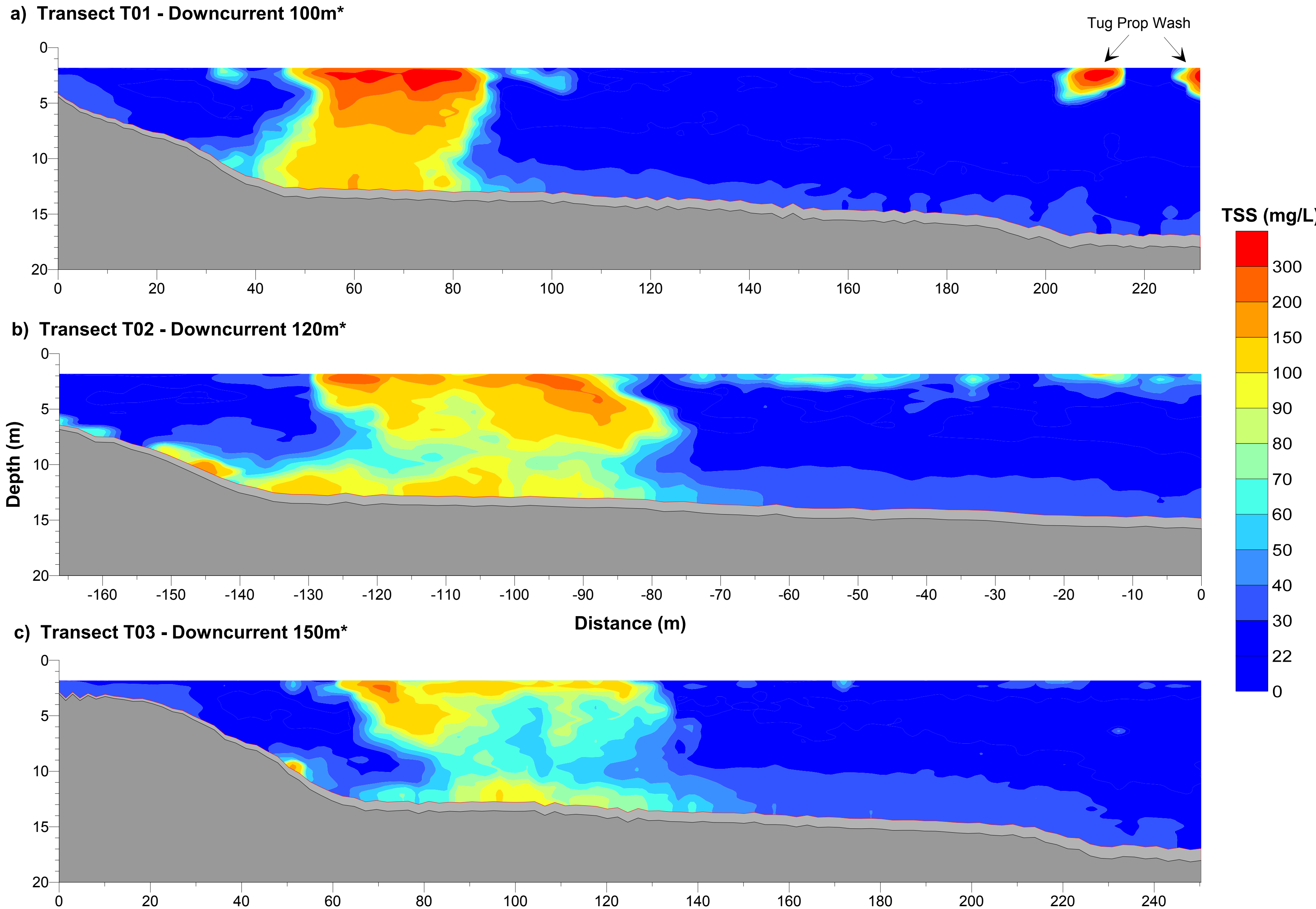
Dredge position indicated by black dot

Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-NB-1	ADCP Average TSS Values with Respect to their x, y, and z Coordinates Superimposed on Channel Bathymetry 02 February 2008	Tide
9			Ebb



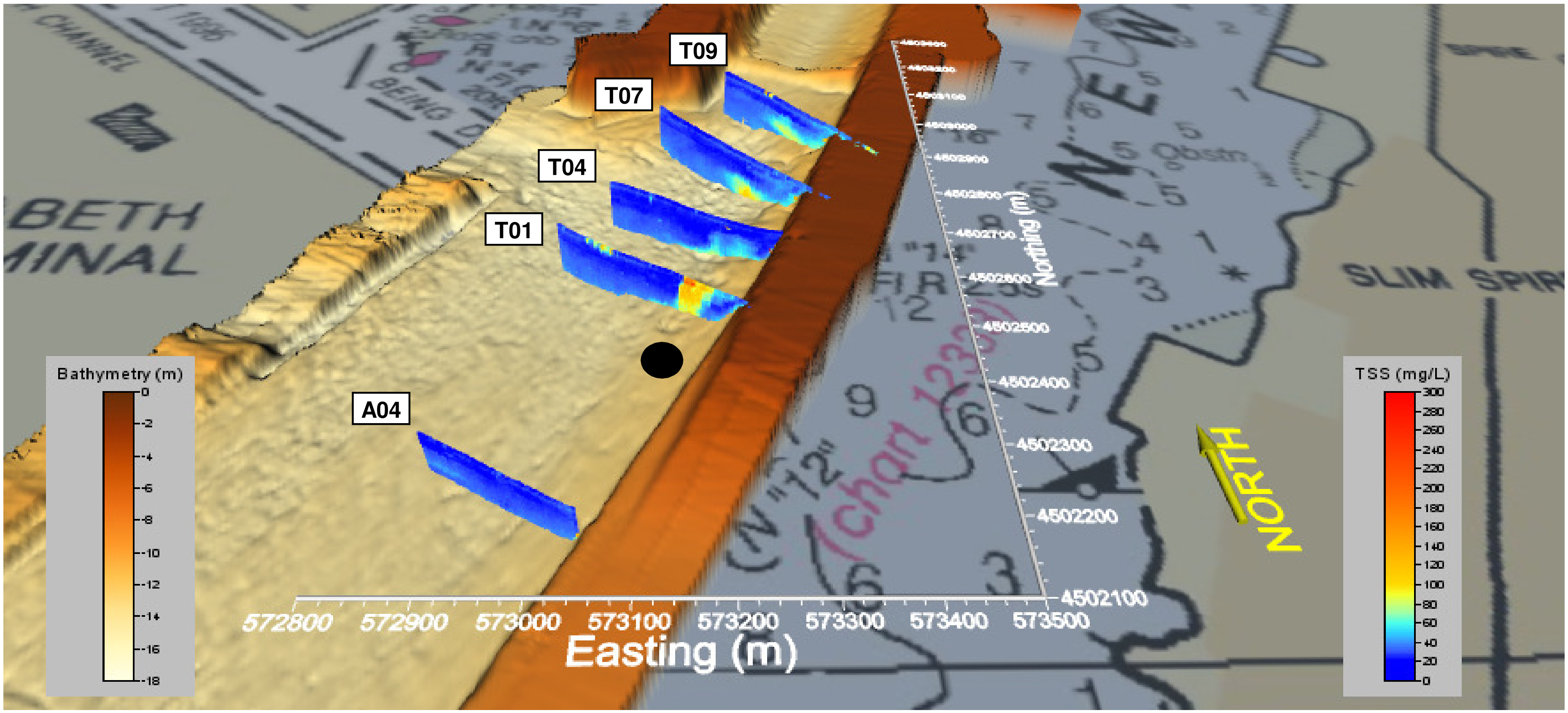
Dredge position indicated by black dot

Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-NB-1	ADCP Average TSS Values with Respect to their x, y, and z Coordinates Superimposed on Channel Bathymetry 14 February 2008	Tide
10			Flood



*Approximate distance from source

FIGURE	*USACE Harborwide TSS*	Vertical Profiles of ADCP Average TSS	TIDE
11a-c	*Far Field Survey* *HDP Contract Area: S-NB-1: B1*	18 November 2008 - Flood Tide, Transects T01, T02, T03	Late Flood

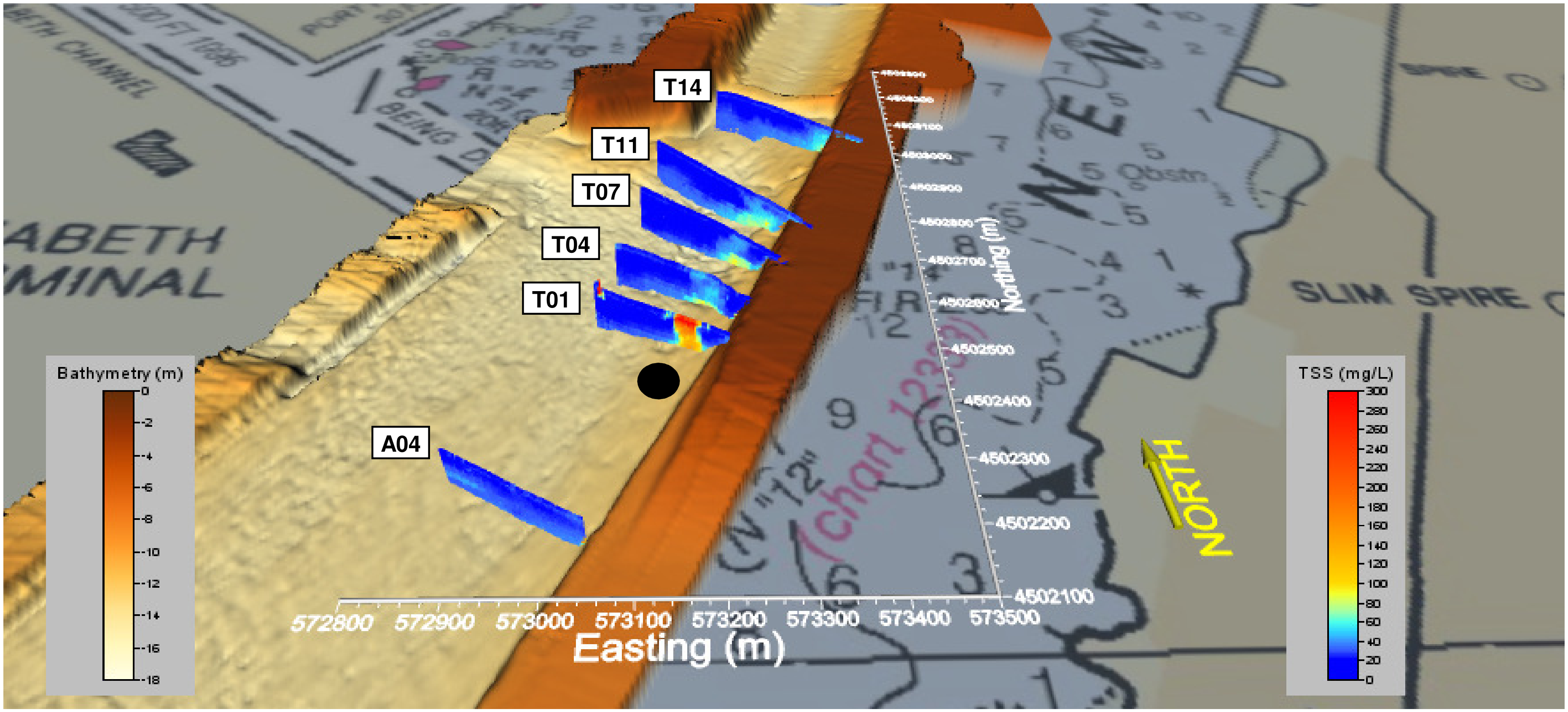


Bathymetry provided by: US Army Corps of Engineers, NY District

Z Scale Exaggerated 6x

= Dredge Location

Figure	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-NB-1: B1*	**ADCP Average TSS Values with Respect to their x, y, and z Coordinates** **Superimposed on Channel Bathymetry** **18 November 2008**	**Tide**
12			**Early Flood**

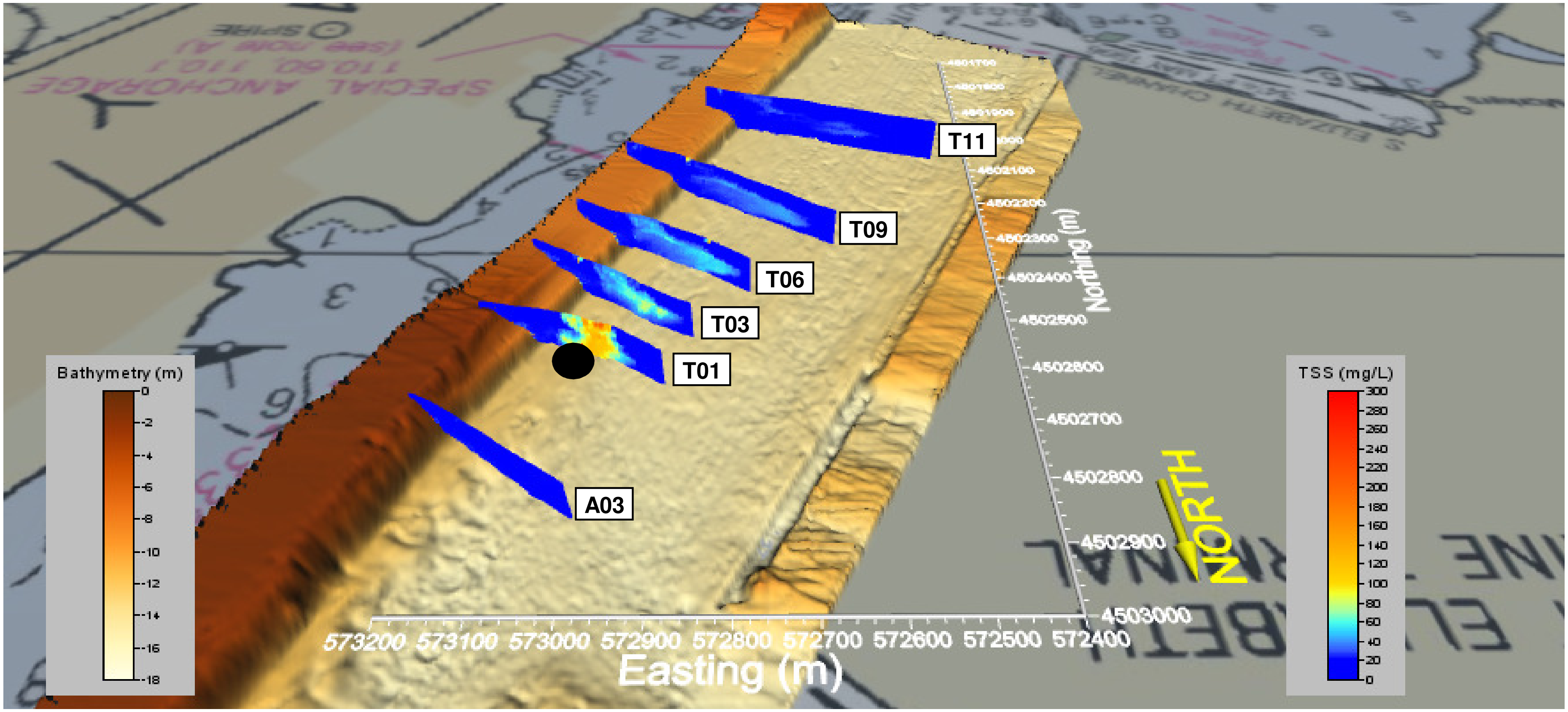


Bathymetry provided by: US Army Corps of Engineers, NY District

Z Scale Exaggerated 6x

● = Dredge Location

Figure			Tide
13	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-NB-1: B1*	**ADCP Average TSS Values with Respect to their x, y, and z Coordinates** **Superimposed on Channel Bathymetry** **18 November 2008**	Late Flood

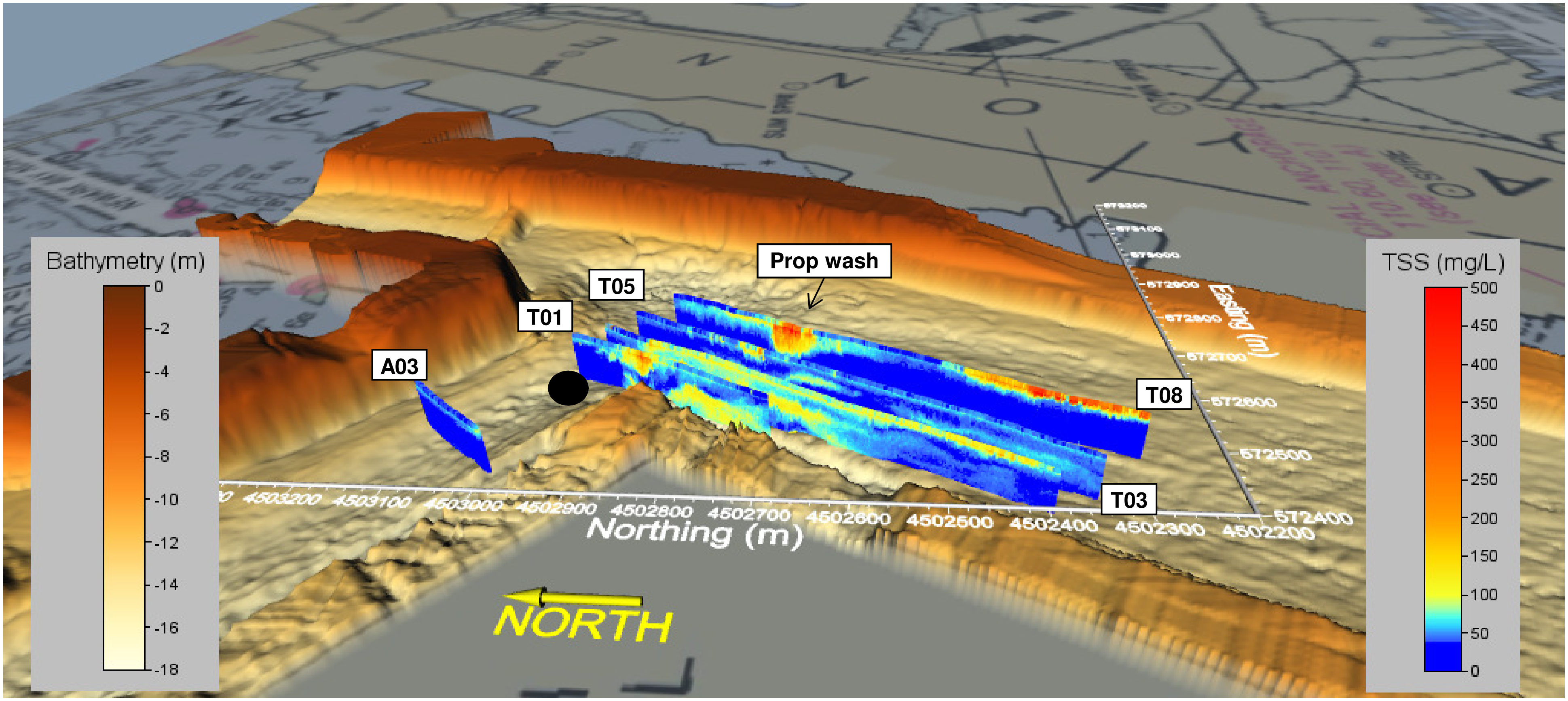


Bathymetry provided by: US Army Corps of Engineers, NY District

Z Scale Exaggerated 6x

= Dredge Location

Figure	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-NB-1: B1*	**ADCP Average TSS Values with Respect to their x, y, and z Coordinates** **Superimposed on Channel Bathymetry** **19 November 2008**	**Tide**
14			**Ebb**

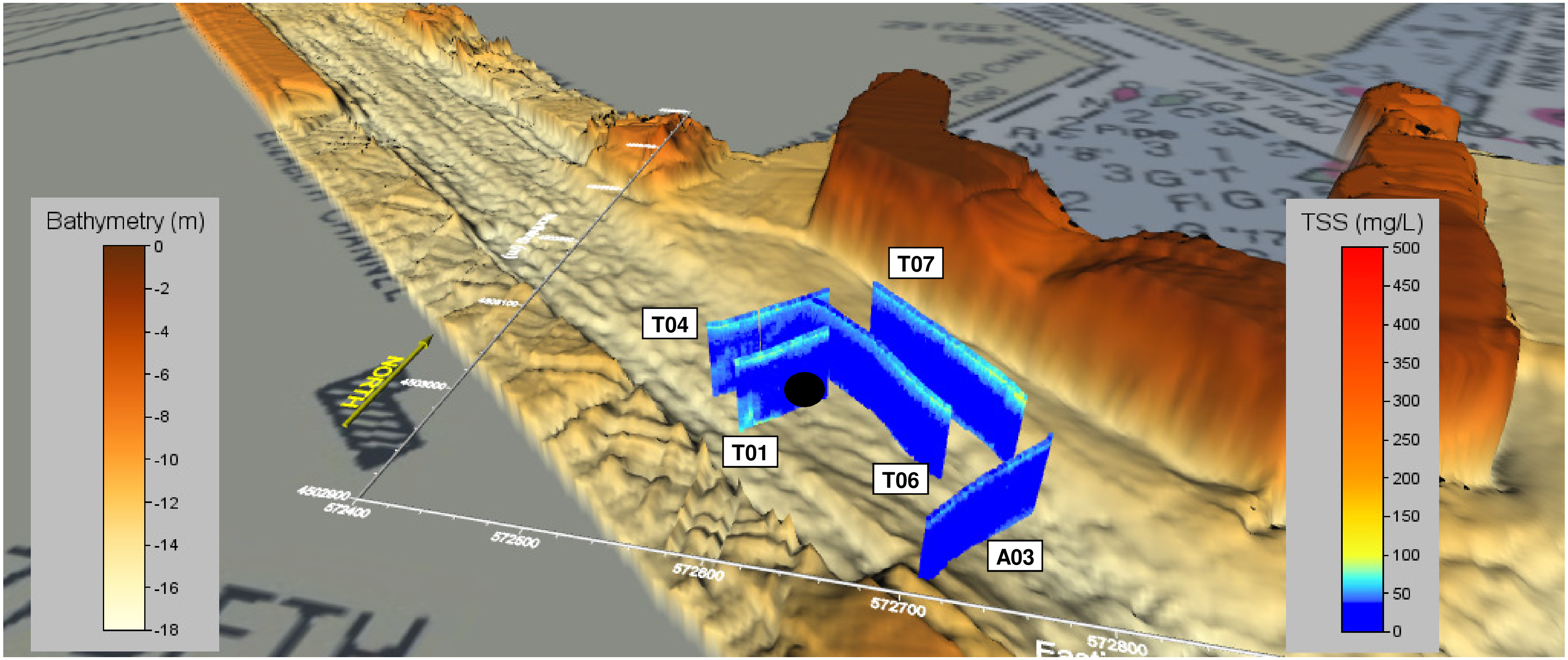


Bathymetry provided by: US Army Corps of Engineers, NY District

Z Scale Exaggerated 6x

● = Dredge Location

Figure	*USACE Harborwide TSS Far Field Survey HDP Contract Area: S-E-1: B*	**ADCP Average TSS Values with Respect to their x, y, and z Coordinates Superimposed on Channel Bathymetry 27 April 2009**	Tide
15			Ebb



Bathymetry provided by: US Army Corps of Engineers, NY District

Z Scale Exaggerated 6x

● = Dredge Location

Figure	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-E-1: B*	**ADCP Average TSS Values with Respect to their x, y, and z Coordinates** **Superimposed on Channel Bathymetry** **28 April 2009**	Tide
16			Flood

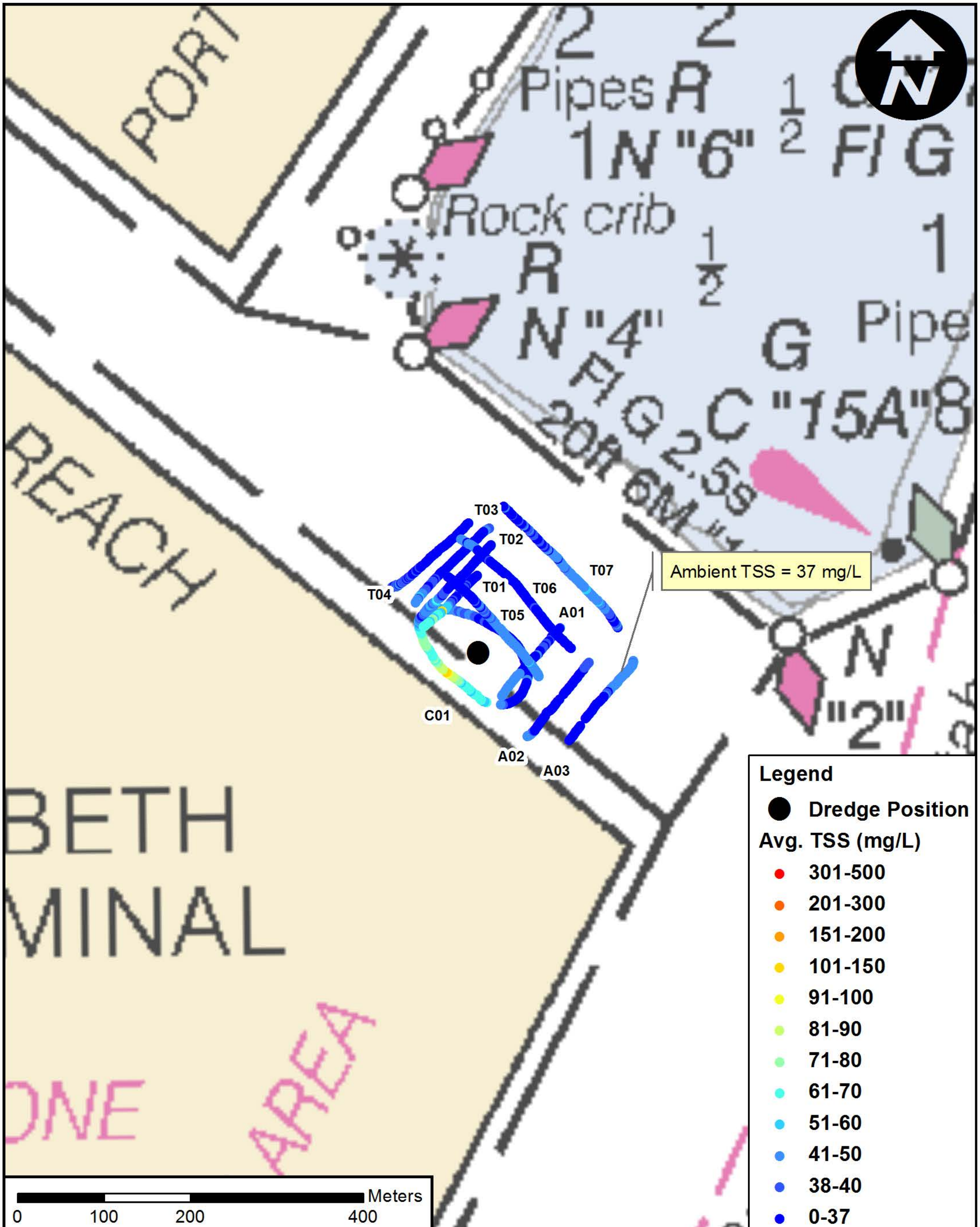


Figure	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-E-1: B*	**ADCP Average TSS - 28 April 2009** **14-16 Meter Depth Interval**	Tide
17			Flood

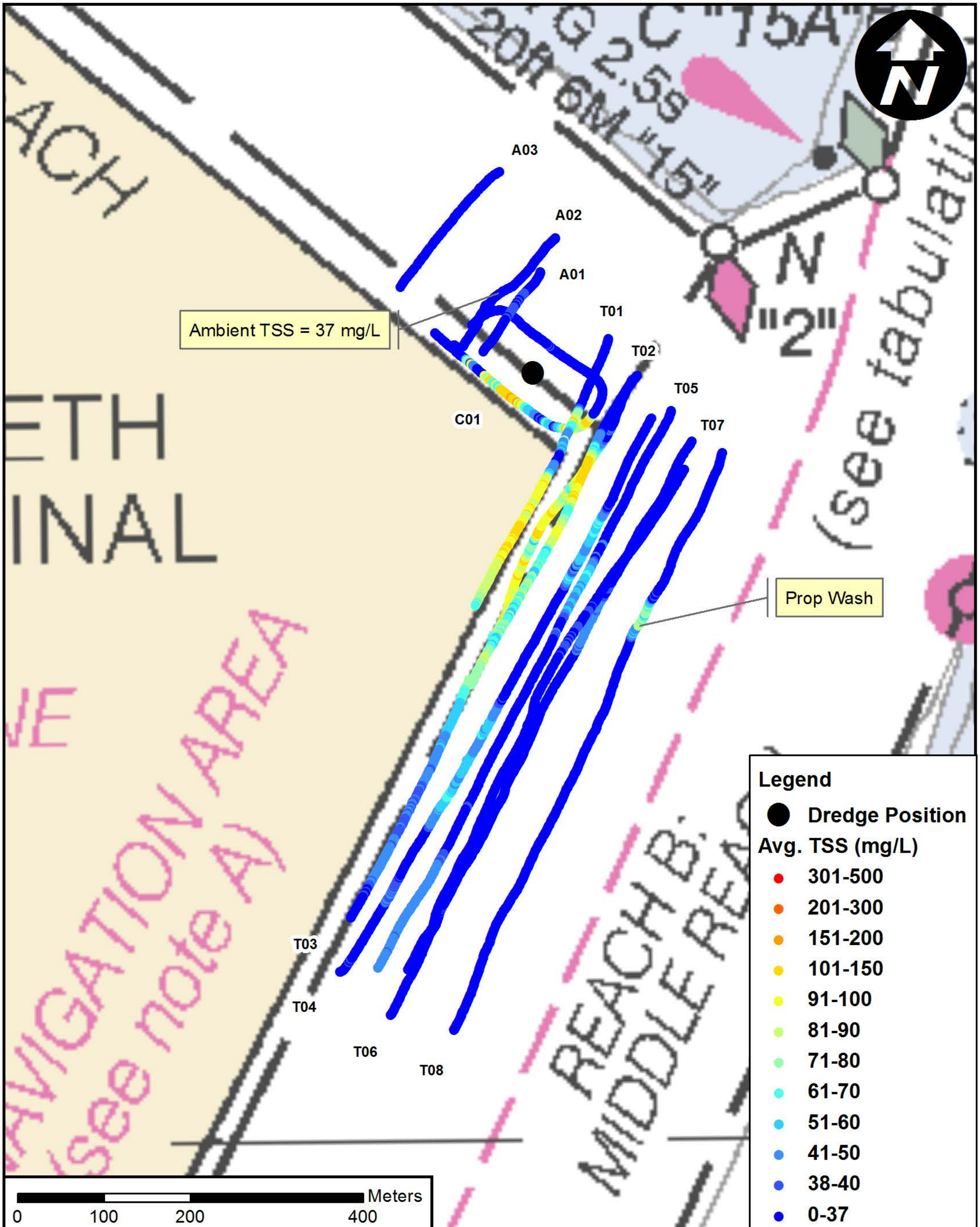
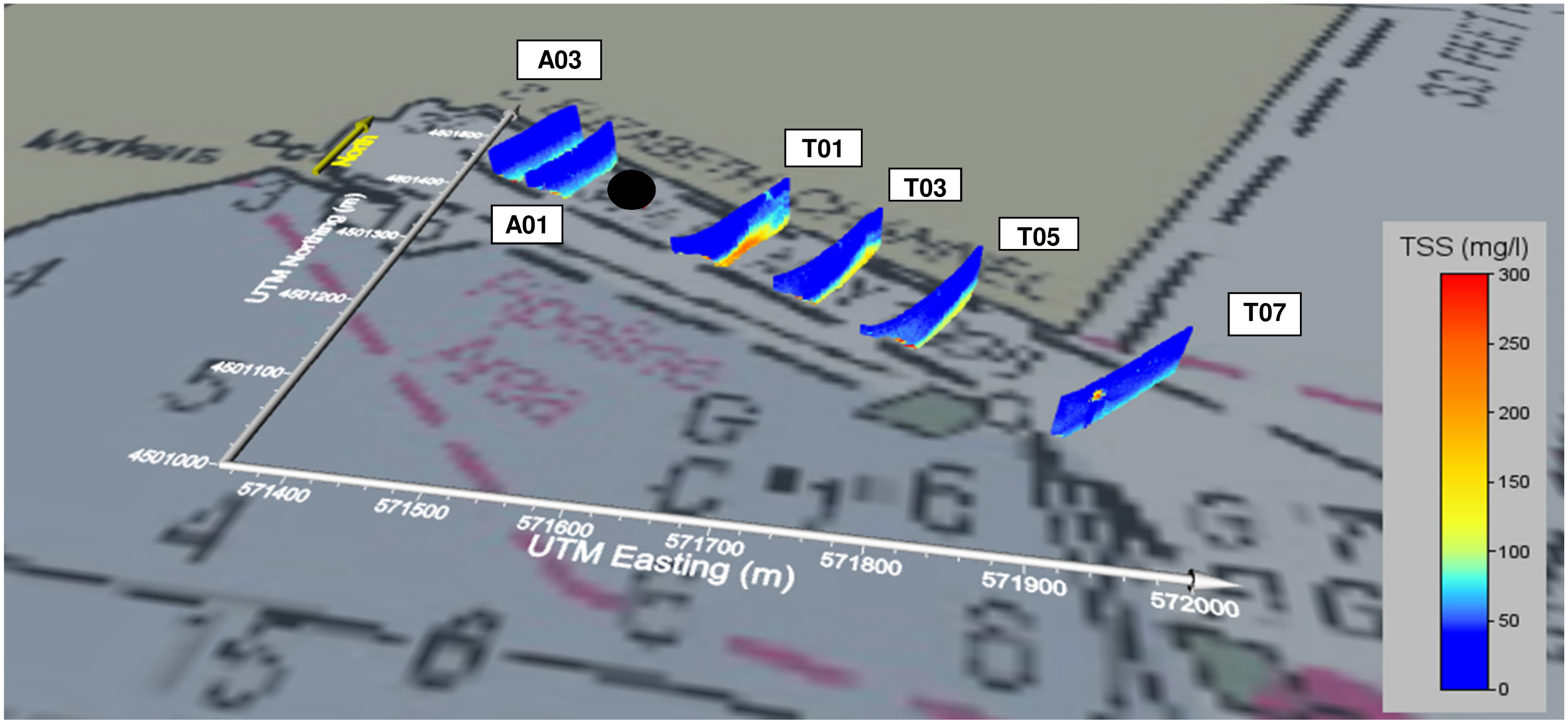


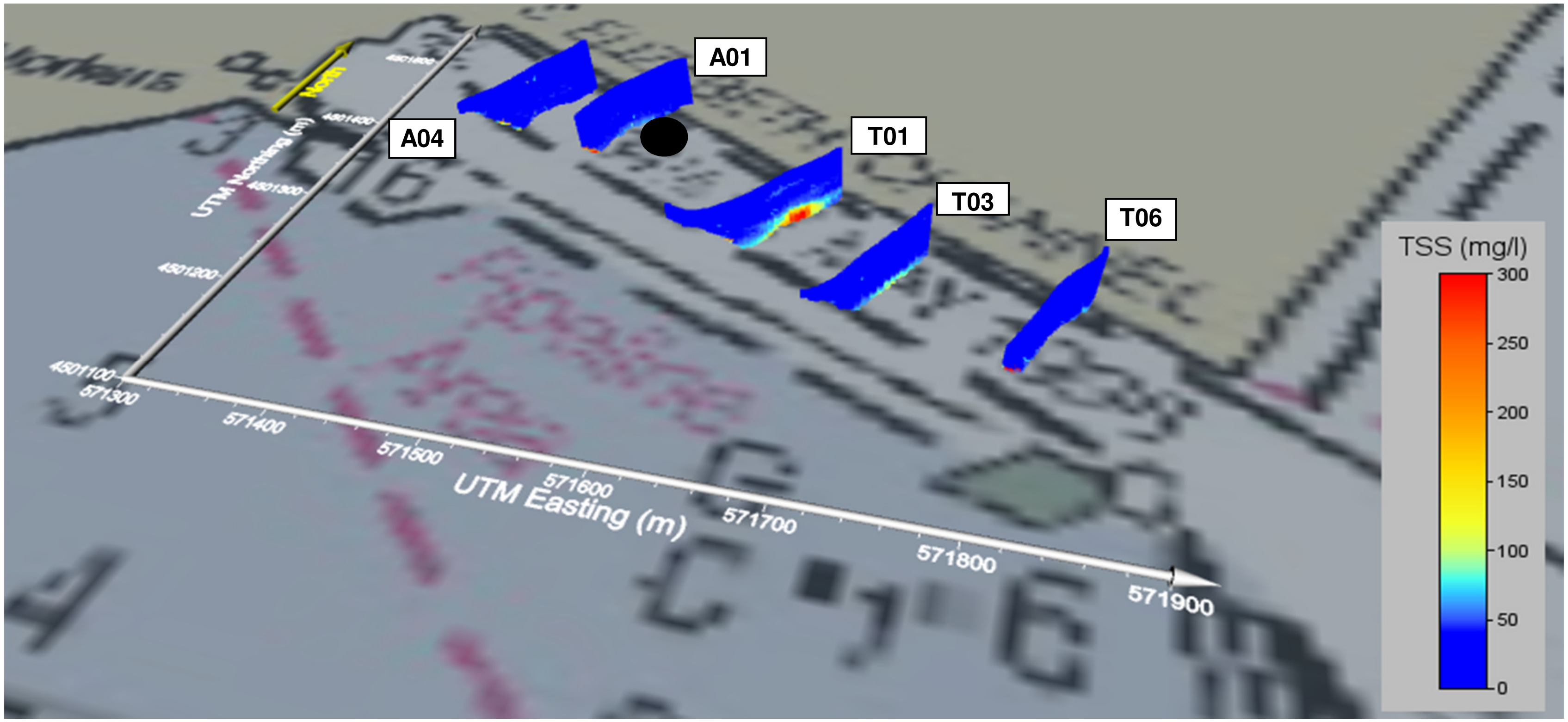
Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-E-1: B	ADCP Average TSS - 27 April 2009 10-12 Meter Depth Interval	Tide
18			Ebb



● = Dredge Location

Z scale exaggerated 6X

Figure	*USACE Harborwide TSS Far Field Survey HDP Contract Area S-NB-2*	ADCP Average TSS Values, 3D View of Selected Transects 26 July 2011	Tide
19			Flood



= Dredge Location

Z scale exaggerated 6X

Figure	*USACE Harborwide TSS Far Field Survey HDP Contract Area S-NB-2*	ADCP Average TSS Values, 3D View of Selected Transects 27 July 2011	Tide
20			Ebb

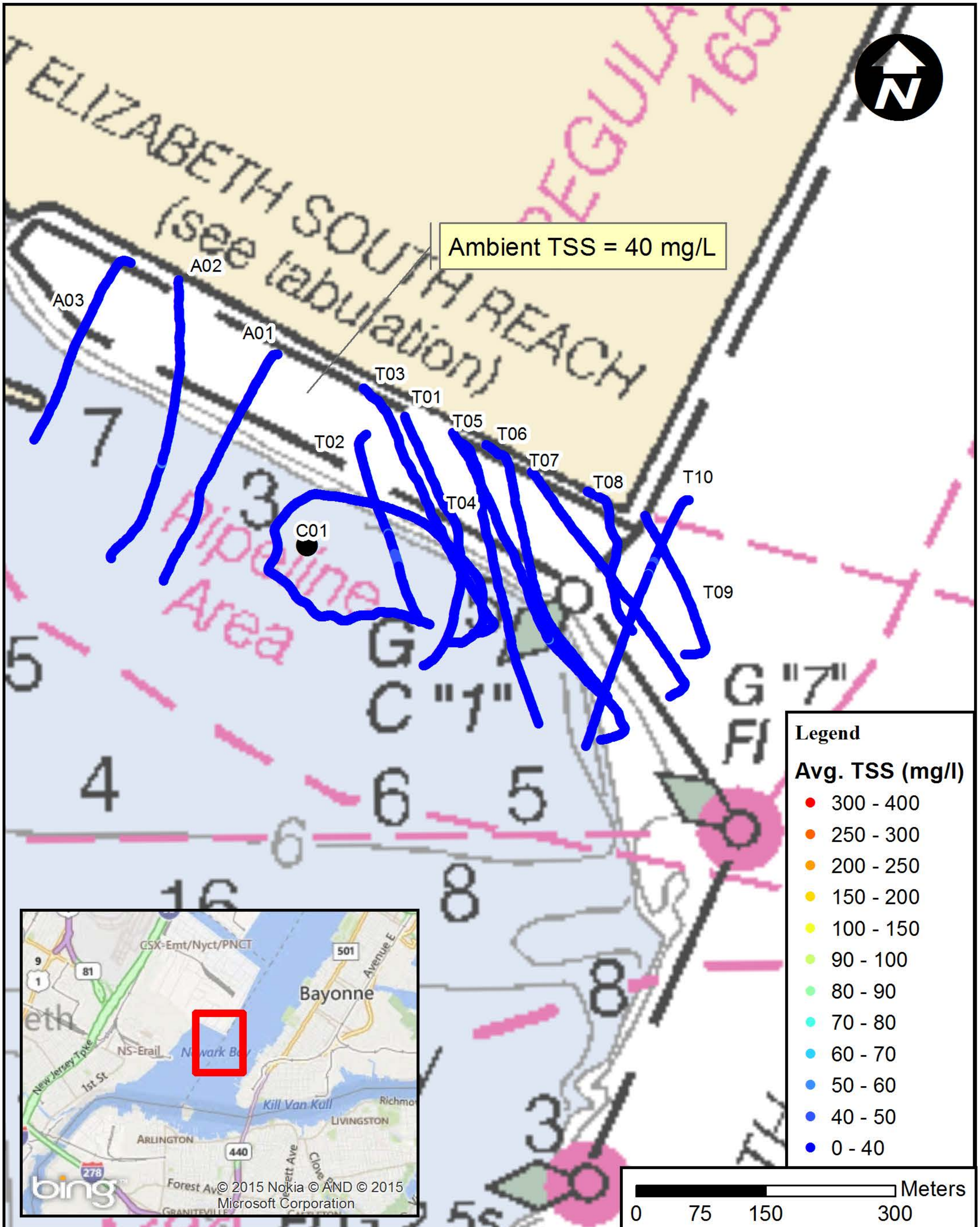


Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-NB-2	ADCP Average TSS - 04 October 2011 2-4 Meter Depth Interval	Tide
21			Flood

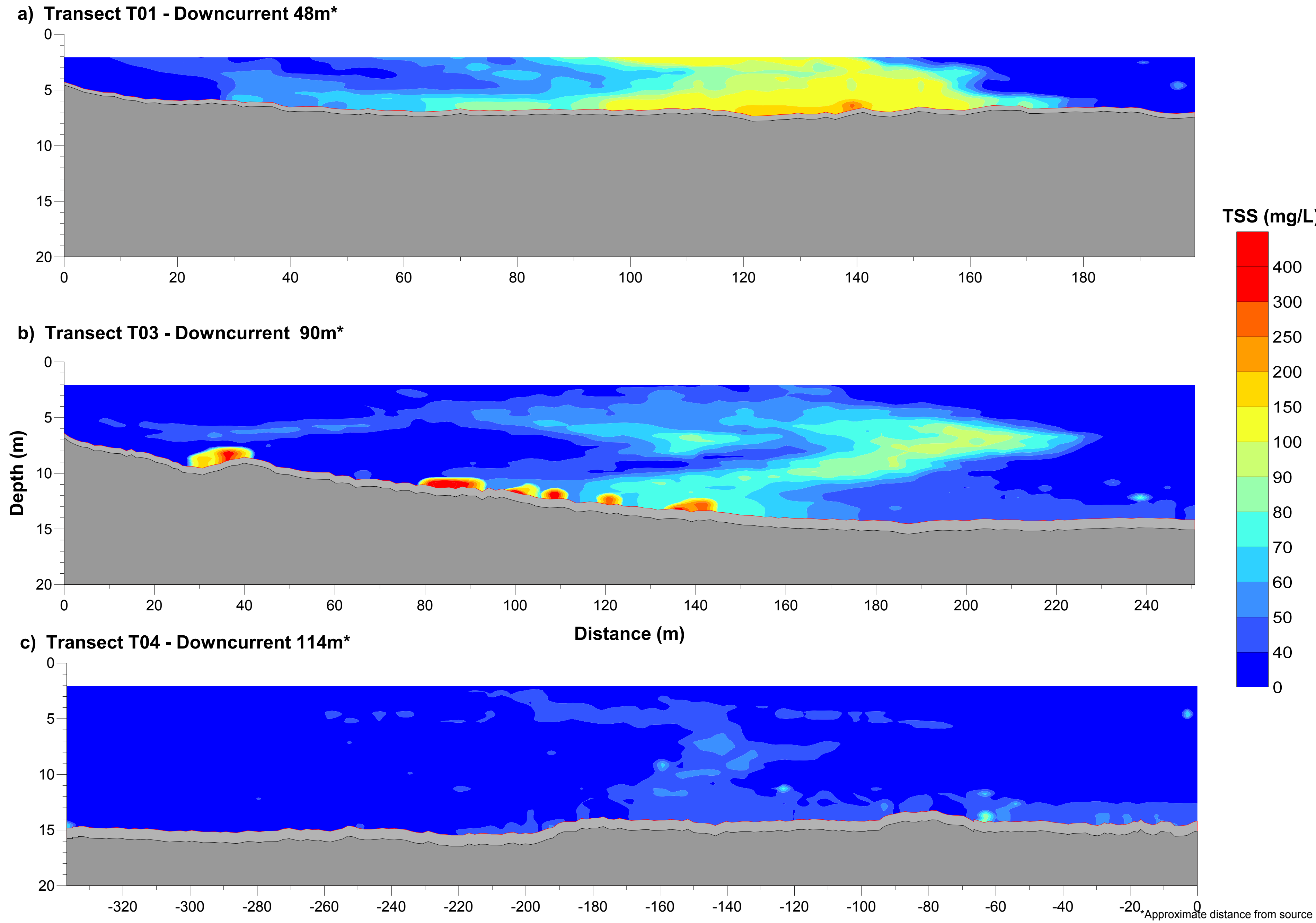
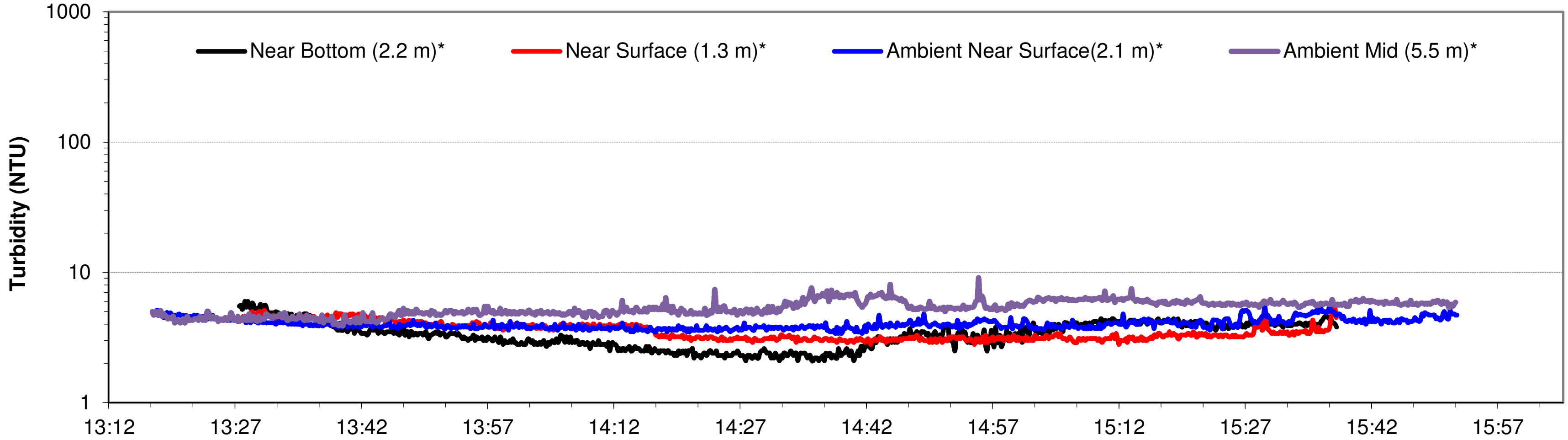
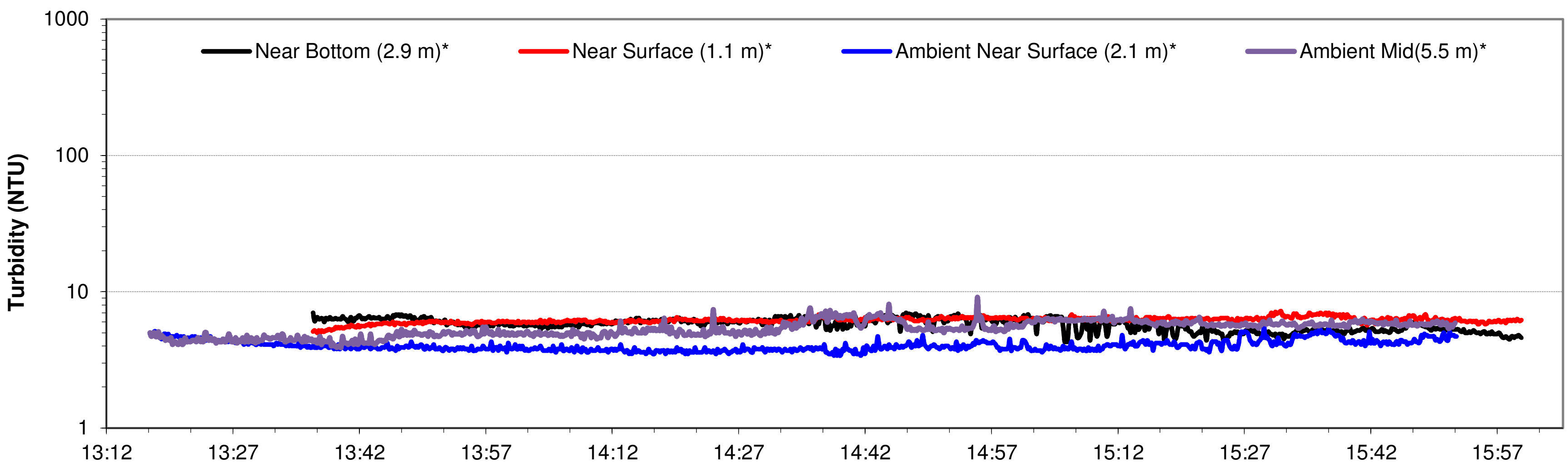


FIGURE	USACE Harborwide TSS Far Field Survey S-NB-2	Vertical Profiles of ADCP Average TSS 07 October 2011 - Ebb Tide, Transects T01, T03, T04	TIDE
22a-c			Ebb

a) 85 meters Down Current from Dredge



b) 300 meters Down Current from Dredge



*Number in parentheses is average depth of instrument over period recorded

Figure	*USACE Harborwide TSS* *Far Field Survey* *S-NB-2*	**Surface and Bottom OBS Turbidities at a) 85 m and b) 300 m Downcurrent of Dredge.** **Ambient Station Located 370m Upcurrent of Dredge** **05 October 2011 TSS Survey**	Tide
23			Flood

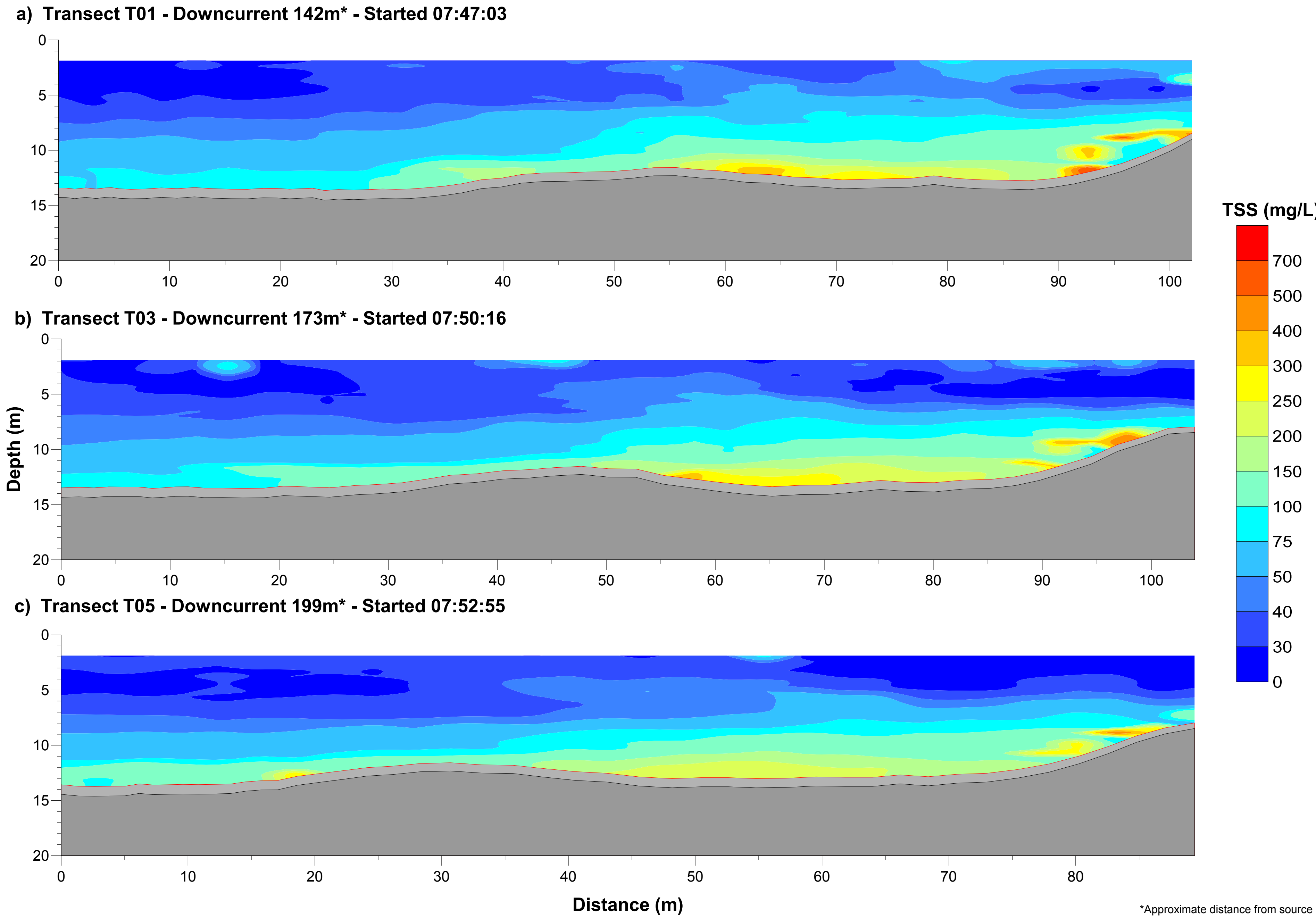
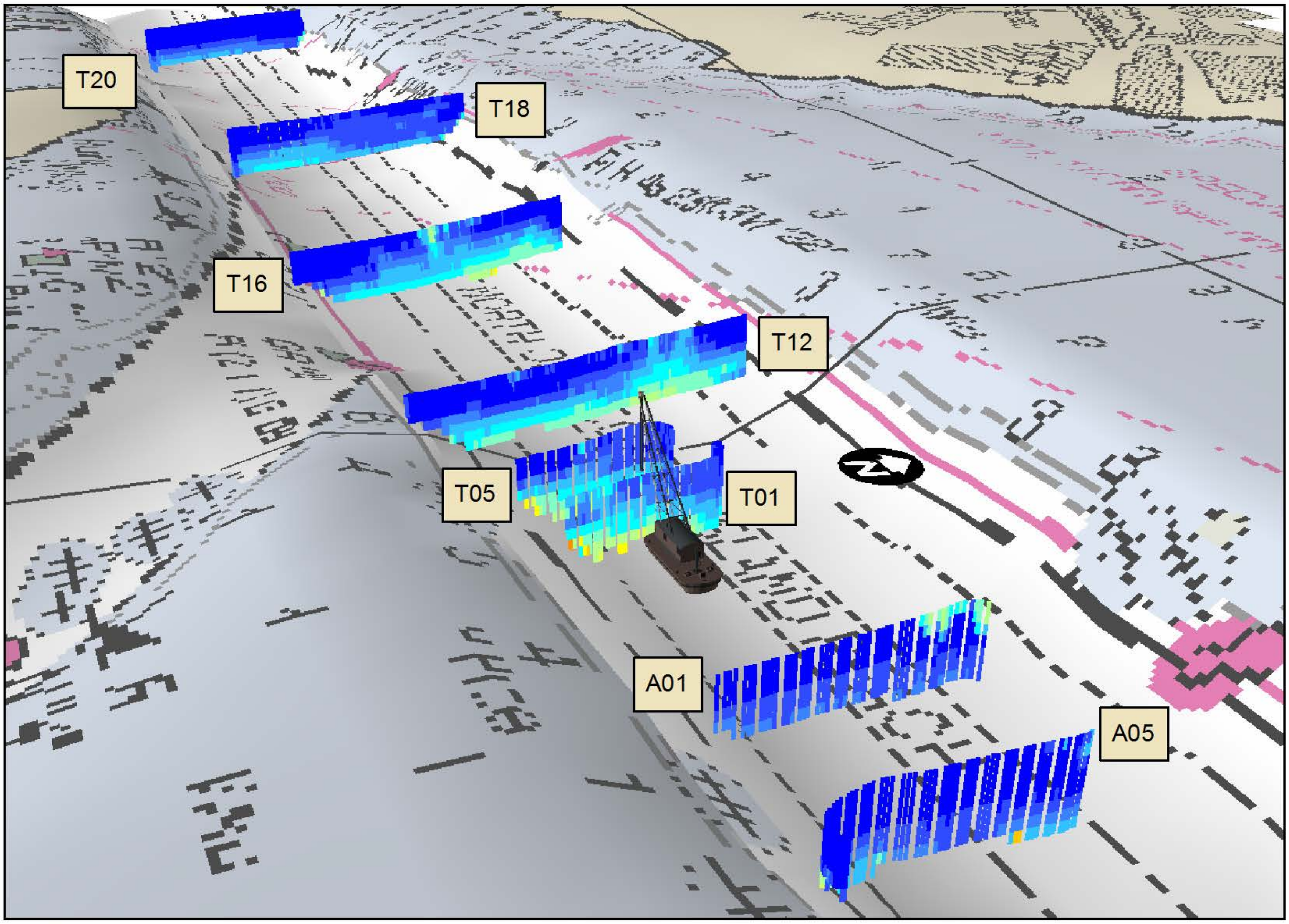
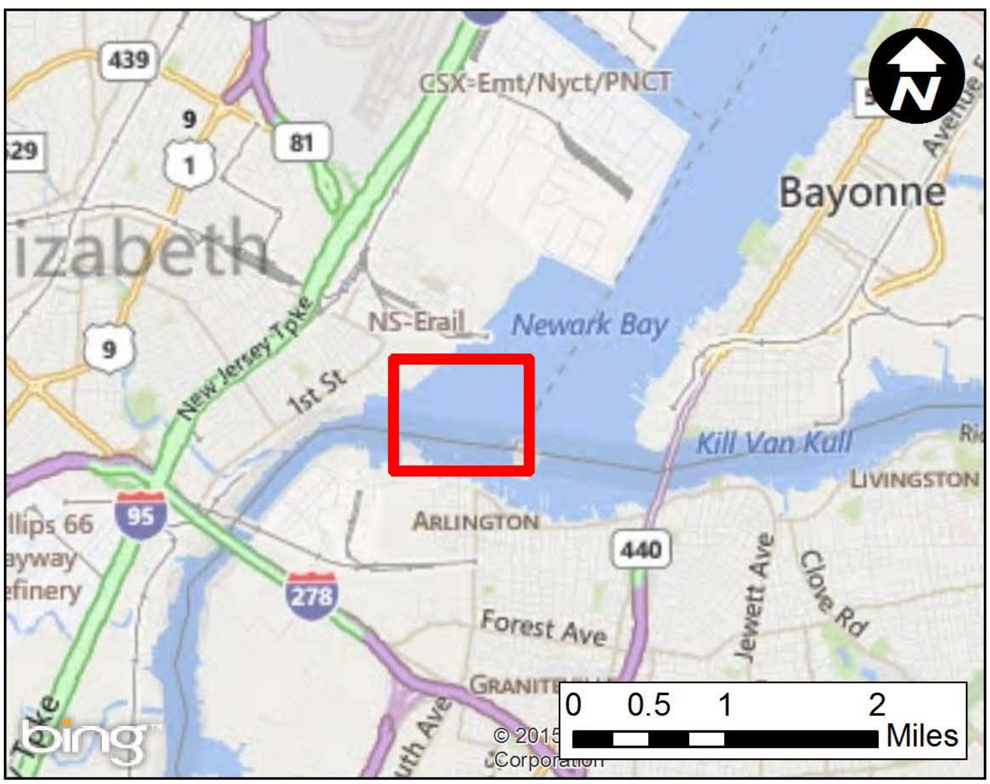


FIGURE	*USACE Harborwide TSS Far Field Survey S-AK-2*	**Vertical Profiles of ADCP Average TSS 16 March 2012 - Ebb Tide, Transects T01, T03, T05**	TIDE
24a-c			**Ebb**





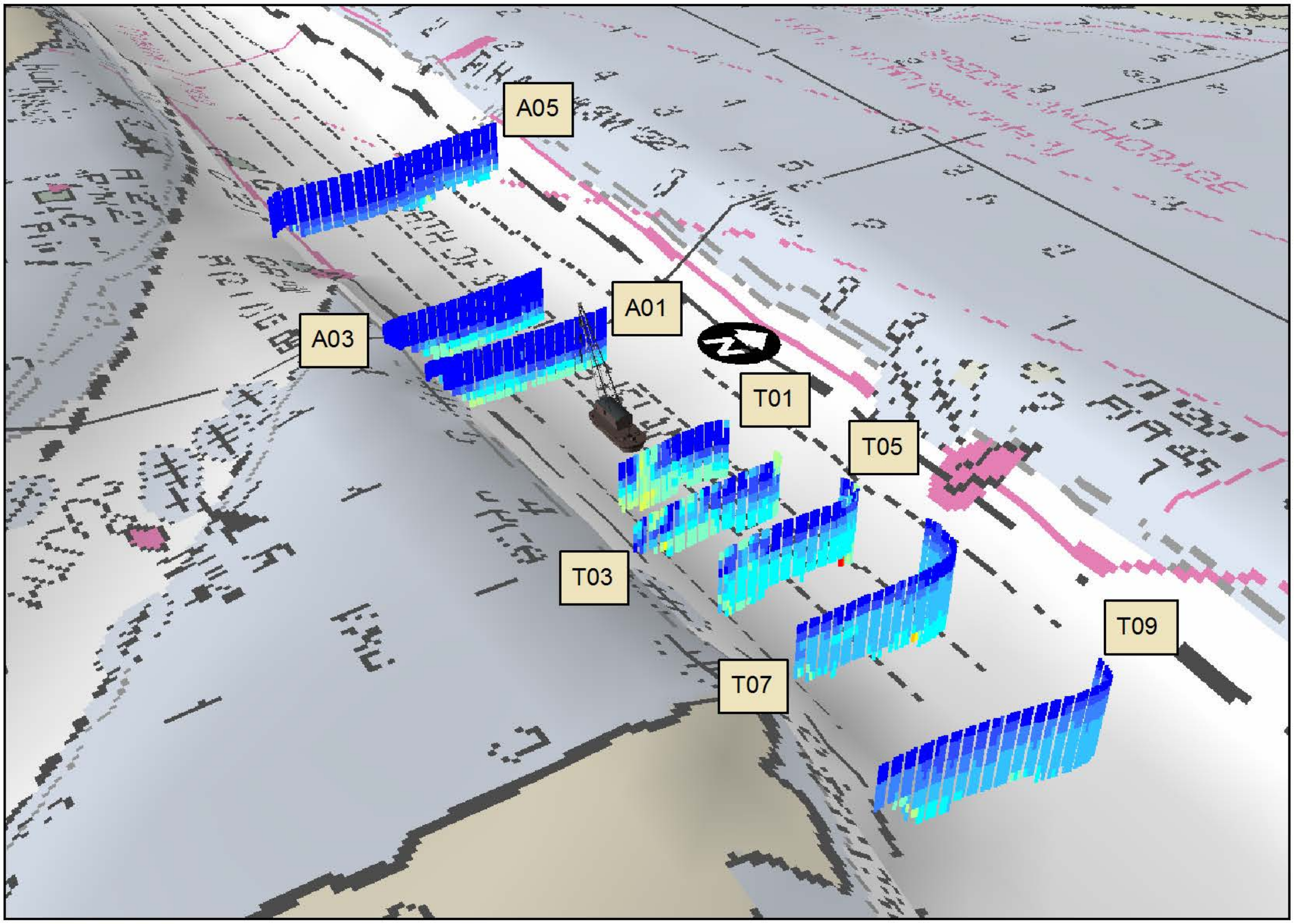
Legend

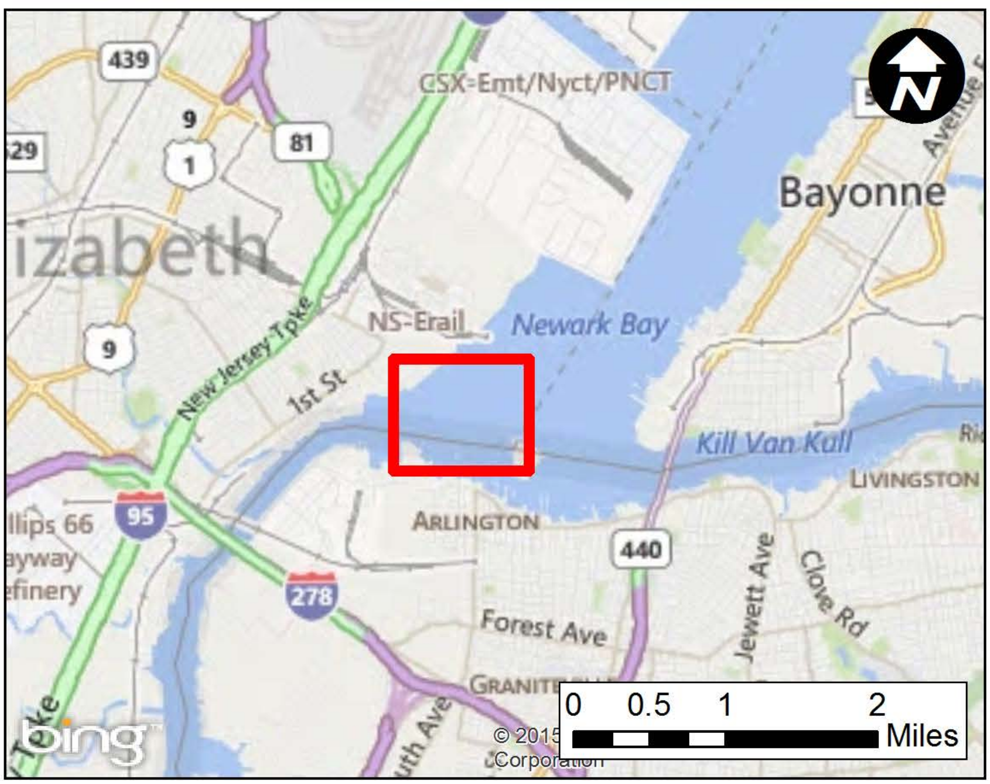
Dredge Position

Avg TSS (mg/L)

- 0 - 30
- 30 - 40
- 40 - 50
- 50 - 75
- 75 - 100
- 100 - 150
- 150 - 200
- 200 - 250
- 250 - 300
- 300 - 400
- 400 - 500
- 500 - 700
- > 700

Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-AK-2	ADCP Average TSS - 16 March 2012 Isometric View of Selected Transects	Tide
25			Ebb



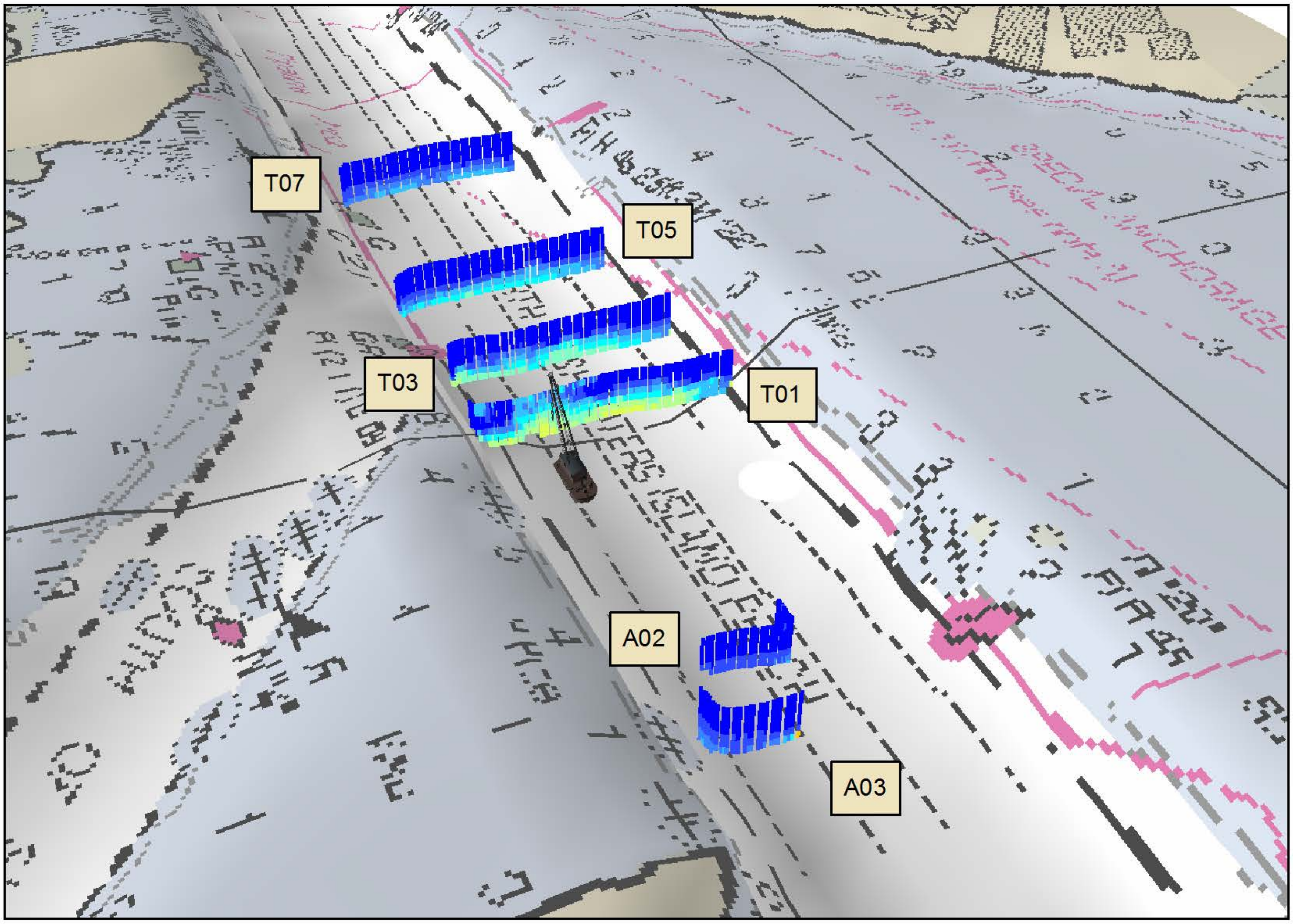


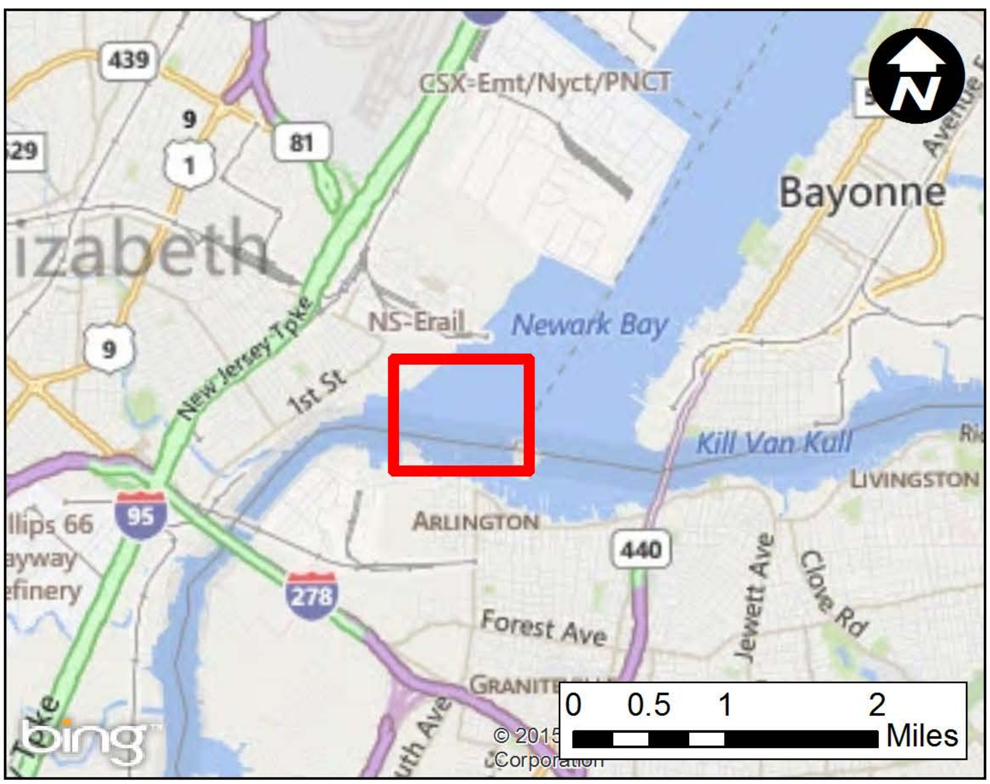
Legend

Dredge Position

Avg TSS (mg/L)
- 0 - 30
- 30 - 40
- 40 - 50
- 50 - 75
- 75 - 100
- 100 - 150
- 150 - 200
- 200 - 250
- 250 - 300
- 300 - 400
- 400 - 500
- 500 - 700
- > 700

Figure	*USACE Harborwide TSS Far Field Survey HDP Contract Area: S-AK-2*	**ADCP Average TSS - 15 March 2012 Isometric View of Selected Transects**	Tide
26			Flood





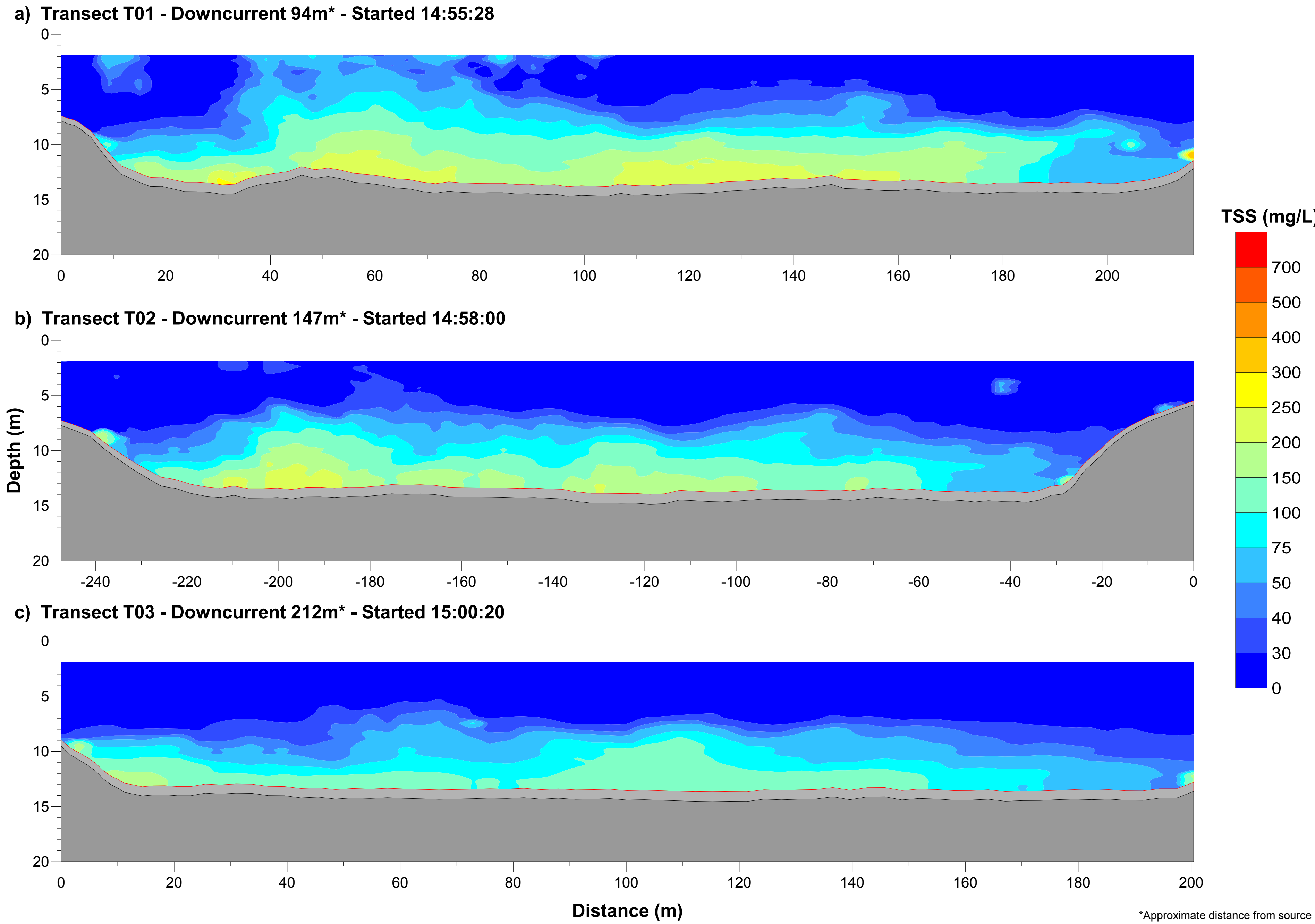
Legend

Dredge Position

Avg TSS (mg/L)

- 0 - 30
- 30 - 40
- 40 - 50
- 50 - 75
- 75 - 100
- 100 - 150
- 150 - 200
- 200 - 250
- 250 - 300
- 300 - 400
- 400 - 500
- 500 - 700
- > 700

Figure	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-AK-2*	**ADCP Average TSS - 12 March 2012** **Isometric View of Selected Transects**	**Tide**
27			**Ebb**



*Approximate distance from source

FIGURE	*USACE Harborwide TSS Far Field Survey S-AK-2*	Vertical Profiles of ADCP Average TSS 12 March 2012 - Ebb Tide, Transects T01, T02, T03	TIDE
28a-c			Ebb

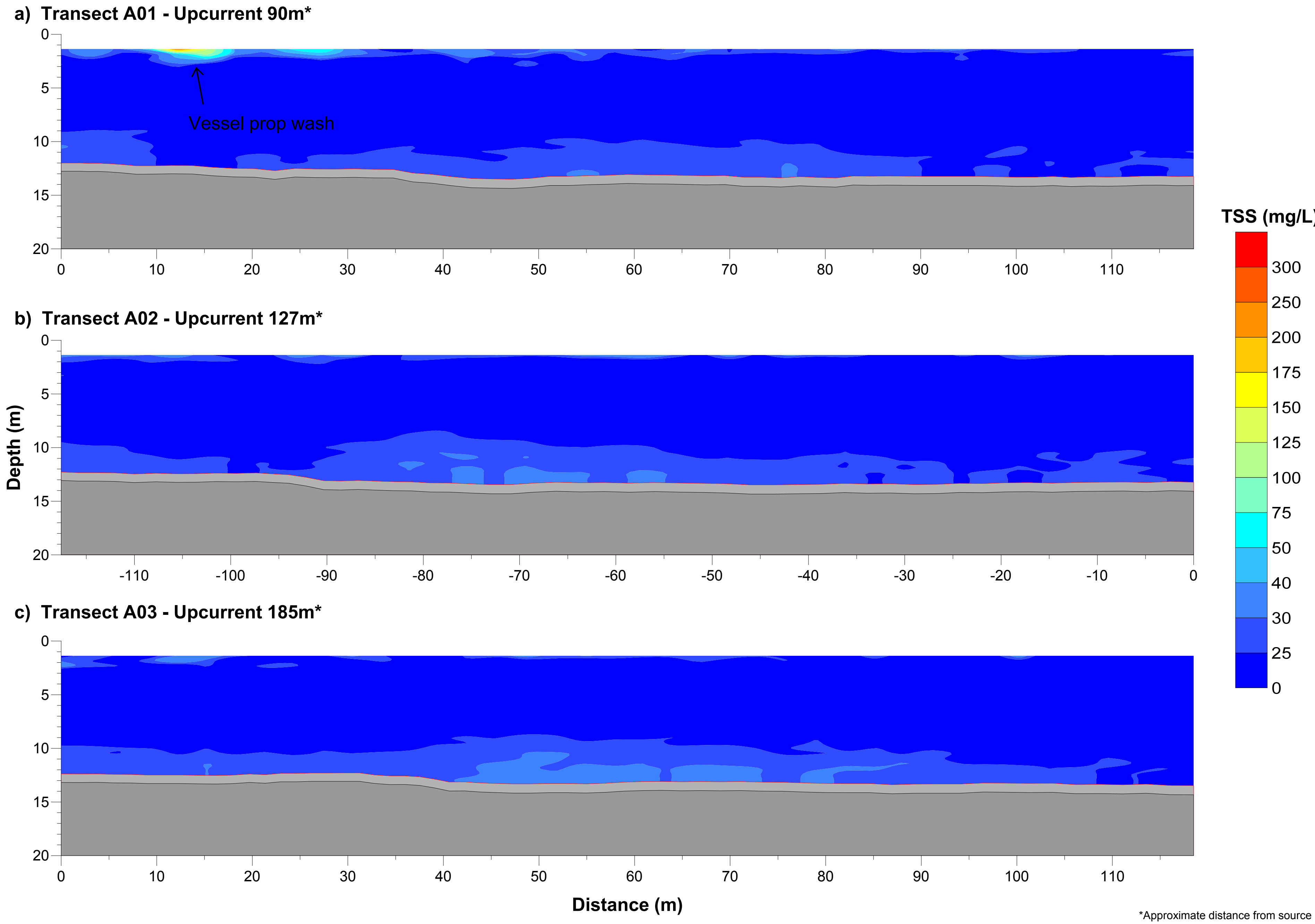
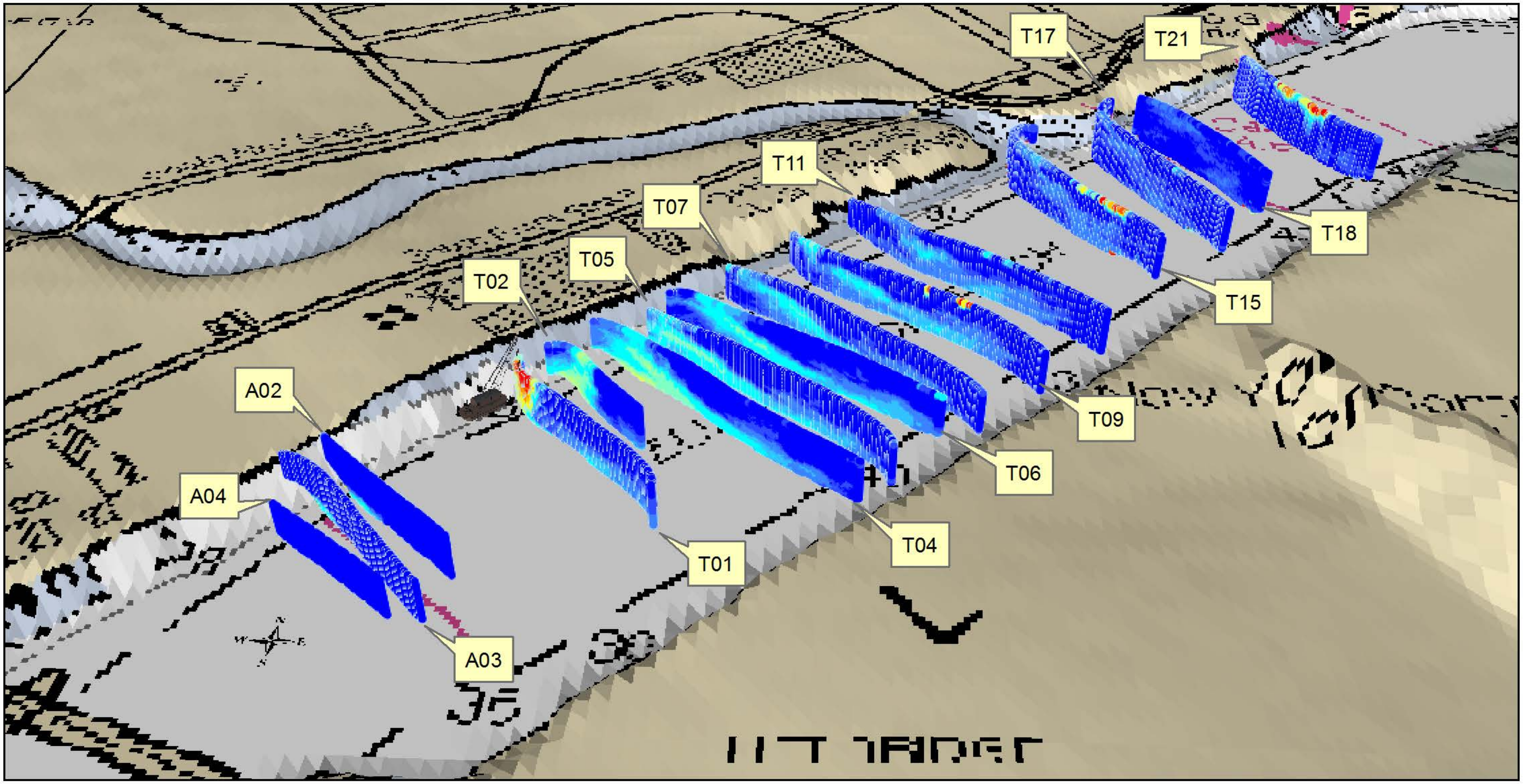
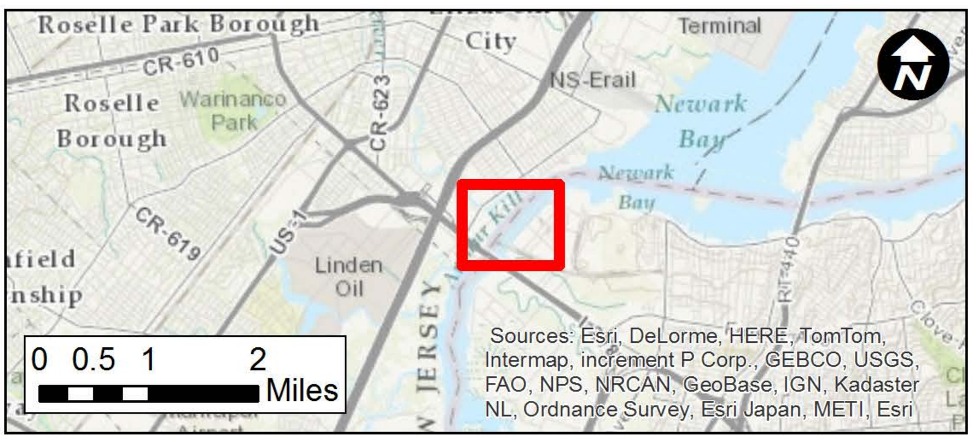


FIGURE	USACE Harborwide TSS Far Field Survey S-AK-3	Vertical Profiles of ADCP Average TSS 18 November 2013 - Ebb Tide, Transects A01, A02, A03	TIDE
29a-c			Ebb





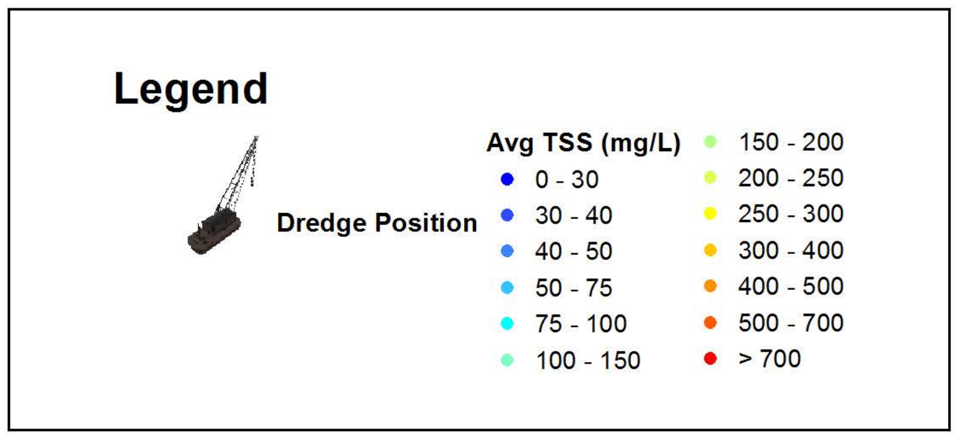


Figure	*USACE Harborwide TSS* *Far Field Survey* *HDP Contract Area: S-AK-3*	**ADCP Average TSS - 25 November 2013** **Isometric View of Selected Transects**	Tide
30			Flood

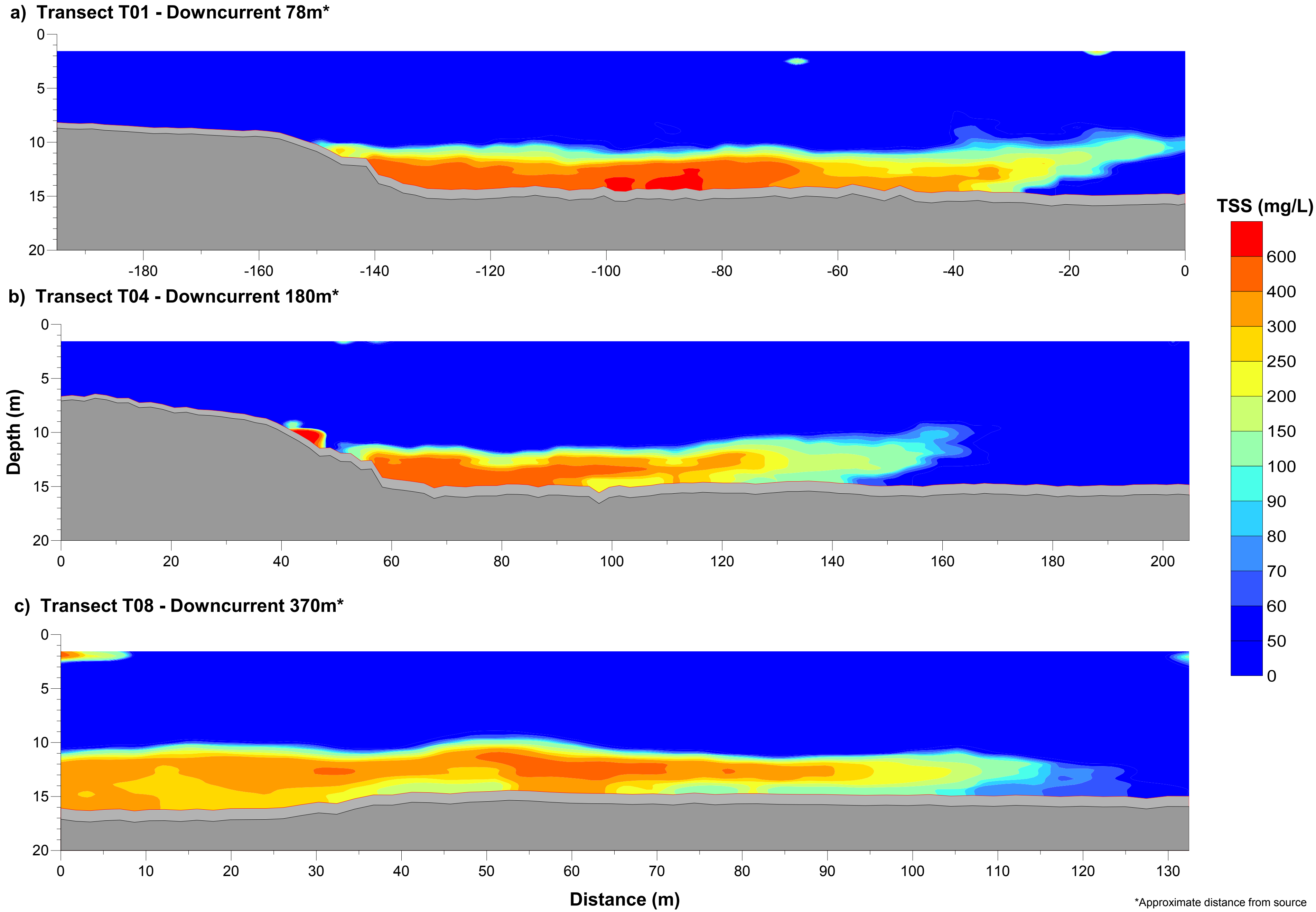


FIGURE	USACE Harborwide TSS Far Field Survey S-KVK-1	Vertical Profiles of ADCP Average TSS 19 June 2009 - Flood Tide, Transects T01, T04, T08	TIDE
31a-c			Flood

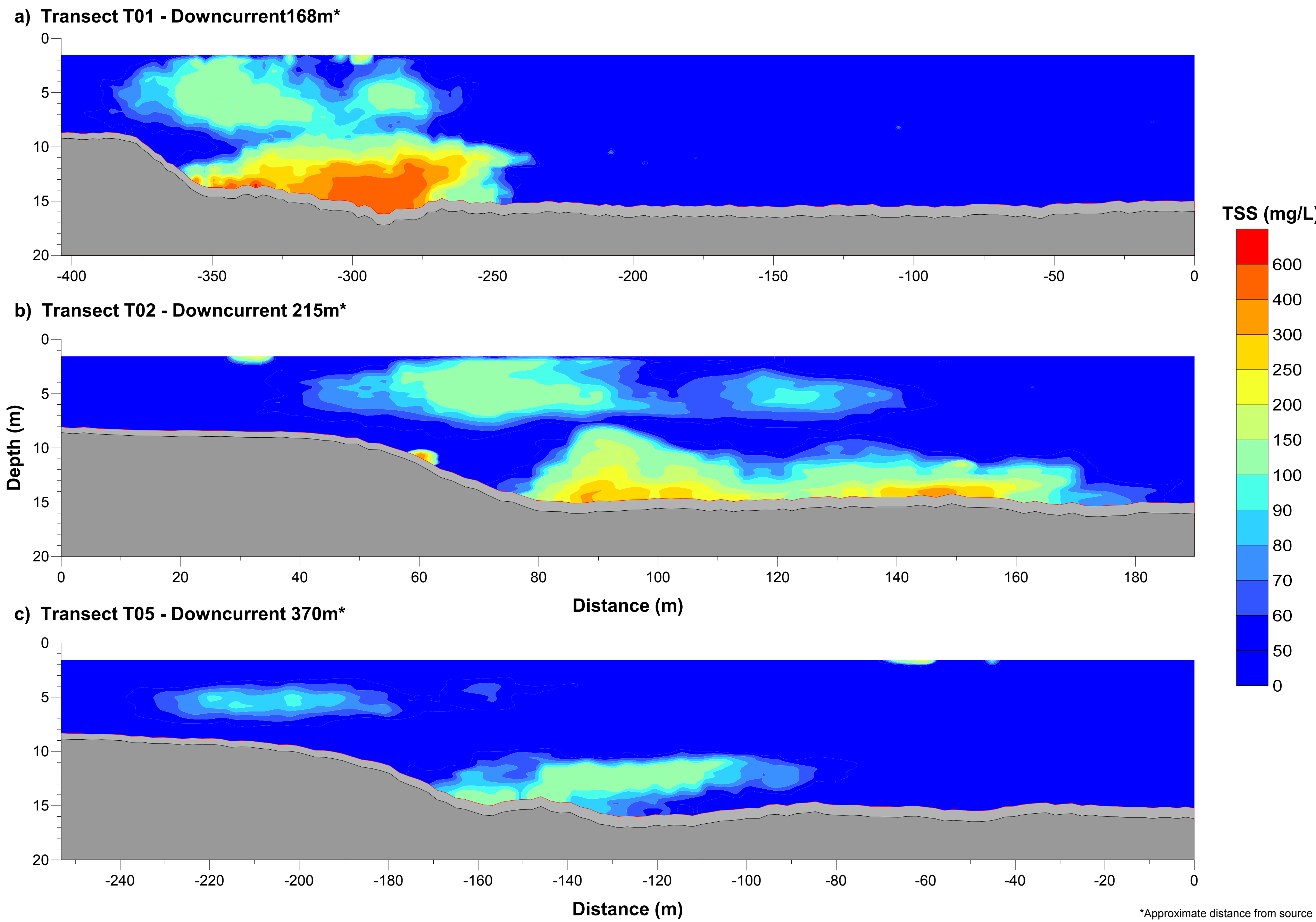


FIGURE	*USACE Harborwide TSS Far Field Survey S-KVK-1*	**Vertical Profiles of ADCP Average TSS 22 June 2009 - Ebb Tide, Transects T01, T02, T05**	TIDE
32a-c			Ebb

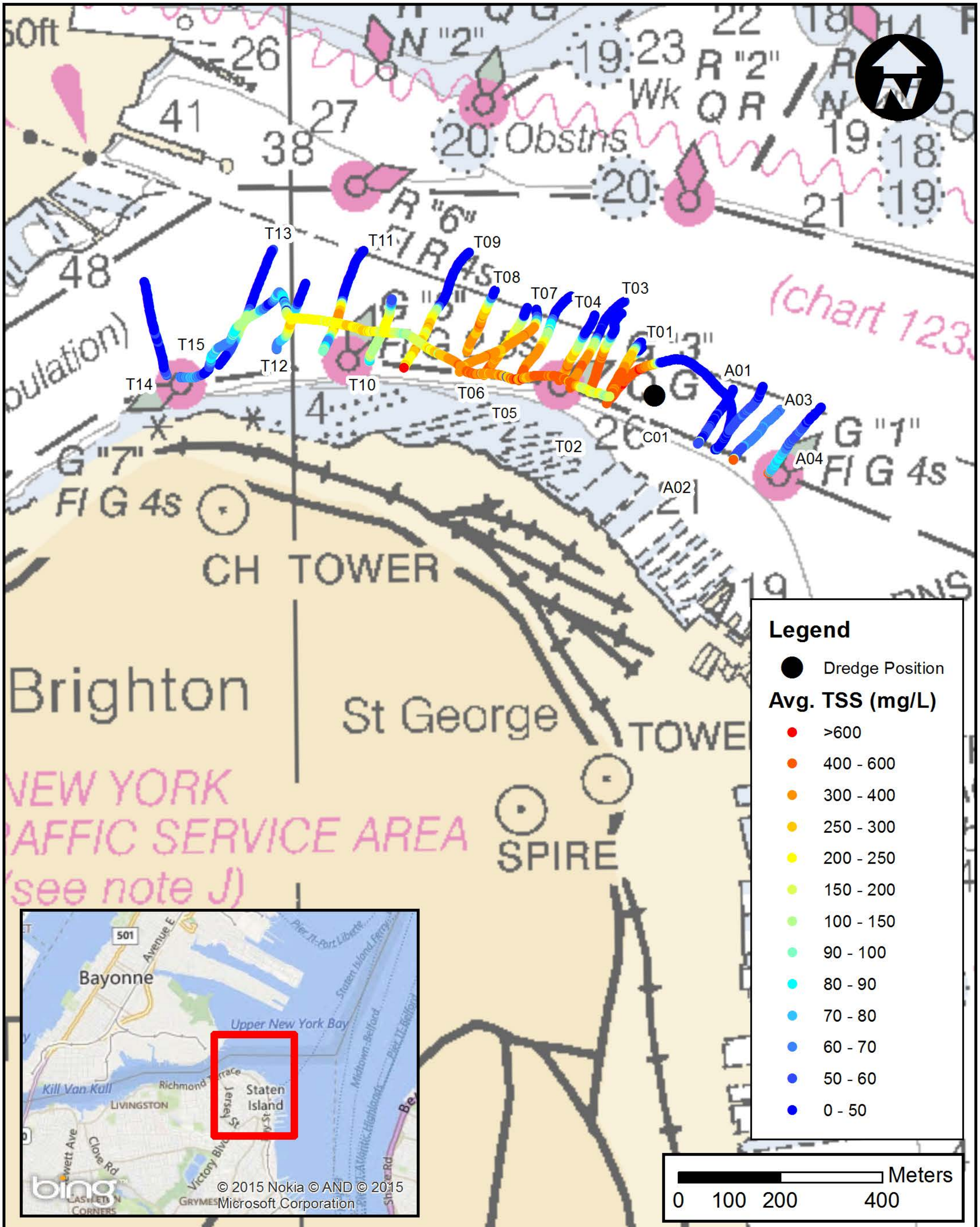


Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-KVK-1	ADCP Average TSS - 19 June 2009 12-14 Meter Depth Interval	Tide
33			Flood

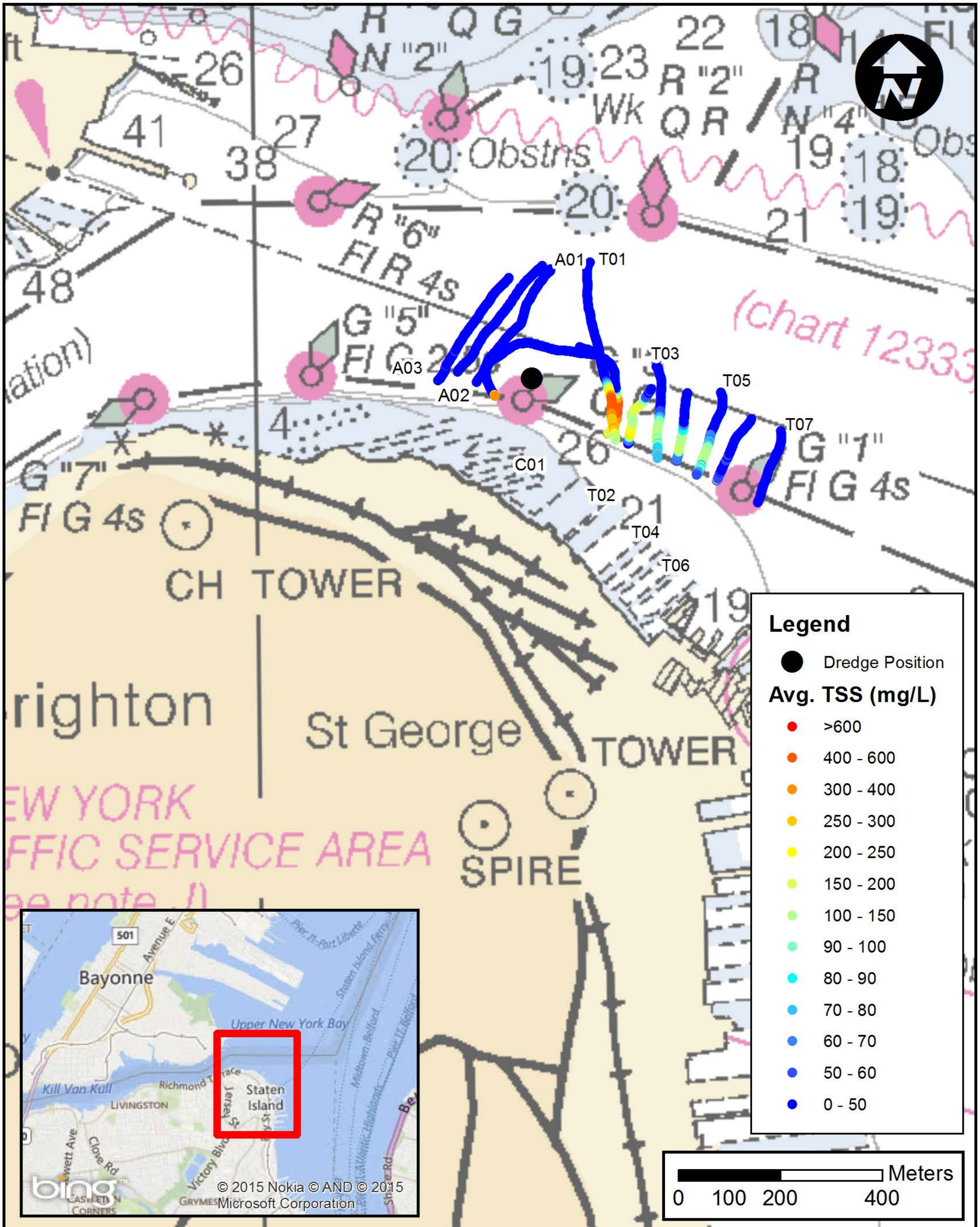
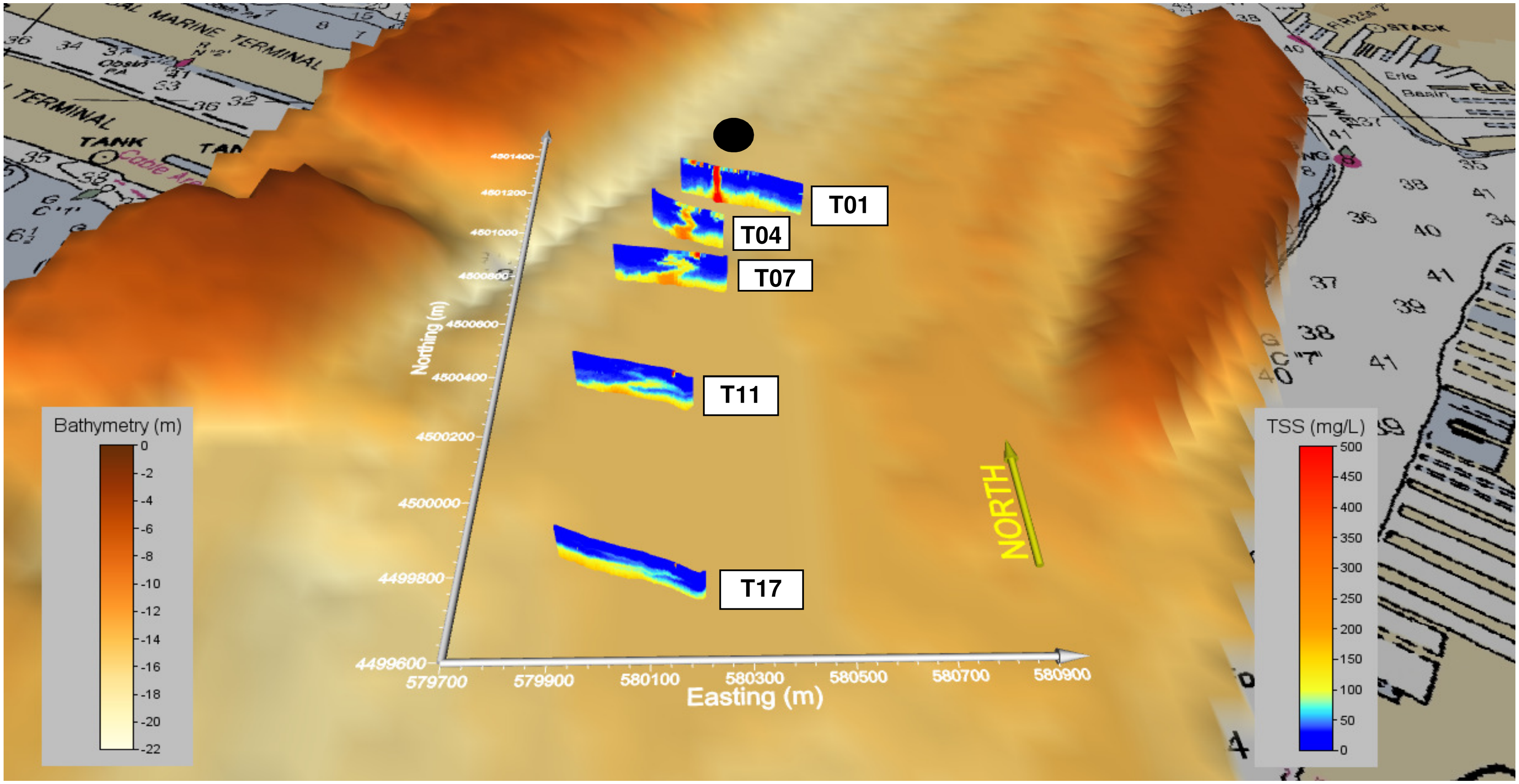


Figure	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-KVK-1	ADCP Average TSS - 22 June 2009 12-14 Meter Depth Interval - Set 1	Tide
34			Ebb



Bathymetry produced by NOAA soundings ⬤ = Dredge Location Z scale exaggerated 6X

Figure	*USACE Harborwide TSS*	ADCP Average TSS Values, 3D View of Selected Transects	Tide
35	*Far Field Survey* *HDP Contract Area S-AN-2*	Superimposed on Channel Bathymetry 04 January 2011	Ebb

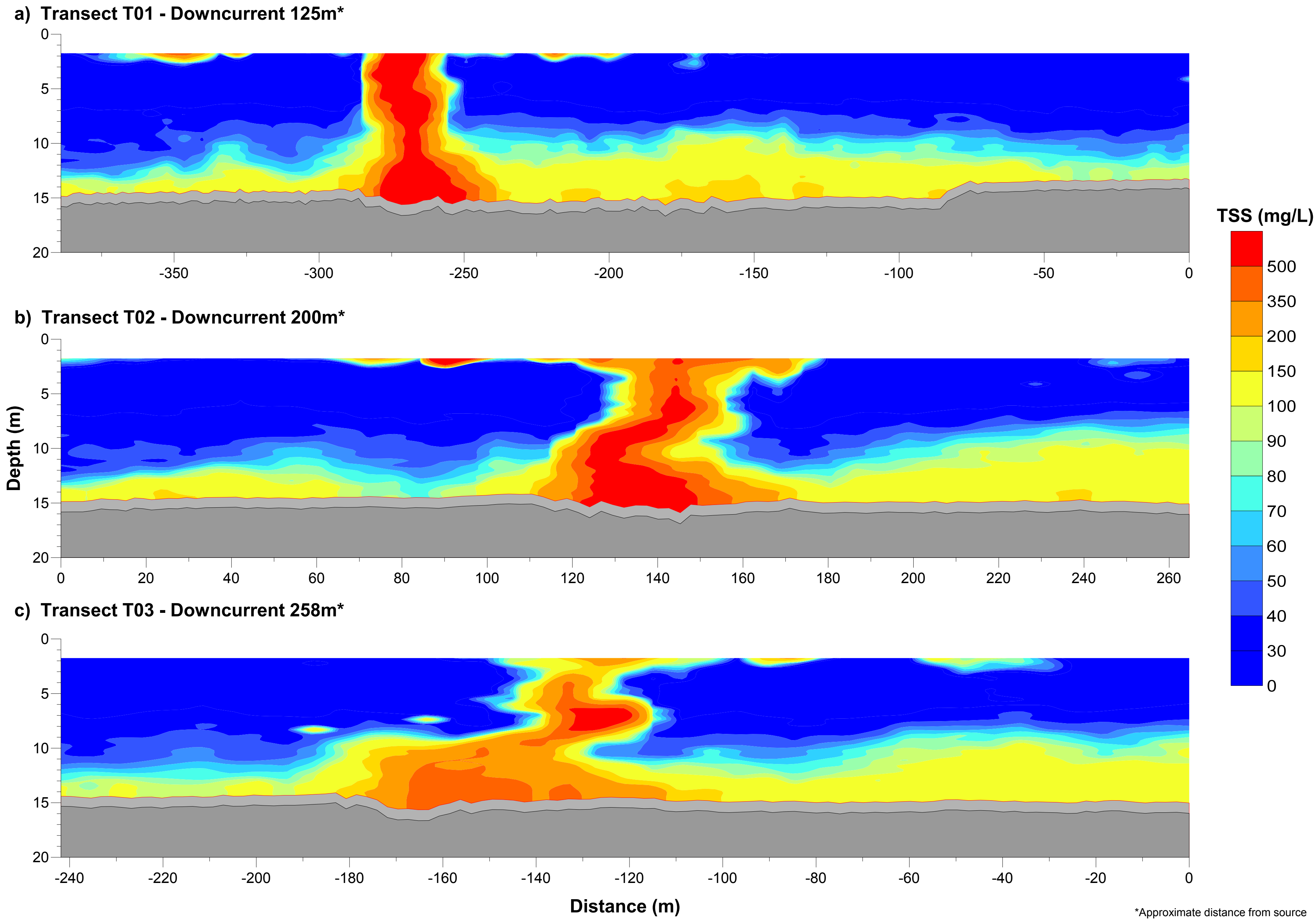


FIGURE	*USACE Harborwide TSS Far Field Survey HDP Contract Area: S-AN-2*	**Vertical Profiles of ADCP Average TSS 04 January 2011 - Ebb Tide, Transects T01, T02, T03**	TIDE
36a-c			Ebb

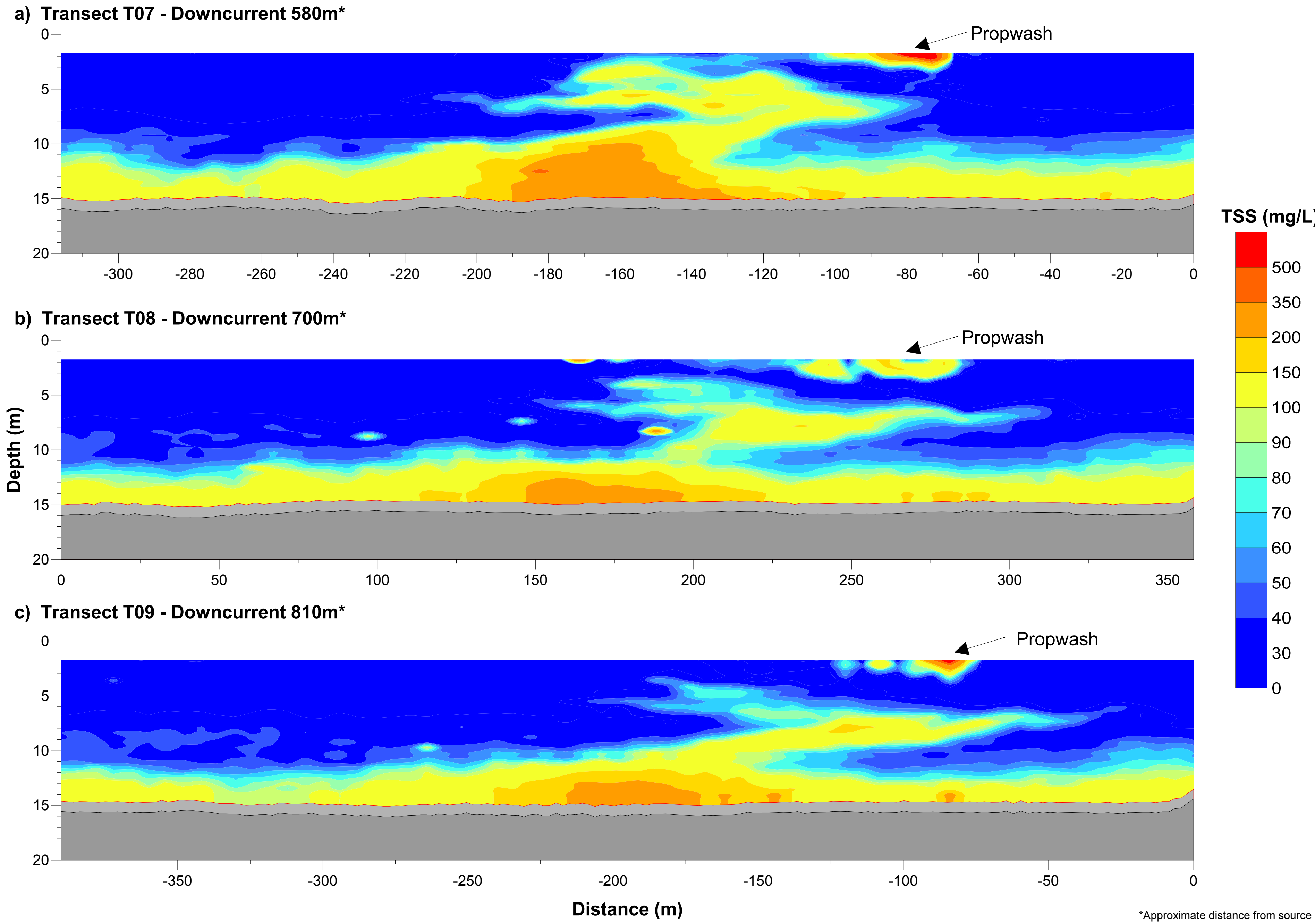
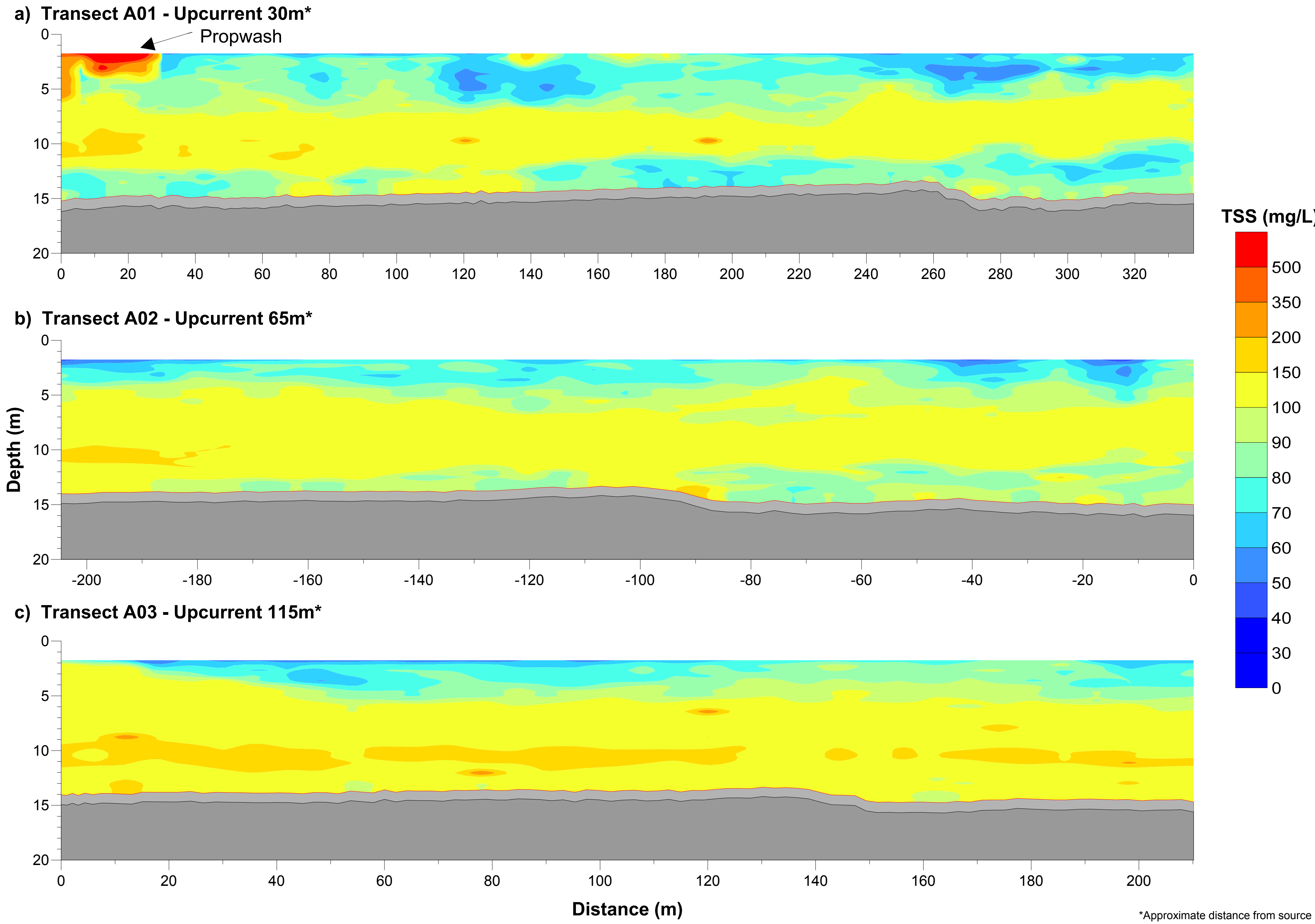


FIGURE	*USACE Harborwide TSS Far Field Survey HDP Contract Area: S-AN-2*	**Vertical Profiles of ADCP Average TSS 04 January 2011 - Ebb Tide, Transects T07, T08, T09**	TIDE
37a-c			**Ebb**



*Approximate distance from source

FIGURE	USACE Harborwide TSS Far Field Survey HDP Contract Area: S-AN-2	Vertical Profiles of ADCP Average TSS 04 January 2011 - Ebb Tide, Transects A01, A02, A03	TIDE
38a-c			Ebb

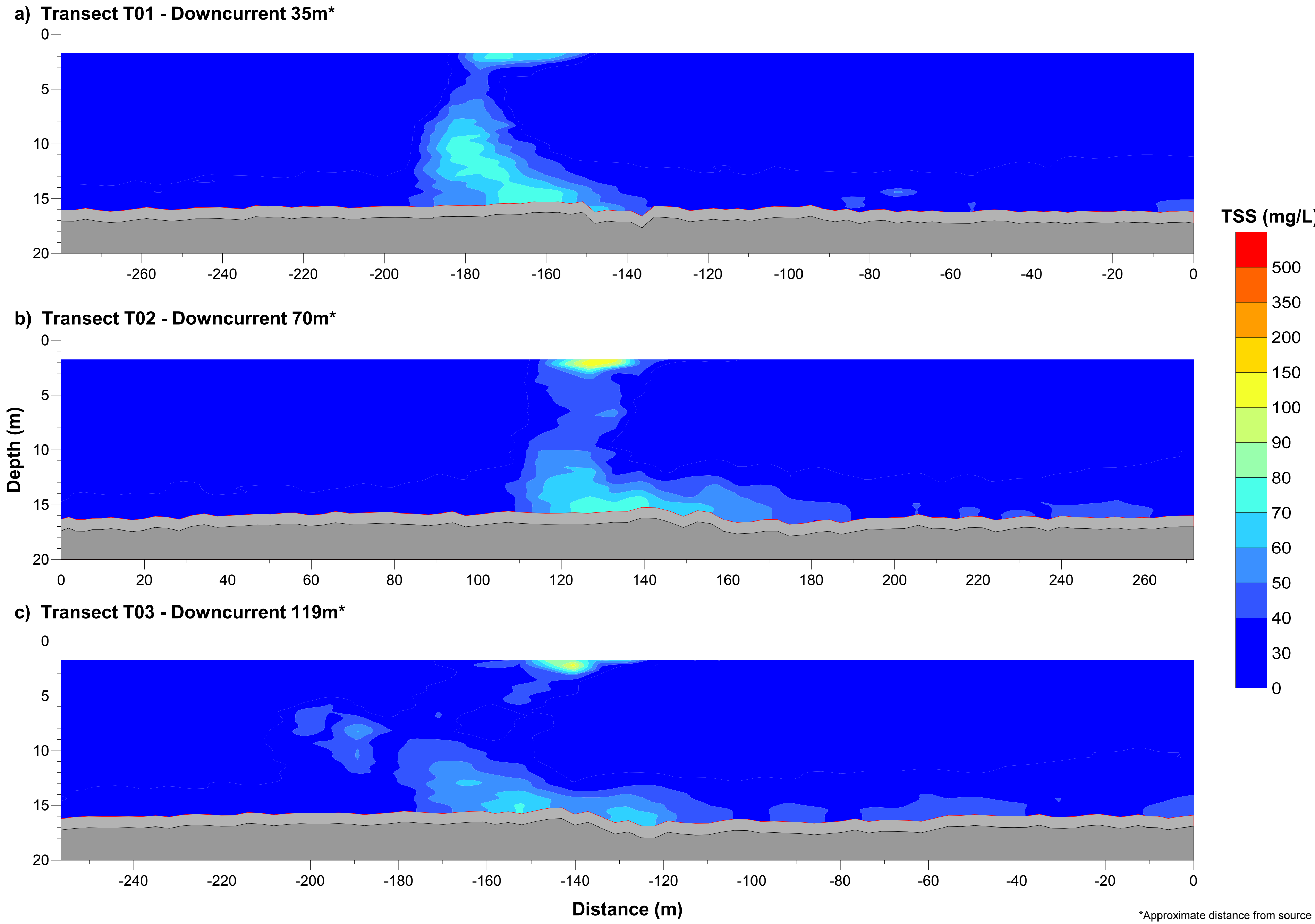
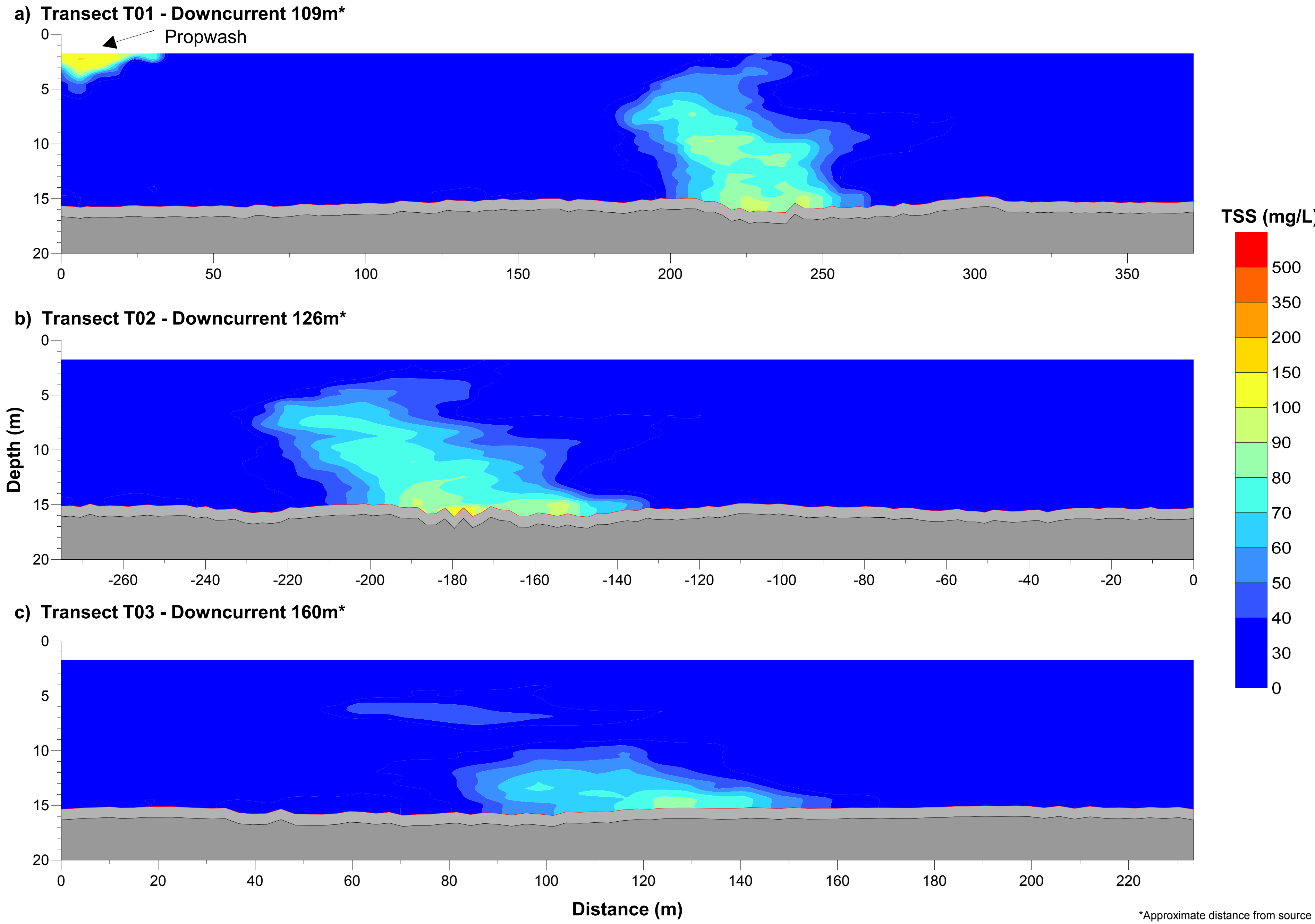
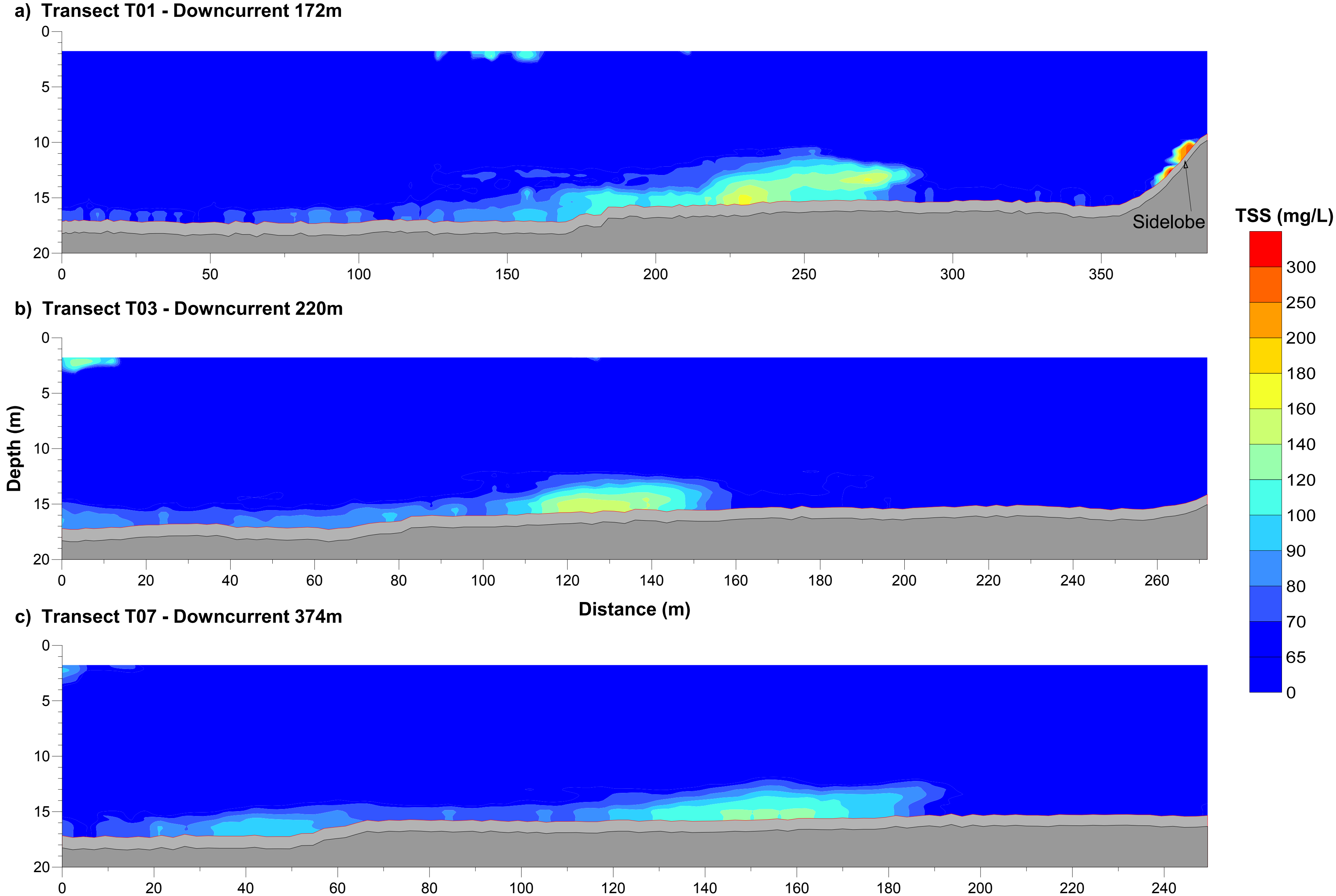


FIGURE	*USACE Harborwide TSS Far Field Survey HDP Contract Area: S-AN-2*	Vertical Profiles of ADCP Average TSS 06 January 2011 - Flood Tide, Transects T01, T02, T03	TIDE
39a-c			Flood



*Approximate distance from source

FIGURE	*USACE Harborwide TSS*	**Vertical Profiles of ADCP Average TSS**	TIDE
40a-c	*Far Field Survey* *HDP Contract Area: S-AN-2*	**06 January 2011 - Ebb Tide, Transects T01, T02, T03**	Ebb



*Approximate distance from source

FIGURE	*USACE Harborwide TSS Far Field Survey KVK Cutterhead*	**Vertical Profiles of ADCP Average TSS 23 March 2011 - Flood Tide, Transects T01, T03, T07**	TIDE
41a-c			**Flood**

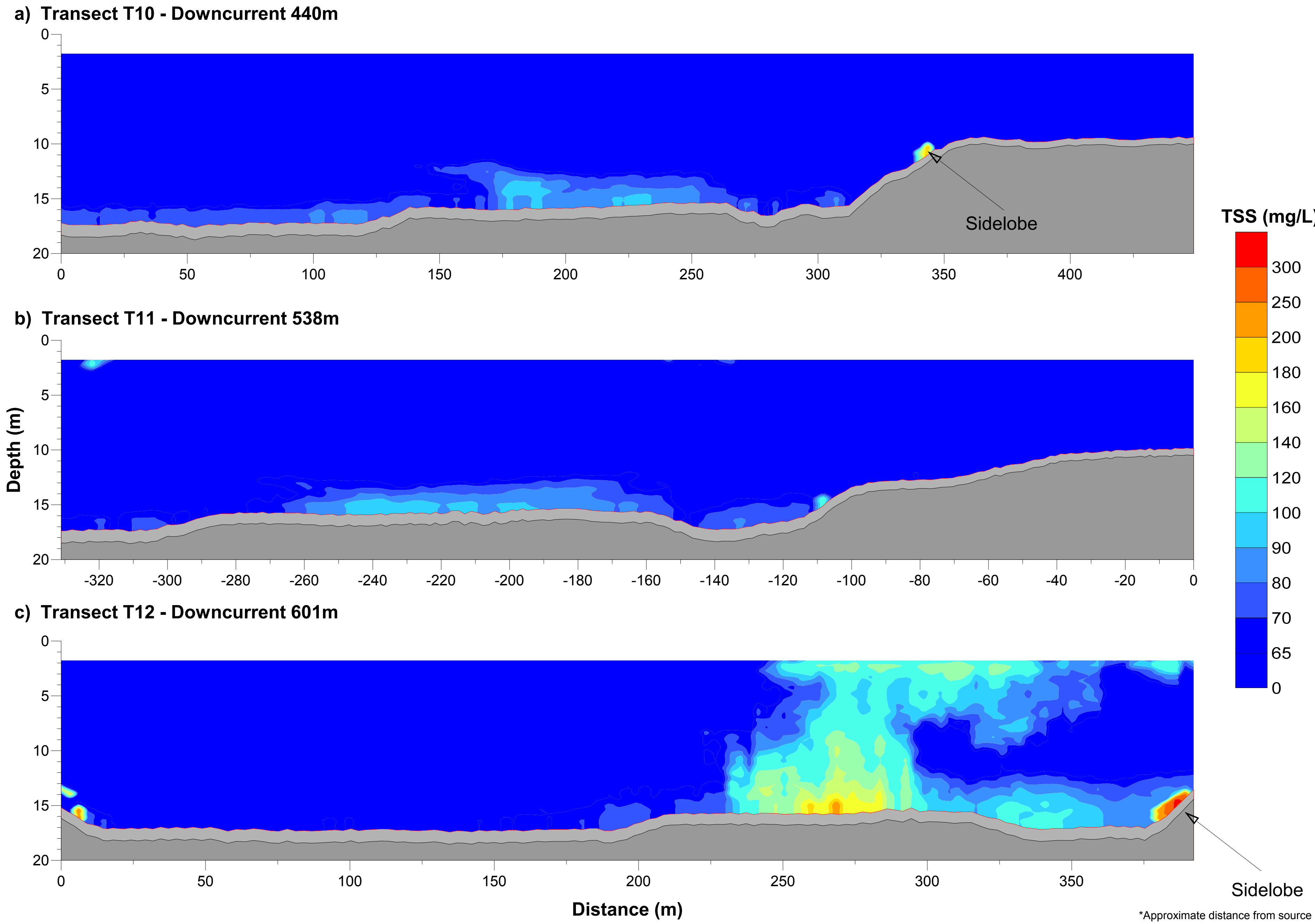
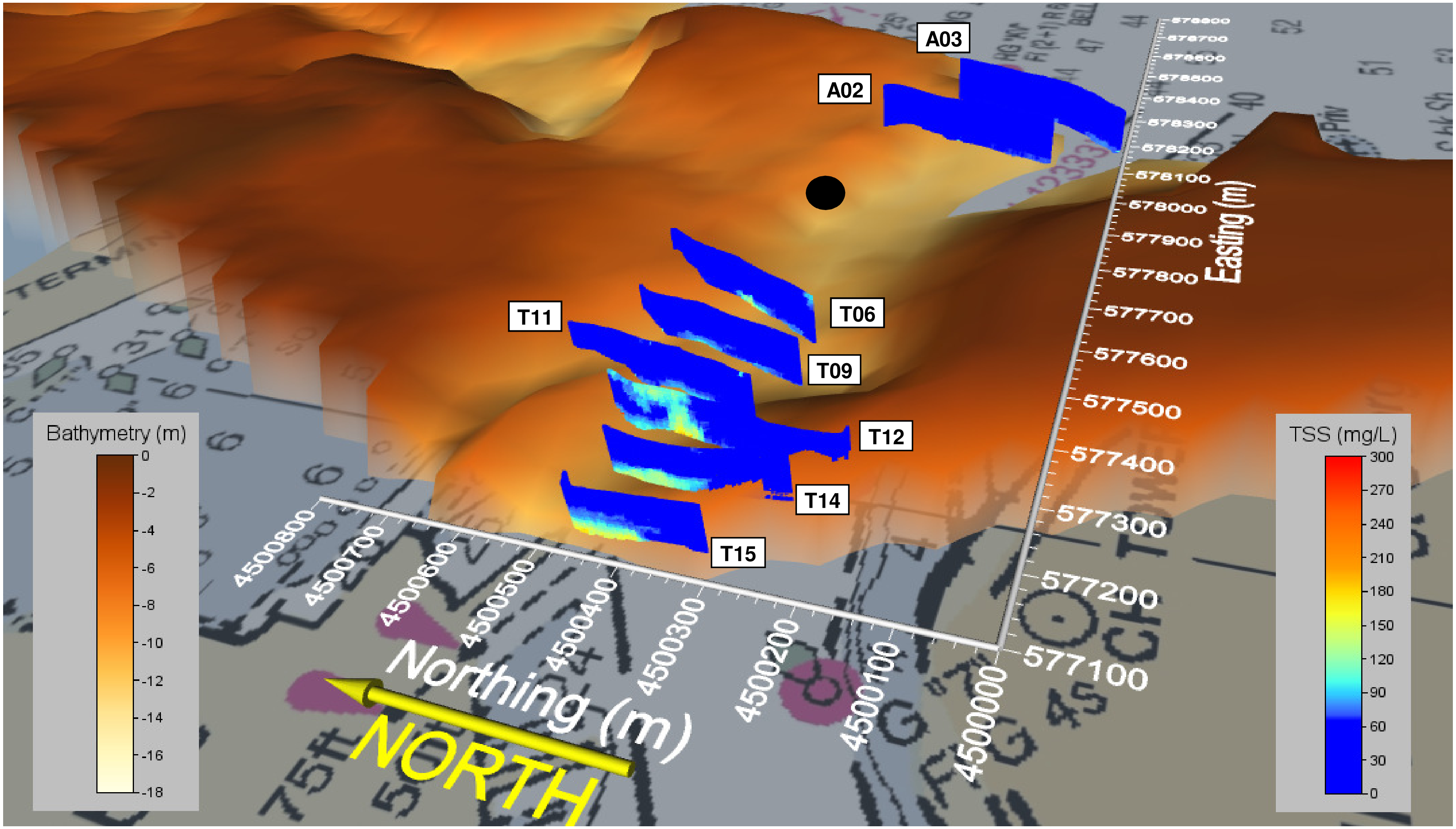


FIGURE	*USACE Harborwide TSS Far Field Survey KVK Cutterhead*	**Vertical Profiles of ADCP Average TSS 23 March 2011 - Flood Tide, Transects T10, T11, T12**	TIDE
42a-c			**Flood**



Bathymetry produced from NOAA soundings

Z Scale Exaggerated 6x

● = Cutterhead Location

Figure	*USACE Harborwide TSS* *Far Field Survey* *KVK Cutterhead*	**ADCP Average TSS Values with Respect to their x, y, and z Coordinates** **Superimposed on Channel Bathymetry** **23 March 2011**	Tide
43			Flood

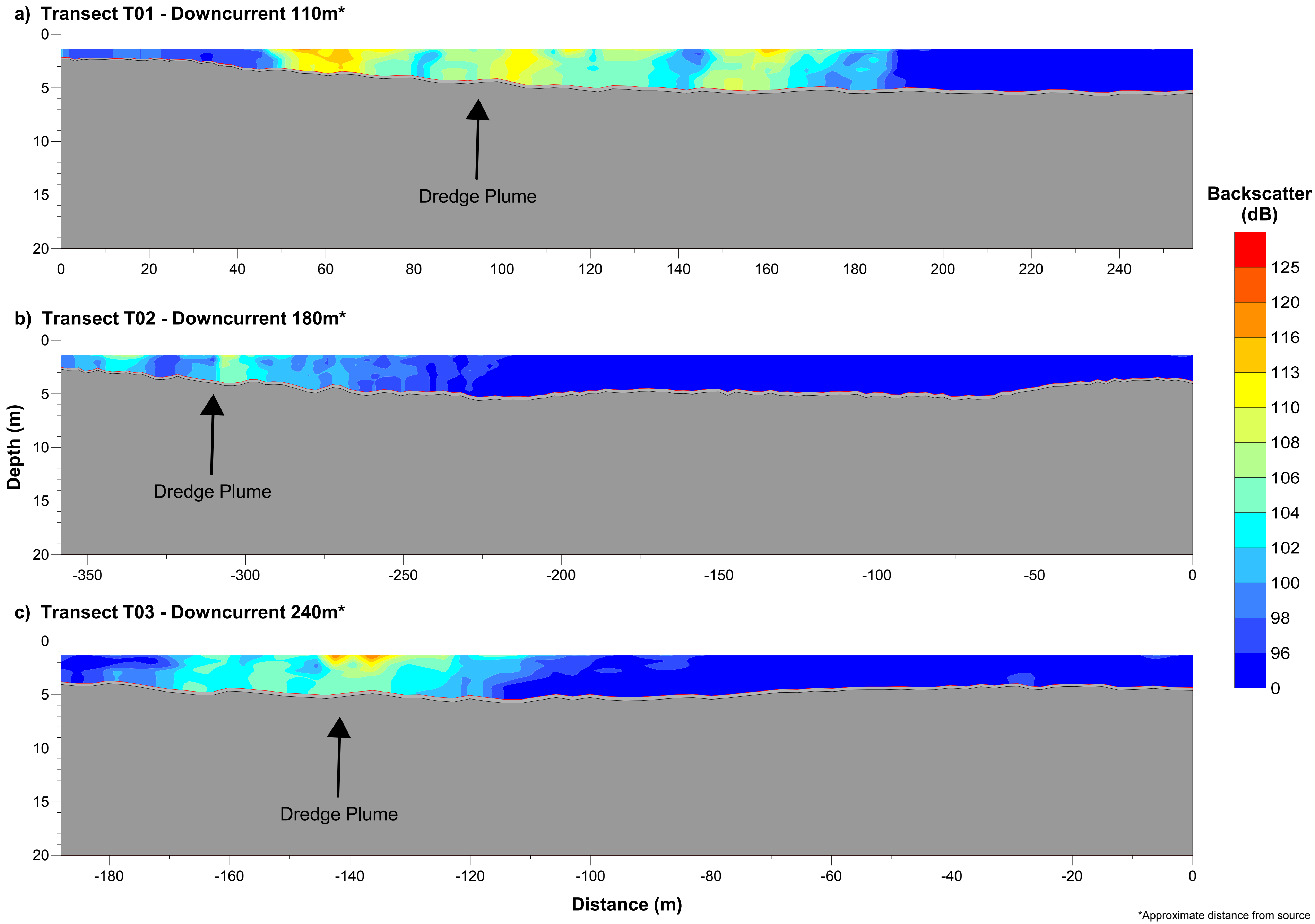
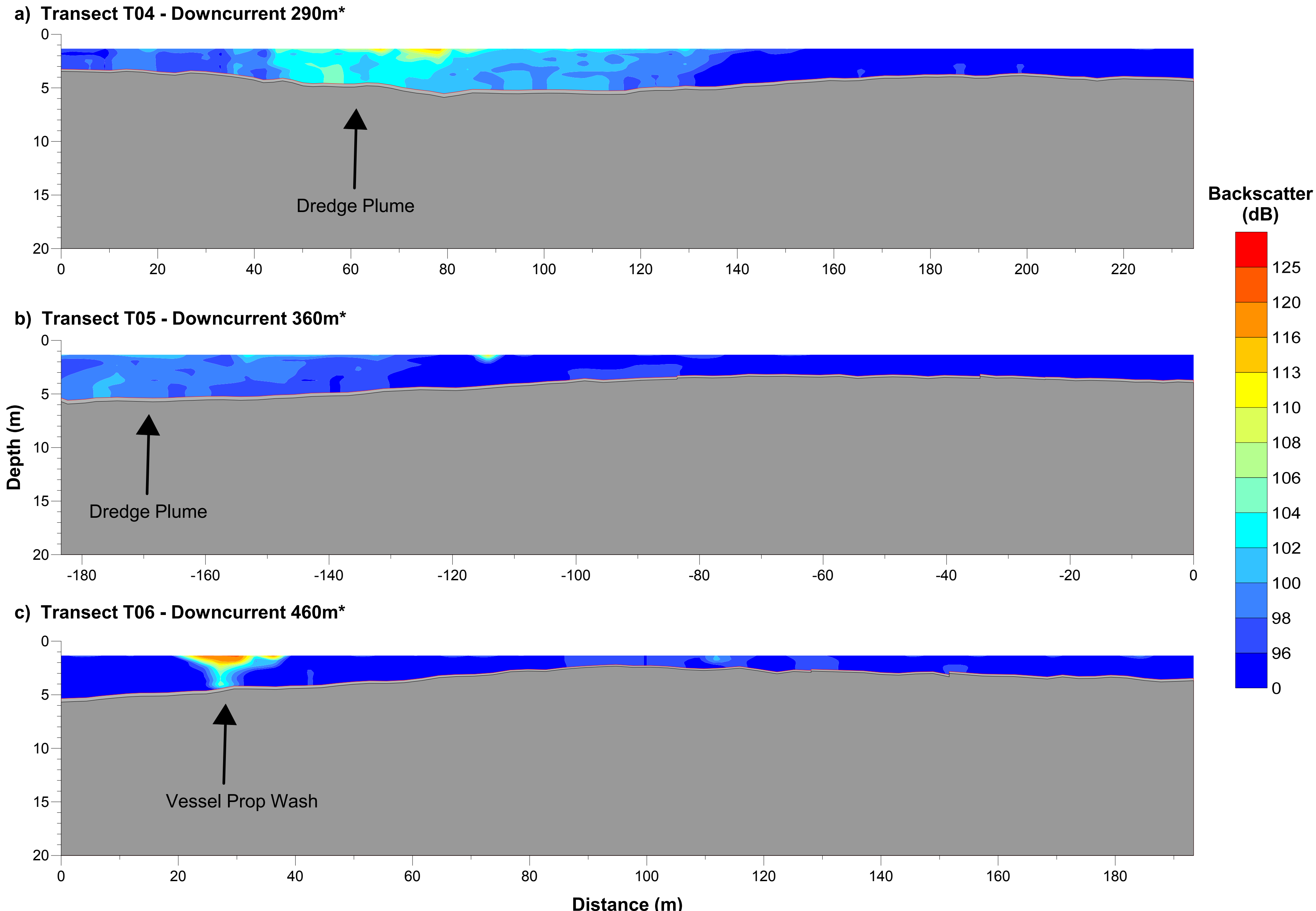


FIGURE	*USACE Harborwide TSS Far Field Survey Jones Inlet*	Vertical Profiles of ADCP Average Backscatter (dB) 27 January 2014 - Flood Tide, Transects T01, T02, T03	TIDE
44a-c			Flood

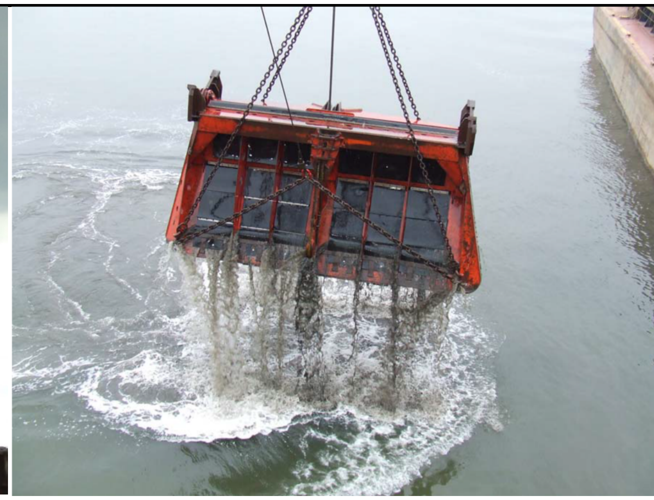


*Approximate distance from source

FIGURE	USACE Harborwide TSS Far Field Survey Jones Inlet	Vertical Profiles of ADCP Average Backscatter (dB) 27 January 2014 - Flood Tide, Transects T04, T05, T06	TIDE
45a-c			Flood

Appendix A: Photo Record of Working Dredges during Harbor Deepening Project Surveys

AK 2/3 – Dredge *Michigan*



S-NB-1 - Dredge *#53*

S-E-1 - Dredge *Delaware Bay*

S-KVK-1 – Dredge *Illinois*

S-AN-2 – Dredge *Michigan*

S-KVK-1 – Dredge *Florida*

S-NB-2 – Dredge *Delaware Bay*

S-AK-2 – Dredge *Delaware Bay*

S-AK-3 – Dredge *54*

Jones Inlet – Dredge *C.R. McCaskill*