Final Report:

Impacts of shoreline modifications on fishes and crabs in New York Harbor

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Executive Summary

We sampled fishes along a variety of shorelines (bulkheaded, rock-armored, and sloping sand) in New York Harbor over the summer and fall of 2011 and 2012 using a visual census approach. Because of turbidity and nighttime darkness, we used DIDSON sonar as a proxy to visualization. We sampled 3 to 4 long-shore transects at approximately 2, 12, 22, and 32 m from the shoreline during daytime and nighttime to account for diurnal habitat shift in fishes, applying a kayak in shallow water to minimize fish disturbance. Reviewers translating DIDSON imagery to numerical abundance and fish size data, but were constrained to classifying ecological functional groups rather than species because of limits to sonar resolution. Transect occupations were supported by ground truthing and enumeration using traps, cast nets, gill nets and beach seines; however, use of these collection devices are exclusive to or highly biased in function among different habitat types while the DIDSON is much less so. Sampling for fishes was accompanied by physical/chemical sampling (salinity, temperature, dissolved oxygen concentration, depth, and water flow from an ADCP) to examine correlates of fish distribution among shoreline types.

Sampling yielded an unbalanced design because shoreline modifications are, by intent, exclusive to different habitats characterized chiefly in terms of depth and energy. Naturalized shorelines with gentle slopes persist only in relatively quiescent areas and correspond with shallows, while bulkheads and large rock rip-rap correspond to steep vertical profiles proximal to deep water and strong flows. Thus it was not possible to completely disassociate all independent variables at shorelines. Therefore, we also sampled an expanse of shallow water away from any shorelines.

Almost all habitats were dominated by pelagic fishes either as aggregations, schools, or singletons. The riprap habitat had the most representatives of all the fish categories (11) with marsh and shallows having much fewer (6). The most abundant of these categories were small pelagic singletons throughout all habitats (52.3 – 82.1%). Benthic fish and small aggregations of large pelagic fish were the most infrequently encountered of all of the categories. The riprap was dominated by small pelagic singletons (58.1%), small schools of pelagic fish (20.5%) and large pelagic singletons (9.1%). Bulkhead habitats had a similar composition, i.e. small pelagic fish (52.3%), small schools of small pelagic fish (20.9%), and large pelagic fish (11.2%). Beaches were similar with small pelagic singletons dominating (63.4%) followed by small schools of small pelagic fish (26.6%). The marsh and shallows habitat were the least diverse in fish categories and, of these, small pelagic singletons (82.1% and 74.7%) dominated. In the marsh the abundance was similarly spread between small schools, large aggregations and singletons of small pelagic fish (30.0 – 35.8%). A large proportion of those at the beach were small schools of small pelagic fish (43.0%), and large schools of small pelagic fish (27.9%). At the riprap, large aggregation of small pelagic fish (42.9%) and large schools of small pelagic fish (35.9%) were the categories with the most fish. At the bulkhead habitats the largest proportion was large aggregation of small pelagic fish (46.5%). The first and second axes of a PCA accounted for 69.1 % of intersample variataion in class assemblages (35.7 % and 33.4 % respectively). The first axis cleanly differentiated night and day samples, with large schools of small fish (during the day) and large aggregations of small fish (during the night) driving the separation; this was a result of a change in behavior of fish, primarily Atlantic silversides, rather than a turnover in habitat use. The second axis, similarly important, moderately differentiated marsh sites, with a relatively greater abundance of benthic species, from all other sites.

Water along deeper shorelines tended to have more pelagic fishes, notably a mix of anchovies and Atlantic silversides classified as “small schooling pelagic fish” and Altantic menhaden. The abundance appeared to respond especially to depth, rather than shoreline type among deep water types, irrespective of distance from shore; however, they were much more abundant within deep, calm Liberty State Park than at similarly deep but energetic environments along the Brooklyn water front. Other fishes, most notably juveniles of large species (such as striped bass and bluefish) and fish that remained small as adults, (primarily benthic oriented mummichogs but also mullet) as well as crabs (primarily blue crabs), were exclusive to gently sloping shallow shorelines. Because of the mutual association of shoreline type with depth and energy profile, the effect of fish distribution could be potentially explained by depth and energy alone, while recognizing that that the modifications themselves are the principal agents of persistence or creation of those profiles. Thus, when shoreline modifications alter depth and energy profiles regardless of their type, they remove important calm, shallow water habitats that are the exclusive habitats of some fishes or life stages. In summary, shorelines sampled in the New York harbor by DIDSON, which is biased towards visualization of pelagic fishes, were characterized by the same assemblages as adjacent open regardless of modification type, while these were largely absent from shallow marsh shoreline habitat. However, sampling for benthic and cryptic fishes revealed a greater abundance and diversity of these in quiescent marsh shoreline habitats.

Introduction

One of the most important modifications that impacts shoreline habitat is a barrier between water and land meant to dissipate or steer wave or current energy to prevent erosion to beachfront property or deposition of sediments (Cox et al. 1994, Nightingale and Simenstad 2001, Bulleri and Chapman 2010). Thus, this “barrier” modification cuts off sediment and surface water exchange and can drastically change the shoreline’s vertical profile. Seawalls, revetments, groins, rip-rap, and jetties are in this class. In blocking sediment and water exchange, they also block exchange of detritus from beach or marsh vegetation, a primary driver of shallow water primary production (Weinstein and Kreeger 2000), and they block the movement of fauna into shallow productive water, altering their ability to feed, spawn (e.g. mummichog, horseshoe crabs), and avoid predators (e.g. Hodson et al. 1981, Smith et al. 1984, McIvor and Odum 1988, Rozas and Odum 1988, Kneib 1997, Rypel et al. 2007).

As a result of the above, several questions arise. How do fish and crabs distribute along natural (vegetated or unvegetated) sloping, simple (e.g. bulkheaded), or complex (e.g. rip-rap) armored edges? Does slope steepness or substrate matter? Quantification of fish response to these and other shoreline modification is lacking despite knowledge that bulkheading or other armoring corresponds with a break in trophic exchange and pathways to spawning and nursery habitat (Smith et al. 1984, Rozas and Odum 1988, Rypel et al. 2007, Dugan et al. 2008).

Here we report on a project that is relevant to understanding the effects of shoreline modification on estuarine function as critical habitat for fishes and crabs, and to the successful management or mitigation of those effects. Human modification of shorelines, by intention, alters physical properties at the land-water interface. While this provides numerous benefits to commerce and property protection, it may alter the function of estuaries as essential habitat for fish and crabs, some of which rely on the shallow water common to estuaries (Ruiz et al. 1993, Dittel, et al. 1995, Rypel et al. 2007, Able and Fahay 2010). The nature of a response by different species of fishes and crabs and different life history stages to this modification depends on the type of impact, and the strength of the response might vary as some function of the amount of modification. A response may also be to the indirect effects of the modification, such as a change in sediment deposition resulting from the direct effect of wave energy dissipation. Therefore, the faunal response is not always intuitive or linearly related to the extent of the structural modification, but might, for example, follow threshold dynamics, or promote "edge-effects" in distribution or abundance by the juxtaposing of different resources (e.g. shelter and food) (Reese and Ratti 1988, Austin 2002) or by "reflection" (e.g. when animals encounter a modification and turn around, thus accumulating nearby). The known modifications of the shoreline, although usually static, exist within spatially diverse environments and in physically dynamic conditions, thus the interaction affects, whether additive or threshold, are very difficult to assess except empirically.

We used Dual Frequency Identification Sonar (DIDSON) for understanding the effects of shoreline modification on estuarine function as critical habitat for fishes and crabs, and to support the successful management or mitigation of those effects.

State of Current Knowledge

The value of estuaries to the persistence of healthy populations for several important fish and crabs species has been well documented (Able and Fahay 1998, 2010, Beck et al. 2001) including for the Hudson River (Waldman et al. 2006a, b). Despite their recognized importance, estuaries have been greatly altered through increasing development and urbanization and the Hudson River estuary is the epitome of these types of alteration. Alterations include bulkheads for commercial operations along shorelines and stabilization and extension of property for large commercial buildings. These structures dominate the shoreline of the lower Hudson River estuary to the near exclusion of natural shoreline (Squires 1992), but their impact on living natural resources, particularly fishes and crabs, still needs to be quantified and perhaps should be the focus of mitigations efforts.

The concerns about the impacts of shoreline modifications are validated in our recent work in the Hudson River Estuary and the work of others, particularly in Puget Sound (Nightingale and Simenstad 2001). Other published studies have been in the Hudson River estuary, using approaches best suited to the narrowly defined questions they addressed, and limited in scale by the state of technology. Nevertheless, these have been very revealing and form a solid foundation on which to build a further understanding. These studies have primarily used nets or cages and, in limited applications, low-light video as detailed below.

Conventional sampling techniques may be greatly biased in quantifying assemblage differences among naturalized and highly modified nearshore habitats because of the need to use specific gears in each different habitat type and the hindrance that structures create for the use of towed nets, seines, and gill nets (e.g. Able 1999). Work directly focused on shoreline fishes in the

Hudson River estuary has most often used beach seines (e. g. Hurst et al. 2004). This work usually targets assessment of young-of-the-year sportfish (e.g. striped bass) but has revealed that many species are at least occasionally found in shallow water along smooth, sloping shorelines. These assemblages are dominated by Atlantic silversides, temperate basses (moronids), and shad and river herring (alosines) but contained as many as 60 species (Hurst et al. 2004). However, seines can only be used along unstructured, sloping beaches, and there is no way to judge where the captured fish occurred in the cross-shore gradient, so the distribution of fish relative to the shoreline or its modification cannot be determined.

In deeper water, trawls have been used to sample parallel to a variety of beaches with different slope or structure. This includes comparisons of trawl surveys from similar water depths but adjacent to natural and bulkheaded shorelines in Barnegat Bay, NJ, (Paul Jivoff, Rider College, unpublished data). There, water off bulkheads lacked shallow (<1m) water depths. Sediment composition also differed among the shoreline types, with bulkheaded sediments losing silt fractions to medium through gravel-sized particles. In apparent response, fish and crab diversity and abundance were reduced in front of bulkheads as compared with the natural shorelines (both beach and marsh). Boat-pulled trawls were also used to sample fishes alongside pier structures and in adjacent open waters in the lower Hudson River estuary, finding an assemblage reflective of "open water" rather than shallow estuarine habitat (Bain et al. 2006). In all cases, trawling with a motor boat in shallow water poses a potentially great disturbance to which mobile fish can react. Further, it is limited to smooth bottom rather than bottom where structures such as pilings or rip-rap are present.

Other studies, especially our own, have extensively commented on the impacts of large commercial piers at shorelines in the Lower Hudson River estuary. These include, specifically, fish response to piers (e.g. Duffy-Anderson and Able 1999, Able et al, 1997, Able and Duffy-Anderson 2005) in which we examined the distribution of benthic and structure oriented fishes using traps. We also evaluated the effect of pier habitat on growth. On time scales of weeks, juveniles of most tested benthic fish species caged under piers grew slower, suffered higher mortality rate, and had less full stomachs than fishes caged in open water despite higher prey (invertebrates) availability under piers. Presumably, this was a function of decreased ability to see prey in the dark under shaded piers. These studies clearly identified a negative effect of the mechanism (shading) on shallow water habitat suitability and fish production. However, pelagic fishes such as bay anchovy, silversides, river herring, weakfish, bluefish, and larger striped bass could not be studied by this method. In nature, fish may utilize both shallow and deep, open and under pier habitat for different ecological services at different time scales (such as feeding in open water at night and sheltering under piers during the day) at much shorter time scales than can be examined in caging studies. Thus, benefits of periodic or episodic use of these habitats could have been hidden.

Description of the Approach

Study Site

The study was carried out along the shorelines of the New York Harbor region of the lower Hudson River estuary between Brooklyn Bridge Park and Liberty State Park on the New Jersey side, but also extended up to the mouth of the Bronx River (Table 1, Fig. 1). These shorelines are heavily modified with bulkheads (a retaining wall), rip-rap (a foundation of rock used to armor shorelines), jetties, and other structures (Squires 1992) that prevent shoaling at the land-water interface and cut off water from shoreline vegetation and soil, but may provide habitat for fishes and crabs. There is a small region of semi-natural shoreline between Caven Point and Liberty State Park (Fig.1) on the New Jersey side of the river that was a mitigation site (Princeton Hydro) that served as a reference site. At that site, the shoreline is naturally sloping sediment fronted by common reed (*Phragmites australis)* and smooth cordgrass (*Spartina alterniflora*) dominated banks (marsh). Next to the naturalized shoreline is a set of ripraps and bulkheads adjacent to a public boat ramp. One bulkhead is corrugated metal whereas the other is a wooden piling bulkhead. The riprap at this site differs; one is smaller boulders (10-30 cm) whereas the other is large boulders (25-80 cm). In addition there is a wide area of shallow (0.5 – 2 m at low tide) naturalized sloping beaches (mixture of sand and gravel).

Along the southeast perimeter of Governor's Island (Fig. 1) there is an area where depositional flow has created naturally sloping beaches that end on the landward side in bulkheading, e.g. naturalized beach but not adjacent to upland habitat. A small oyster reef is located approximately 22 m out from the beach and is marked by a buoy. The area was crossed during our transects. In the boat basin at the north end of Governor's Island there is a wooden bulkhead leading up to a very small beach and riprap. At Brooklyn Bridge Park (Fig. 1), there is a more naturalized landscape that replaced derelict piers in 2010 (Urbanki and Gleeson 2012), as well as both corrugated metal bulkheads and 2 separate sets of riprap (10-80 cm boulders). A small sloping beach site is located just south of the Brooklyn Bridge on the east side of the East River in a little cove surrounded by riprap and some broken down pilings. The beach contains numerous small rocks and glass mixed in sand. An oyster reef restoration site is located at Soundview Park in a semi protected area where the Bronx River opens into the East River. The park is surrounded by riprap (136-742 m) made up of large boulders.

Technical approach

DIDSON multibeam sonar was used to sample both large and small fishes in the Hudson River estuary. We used a kayak sampling platform to allow sampling of very shallow water with minimal disturbance of fishes (see Able et al. 2013, Able et al. in review). The DIDSON images were used to characterize the bottom and the adjacent shoreline type (i.e., sea walls, rip-rap and other man-made structures, salt marsh, other vegetation and beach/flats).

The DIDSON provides high-resolution images across numerous habitat types through the use of dual beam (1.8 MHz and 1.1 MHz) ensonification (Able et al. in review a, b). At the likely range of 1-10 m (oblique through 0.5-5 m water depth) and a 1.25 x 5 m (across by downrange) window, the resolution will vary between 2.5 mm and 10 mm per pixel. A smaller window length (5 or even 2.5 m) is useful in very shallow water and increases resolution but decreases sample radius. Sampling was at a moderate rate of 8-10 frames per second (depth dependent for processor reasons) to detect movement. Dual beam ensonification mitigates many of the concerns of commercial-scale acoustic fish surveys that rely on sound reflection mainly from the swim bladder (Kalikhman and Yudanov 2006). Even individual fish fins, which generally have low reflectance but are valuable to identification, are discernible in DIDSON images (Brown et al. 2007, Able et al. 2013. Able et al. in review). Large fish such as striped bass can be individually counted in DIDSON videos and identified by characteristics of the individual fish image while small must be identified and enumerated based on computed classification algorithms that utilize multivariate characteristics of the schools. These characteristics for small fish must be measured using graphic-user-interface tools and the values exported to other software for multivatriate analysis such as principle components analysis (PCA) or canonical variates analysis, which are useful in describing the strength of gradients (and thus confidence) in characteristics.

Existing DIDSON software allows background subtraction to reveal objects in the water column that can be individually counted and sized using available routines. A splash-proof laptop computer within the kayak cockpit allowed real-time viewing so that the paddler could adjust focus and direction for closer inspection of potential targets. A motor skiff (20' with outboard) stood-by near the kayaks with supplies and to carry the kayak rapidly between sample sites. The position of the survey kayak was tracked using on-board GPS linked directly to the DIDSON software through a port on the host laptop. Notes on shoreline features were dictated onto a voice recorder integral to the DIDSON software and synchronized with the acoustic video files upon playback. Time stamps from the DIDSON recordings were married to navigation recordings to map the position of fish and other targets.

Sample Design and Analysis

Visual census strategies and statistical tools have been developed and vetted for use in complex environments such as forests by ornithologists and for use on coral reefs by ichthyologists (Seaman 2000). We used these visual sample strategies for high resolution, directed, acoustic-imaging surveys capable of discriminating individual fishes in close association with both complex habitats (e.g. rip-rap and bulkheads) and simple habitats (e.g. sloping soft sediment and bulkheads).

Directed sampling in each year took place in two rotations, one in June/July and the other in August/September, when numerous resident and migrant species gather in the lower estuary and young-of the year fish, especially of forage species such as silversides and killifishes, have attained a large enough size to be detected (> 30 mm) with the DIDSON (Able et al. 2013, Able et al. in review). Juvenile fishes sufficiently large to distinguish by ensonification, and adults of small species such as bay anchovy and Atlantic silversides as well as horseshoe crabs, are common beginning in June. Larger individuals, such as subadult or older predatory fishes (e.g. striped bass, white perch, and bluefish) utilize the estuary most in early summer and migrate in fall (Able and Fahay 2010 and unpublished data). Sampling in June/July 2011 consisted of 4, 8 hours shifts that included both day and crepuscular periods. In August/September 2011 and both sampling cycles in 2012 included sampling throughout both the day and night for 4 consecutive days (Table 2).

A transect sample design was used to map distribution of fish and submerged shoreline features among habitats. Sampling measured both fish abundance and the frequency of occurrence of "events" (e.g. schools or singletons both are counted as a single independent event) in a transect. Fish and crab counts were standardized to survey time in post-processing. Up to four parallel transects (each 5 minutes in duration) at each location were paddled in the along-shore direction to quantify abundance as a function of distance from the shoreline edge of interest and depth. In some case along bulkheads in deep water, only 3 transects were accomplished because of safety concerns regarding ship traffic in the river, but by then the kayak was in deep water. Transects were approximately 2, 12, 22, and 32 m from the shoreline. Species occurrences are being mapped to physical and hydrographic features (temperature, salinity, depth, current direction, shoreline type, distance from shore, proximity to other features), and the relationship of abundance and frequency of occurrence to water depth and distance to edge features quantified in ongoing analysis. For the purpose of this report, abundance is examined graphically based on categorical distance from shore (transect) within and across shoreline types.

All transects were accompanied by physical-chemical sampling (temperature, salinity, dissolved oxygen, secchi disk, tidal stage) using a YSI 650 (Yellow Springs Instruments, Yellow Springs OH) and a measure of the length of shoreline habitat sampled using a Global Positioning System (GPS). Flow in 3 dimensions in each habitat was characterized using an ADCP (Workhorse Rio Grand, Teledyne RDI, Poway, CA) during 3 site visits. The ADCP was deployed on a boom mount from a skiff so that it rode at the waterline. The supporting skiff was maneuvered along and across shoreline sampling sites. Data were processed into vertical and horizontal flow profiles to help characterize sites.

Calibration between DIDSON images and observer identifications began under a previous New York City Parks and Recreation funded project both at the Rutgers University Marine Field Station (RUMFS) boat basin in southern New Jersey and in New York Harbor (Able et al. 2013, Able et al. in review). DIDSON files were viewed by two independent reviewers in the host software (Sound Metrics Corporation, 2007), followed by a single reviewer who would consolidate and evaluate their data. Reviewers recorded each event of a fish presence (either school or individual fish). "Abundance" was determined by counting manually (in the event of few fish) or by taking an estimate (for schooling fish) using the average of three grid squares (using the superimposed grid application in the DIDSON software) and multiplying that by the number of squares with fish in them. A range of measurements were also taken for both length and body depth of the fish using the "Mark Fish" tool in the DIDSON software. Reviewers also categorized school organization on a ranked basis of 1-4 from highly organized (parallel swimming, reaction to nearest neighbor) to random milling as a potential metric for classification. These differences can be seen in schools such as Atlantic menhaden and aggregations of Atlantic silversides and bay anchovies (Figure 2). Additional details are available in Able et al. 2013 and Able et al. in review.

Since most small (and difficult to identify) fish occur in monotypic schools, groundtruthing techniques were used to verify species composition. Cast nets (6.35 mm mesh and 1.2 m radius, 9.5 mm mesh and 0.9 m radius, and 9.5 mm mesh and 1.2m radius with a weighted circumference line) were used to capture small pelagic fishes when seen on the surface. Gill nets (multi-mesh and 25 m in length) were used to sample larger pelagic species in the open water. Killitraps (cylinder standard minnow trap with 20 mm opening, 6 mm mesh) were set out from the shoreline and placed at 2, 12, 22, 32 m to collect juvenile fish. Seine nets (6.1 m with 3 mm bar mesh, 6 mm stretch mesh) were used to collect pelagic fishes parallel to beach locations.

Results and Discussion

Habitat Characteristics

The structural components of the sampled habitat types were quite different (Fig. 3, Table 1). The most rugose habitat was rip-rap with piles of individual boulders that varied from 10 – 80 cm in greatest dimension. These occurred from the supratidal to the subtidal and had interstices of various sizes and depths but these were not measured. One of the simplest habitat types consisted of vertical bulkheads, which were often corrugated, and stretched from the supratidal to the subtidal. Both of these shoreline habitats types had consistently deeper waters (bulkhead 2 - 13 m, rip-rap 1.5 - 10 m) than the beach (1.4 – 3.7 m) and marsh habitats (0.8 – 1.1 m) (Table 1). Beaches were small, shallow and had various substrate types (e.g. sand, concrete/brick rubble). The shallow marsh habitat was dominated by *Spartina alterniflora* along the edge with soft mud substrates in the intertidal and subtidal portions of the site. Mud flats with no shorelines were 1 - 2 m deep.

While most environmental characteristics of the aquatic portion of each shoreline habitat were similar, at least by estuarine standards, there was some variation between habitats and sites (Fig. 4,5, Table 1). Temperature at all of the Liberty State Park habitats was generally higher during both 2011 and July of 2012 (22.8-26.5) than all the other sites (21.3-24.1). Temperature was lower at all sites in September of 2012 (19.4-21.1). Salinity varied between habitats and months at the same sites. The highest values occurred during June of 2011 at all the habitats at the Liberty State Park site (27.7) and July of 2012 at the bulkhead at Governor's Island (27.4). The lowest salinities occurred at all the habitat types at Liberty State Park in August (0.1 – 3.7). The values for dissolved oxygen were less frequently taken in 2011 due to malfunctions with the probes but were consistently high and ranged from 5.2-13.1 while in 2012 the range was from 4.0-12.9.

Flow at the sites varied greatly (Appendix). Flow at quiescent Liberty State Park and Sound View sits sites were often less than 0.16 m/s while flows at Brooklyn Bridge State Park and Governors Island Oyster Reef approached or 2 m/s and were characterized by strong horizontal shear at channel edges as well as by eddy fields at the end or break in physical features such as at the end of a bulkhead or the shoal that supported the oyster reef.

Fish Taxa/Categories, Size Composition and Abundance

Groundtruthing with a variety of gears provided species specific fish identifications, habitat use pattern, (Table 3) and helped to determine those species represented in DIDSON images. Overall, 39 species of typically estuarine fishes [two exceptions were freshwater species, the bluegill (*Lepomis macrochirus)* and yellow perch (*Perca flavescens*)] were collected, most of these (38 species) were from seine hauls on beaches. The most abundant fishes caught with these methods were Atlantic silverside (*Menidia menidia)* (Table 3). Their size ranges from groundtruth sampling (18-117 mm) overlapped the values obtained with DIDSON, thus confirming that these species probably made up the bulk of small pelagic singletons/schools (Figure 6). The next most abundant species were mummichog (*Fundulus heteroclitus),* bay anchovy (*Anchoa mitchilli*), Atlantic menhaden (*Brevoortia tyrannus*), and striped bass (*Morone saxatilis)* (Table 3). These species varied depending on habitat and gear. All other species were less frequent across all gear types. The numerous fishes collected by seine in beach habitats allowed the identification of location/habitat differences (Table 3). Most notably, the number of fish species collected at Brooklyn Bridge Park (n =12) was much less than those collected at Governor's Island (n = 21) and Liberty State Park (n = 19). Atlantic silverside, blue crabs, and mummichogs were most abundant at the naturalized sandy beach near Liberty State Park. This site was in close proximity to the adjacent marsh habitat, one of the few places in Upper New York Harbor with this type of habitat.

The DIDSON images detected approximately 25,000 individual fish during 2011 and 79,000 during 2012 (Table 3). Of these, the largest proportion was detected during the nighttime in 2011 and during the daytime in 2012. While the DIDSON was limited in its ability to identify fishes to species in this and other studies (Able et al. 2013, Able et al. in press), in some instances we were able to determine them. For example, the characteristic swimming behavior of adult menhaden (*Brevoortia tyrannus*) (Fig. 3) was evident and could be confirmed visually when fish jumped out of the water and because of their unique schooling behavior. Also, Atlantic silversides were occasionally visible from the kayak by eye during transects and could thus be identified.

The length frequency of fishes for 2011 DIDSON ranged from 10 – 652 mm with a mean of 136.5 mm while 2012 ranged from 10 – 1010 mm with a mean of 83.7 mm (Fig. 6) (although the precision of the measurement of the smallest individuals as a fraction of total size is limited by pixel size). The majority of fish were small (less than 150 mm) in both years. The size of fish detected with a variety of groundtruthing gears (Table 3) ranged from 7 – 350 mm with a much smaller mean value (65.9 mm). This was because groundtruthing undersampled the larger and abundant menhaden and the infrequent but very large predatory fish that were visible to DIDSON. Despite the mean size difference, however, the dominant modal size was 50 – 100 mm both in DIDSON and groundtruthing approaches (Fig. 6).

The composition of fishes detected in this study are similar to those of a previous two year data collection at Pier 40 in the Hudson River as observed in groundtruth sampling with similar gears (Able et al. 2013, Able et al. in press). The only striking difference was in the distribution and abundance of benthic fishes in the prior study. The same applies to the size of fishes, i.e. samples were dominated by small individuals (50 – 100 mm).

Fish Species Composition by Habitat and Location

Preliminary research and our prior experience allowed us to identify several categories of fishes based on DIDSON images at the study site (Table 4a, b). Almost all of these were dominated by pelagic fishes either as aggregations, schools, or singletons. The riprap habitat had the most representatives of all the fish categories (11) with marsh and shallows having much fewer (6). The most frequently occuring of these categories were small pelagic singletons throughout all habitats (52.3 – 82.1%). Benthic fish and small aggregations of large pelagic fish were the most infrequently encountered of all of the categories.

The composition of these categories, as compiled for individual events, varied by habitat (Table 4a). The riprap was dominated by small pelagic singletons (58.1%), small schools of pelagic fish (20.5%) and large pelagic singletons (9.1%). Bulkhead habitats had a similar composition, i.e. small pelagic fish (52.3%), small schools of small pelagic fish (20.9%), and large pelagic fish (11.2%). Beaches were similar with small pelagic singletons dominating (63.4%) followed by small schools of small pelagic fish (26.6%). The marsh and shallows habitat were the least diverse in fish categories and, of these, small pelagic singletons (82.1% and 74.7%) dominated. The abundance of fish, as detected by DIDSON varied by habitat as well (Table 4b). In the marsh the abundance was similarly spread between small schools, large aggregations and singletons of small pelagic fish (30.0 – 35.8%). A large proportion of those at the beach were small schools of small pelagic fish (43.0%), and large schools of small pelagic fish (27.9%). At the riprap, large aggregation of small pelagic fish (42.9%) and large schools of small pelagic fish (35.9%) were the categories with the most fish. At the bulkhead habitats the largest proportion was large aggregation of small pelagic fish (46.5%).

The size composition of fishes varied between and within habitat types (Fig. 7, 8). The largest fish (> 250 mm) were typically observed with the DIDSON at the deepest shoreline types (e.g. bulkhead and riprap habitats). Smaller fish and the peak modal size (50 -150 mm) were found across all habitats and sites in 2011. The smallest average size fish occurred at beaches in both 2011 and 2012 (Liberty State Park = 52.8, 90.6 mm, Governor’s Island = 80.5, 91.9 mm, Brooklyn Bridge = 69.0, 73.5 mm) as well as the bulkhead at Governor’s Island (69.2, 62.1 mm). The largest average size occurred at the Brooklyn Bridge bulkhead in 2011 (122.7 mm) and at the Governor’s Island riprap in 2012 (178.9 mm). Overall there was a larger average size in 2012 than in 2011 at all sites and locations due to an abundance of large Atlantic menhaden that year.

Many of the same fish categories that dominated at the shoreline habitats in this study were also present at Pier 40 on the Hudson River, thus there are no obvious differences in those faunal components, as observed by DIDSON (Able et al. in review a, b). The groundtruthing samples during 2011 and 2012 provided some resolution in species composition by habitat and behavior (Table 3). Many of the fishes detected were those commonly found in these waters including Alosine shads, *Anchoa, Brevoortia, Menidia, Morone, Mugil, Pomatomus*, and a few others (Table 3). A dominant species in marsh/shallow shoreline habitats that are relatively undisturbed or successfully restored in other estuaries is the mummichog (*Fundulus heteroclitus*) (Able and Fahay 2010, Able et al. 2012). This species was commonly collected at the marsh with killitraps and seines and occasionally in seine collections on a riprap shoreline with small rocks. This occurrence in the marsh is not surprising because marsh habitats are essential to most stages in the life history of this species (Able and Fahay 2010).

Fish Composition by Habitat and Distance from Shore

In an attempt to determine the spatial extent of shoreline habitat type effects we sampled with the DIDSON at various distances (approximately 2, 12, 22, 32 m) from each shoreline in each habitat and location (Fig 9, 10). Fish were observed at all transect distances from shore throughout all habitats and sites. In 2012, fish increased in abundance relative to depth, but the opposite was true in 2011, specifically at the Liberty State Park habitats. Again, this owed in part to a higher abundance of large Atlantic menhaden in 2012, but Atlantic silverside were also very common throughout deeper water habitats at Liberty State Park that year. We observed a strong algae bloom at Liberty State Park in 2012 and it was apparent by a sharp change in water color and clarity at the mouth of the basin that concentration was somehow maintained by the particular circultaion there. The majority of fish in the beach habitat were seen in closer distances to shore for both years. If we assume that the fish in the 2 m transect are those that are most likely to reflect preference for different habitats, the patterns of abundance are highest at bulkhead, rip-rap and marsh at Liberty State Park and at the bulkhead at Brooklyn Bridge Park in 2011. The pattern was somewhat similar in 2012 with the highest values at beach, bulkhead and rip-rap at Liberty State Park and at the beach at Brooklyn Bridge Park.

The average length of fish, as a function of distance from each shoreline habitat was often similar across habitat types and sites in both 2011 and 2012 (Fig. 10, 11). This was most often obvious for the smaller fishes at all beach sites and fairly similar to the marsh sites. At bulkheads, most sites had larger average fish with the exception at Governor's Island. Initially, it appears that much of this pattern can be explained by the distribution of large aggregating or schooling menhaden, and the understanding that the deeper, farther transects off bulkheads have essentially transitioned to open, rather than shoreline waters. This observation also supports the argument that results from the 2 m transects alone best reflect how shoreline fish respond to shoreline type. The observed shear in alongshore flow was interesting as it is a gradient with inflection point relative to distance offshore that sometimes coincides with a break in depth but not necessarily with other variables. If fish are able to sense flow even when they can't see bottom, which is possible and likely, then shear may be a defining characteristic in separating "shoreline" and "open water" habitats and deserves further attention especially as it is influenced by the rugosity of the shoreline structure and its profile.

Fish Response to Created Oyster Reef

The environmental characteristics of the oyster reef sites at Governor's Island and Soundview Park (Fig. 1) shared many of the values observed at the other sites. Temperature ranged from 20.8 to 24 °C at both. Salinity was 5.6 to 25.8 parts per thousand. Dissolved oxygen was 4.1 to 5.6 mg/L.

Fish category composition for the created oyster reefs is based on a relatively small sample size of fishes (n = 2431) and thus these observations are preliminary. Several categories that were detected at the other habitat/sites were not detected in the oyster reefs including small schools of large pelagic fish at Governor's Island and large aggregations of small pelagic fish at Soundview Park (Table 5). The most abundant at Governor's Island were both large and small schools of small pelagic fish. The most abundant category at Soundview Park was small schools of small pelagic fish. The sizes of fishes detected at the oyster reef sites were similar to the other sites in that the dominant size category was 50 - 100 mm in 2011, but 0 – 50 mm in 2012 (Fig. 13). However, at the Soundview site there were few smaller fishes and more larger fishes than at Governor's Island, specifically in 2011.

Principle components analysis (PCA) graphically summarizes the variation discussed above. The first and second axes of a PCA on log (y+1) transformed abundance (centered and standardized by fish class) accounted for 69.1 % of intersample variataion in class assemblages (35.7% and 33.4 % respectively) while the third and fourth axes captured less than 10% and 8% variance respectively . Thus, plotting of the first two components against each other presented a reasonable reduction in complexity (Fig. 14 A). The first axis cleanly differentiated night and day samples, with large schools of small fish (during the day) and large aggregations of small fish (during the night) driving the separation (Fig 14 B). This was a result of a change in behavior of fish, primarily Atlantic silversides, rather than a turnover in habitat use. The second axis, similarly important, moderately differentiated marsh beaches from other types (Fig 15B, with a relatively greater abundance of benthic species. Water along deeper shorelines tended to have more pelagic fishes, notably a mix of anchovies and Atlantic silversides classified as "small schooling pelagic fish" and Altantic menhaden, reflected in the classification "small schools of large pelagic fishes" or "small aggregations of large pelagic fishes".

Efficacy of Approach

The usefulness of the DIDSON approach, using a kayak as a platform for data collection has been proven in multiple instances including in New York Harbor (Able et al. 2013, Able et al. in press). Despite the numerous advantages, there remain some difficulties in interpretation and application. First, the categories used in this study are general and typically do not allow identification of species, especially to the level attained by groundtruthing. These two techniques together help to bridge that gap. The DIDSON approach makes it possible to determine abundance and size, important ecological criteria for assessing fish characteristics. Second, the complex nature of selected habitats such as riprap with many interstices where some cryptic fishes can hide, makes detection and enumeration difficult for structure oriented fishes. This same difficulty applies to many traditional gears such as those used in groundtruthing. Third, tidal effects may limit detection. In the case of the marsh habitat, access to the marsh edge was limited to high tide in order to provide sufficient water depth so that a kayak and the attached DIDSON could move into the shallow area. However, at high tide many of the dominant fishes such as killifishes typically enter the flooded marsh surface vegetation (Able and Fahay 2010) and thus could not be detected by the DIDSON. Fourth, water depth varied by site, with deeper water typically occurring at shorelines dominated by bulkheads and riprap. These deeper sites allowed the DIDSON to search a larger volume of water than the shallow water sites, thus at the latter, the abundance of fishes may be underestimated because of the reduced volume of water searched. Despite these limitations, the DIDSON approach provides many advantages in the complex habitat in New York Harbor.

Outreach

Public education and outreach relevant to this project was accomplished through associations with St. Francis College (Brooklyn), New York Harbor School (NYHS, Governor's Island), and the Brooklyn Bridge Park (BBP) Association. St. Francis College faculty (Dr. Kathleen Nolan), graduate students, and undergraduate students participated in DIDSON kayak and skiff sampling efforts and ran additional weekend efforts in the BBP to demonstrate both the technology and the presence of fishes in the urban environment. NYHS high school students received an in-water demonstration of DIDSON and all DIDSON files collected at Governor's Island. Student Garcela Baysmore presented an analysis of these for a science fair under the oversight of Grothues and NYHS faculty Mauricio Gonzalez, and is sharing her experience with other students. In turn, these groups are sharing their files and long-term groundtruthing efforts (beach seine and traps) with us. Grothues also provided outreach as a Keynote Address for the St. Francis College *Symposium on Environmental Health and Health of the Environment*. The BBP published an interview with Grothues on their blog: http://www.brooklynbridgepark.org/news/blog/interview-with-professor-thomas-grothues

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Table 1. Habitat locations and characteristics of study sites during 2011 and 2012. See Fig. 1 for locations of habitats.

Habitat Type	Location	Water Depth (m)	Structure (substrate)	Salinity (Range, ppt)	Temperature (Range, °C)	Dissolved Oxygen (Range, mg/L)	# of DIDSON transects in 2011	# of DIDSON transects in 2012
Bulkhead								
	Liberty State Park	1.9-5.8	metal and wooden, substrate extending from subtidal to supratidal	0.1-27.7	19.4-26.3	4.9-11.7	42	41
	Brooklyn Bridge Park	7.3-13.4	Metal corrugated	5.3-32.0	20.9-24.1	4.9-10.4	18	16
	Governor's Island	2.0-2.9	Wooden	7.9-27.4	20.7-23.7	3.8-5.5	20	16
Rip-rap								
	Liberty State Park	1.9-5.8	10-80 cm boulders	3.4-27.7	19.4-26.3	5.5-10.5	54	41
	Brooklyn Bridge Park	1.5-9.8	10-80 cm boulders	5-32.0	20.6-24.1	4.0-10.4	37	44
	Governor's Island	2.7		7.9-25.3	20.9-23.6	3.8-5.1	3	11
Beach								
	Liberty State Park	1.4-2.0	Gradual sloping, sand and gravel	3.7-27.7	24-26.2	4.6-11.0	20	16
	Brooklyn Bridge Park	1.4-3.7	Sloping with a drop, sand and rocks	10.3-32.0	20.6-23.5	4.0-5.6	19	18
	Governor's Island	1.5-3.4	Drop off, sand with brick fragments	5.6-25.8	20.9-24.0	4.1-5.6	23	17
Marsh								
	Liberty State Park	0.8-1.1	Spartina alterniflora bordered by sloping mud and sand	2.8-25.5	24.0-26.5	5.7-13.1	19	17
Oyster Reef								
	Governor's	1.8-2.4	Low relief	10.7-25.8	20.9-23.7	4.1-5.2	4	4

	Island		enhancement of natural outcrop					
	Soundview Park	1.7	Low relief enhancement over flat bottom	16.4-25.8	20.8-23.1	4.7-5.1	7	3
Shallows	Jersey Flats	1.0-2.0		No data	No data	No data	0	8

Table 2: DIDSON imagery and groundtruthing effort by sampling gear in the Hudson River during 2011 and 2012. (In 2012 the killitraps were set for 24 hrs) (Crep = Crepuscular).

Sampling Gear	Sampling Year	Number of times Deployed			Number of Fish Detected/Captured			Number of Species Captured		
		Day	Night	Crep.	Day	Night	Crep.	Day	Night	Crep
DIDSON	2011	178	78	11	11074	13695	562	-	-	-
	2012	162	83	19	40322	37487	1132	-	-	-
Cast nets	2011	6	-	-	12	-	-	1	-	-
	2012	11	5	-	32	83	-	8	3	-
Killitraps	2011	11	21	-	2	139	-	5	2	-
	2012	-	20	-	-	179	-	-	6	-
Gill Nets	2011	2	-	-	11	-	-	1	-	-
	2012	4	8	1	13	26	7	3	3	3
Seine	2011	20	2	2	605	66	115	24	11	4
	2012	12	7	-	522	896	-	16	19	-
Totals										
DIDSON Samples		340	161	30	51396	51182	1694	-	-	-
Groundtruthing		66	63	3	1197	1389	122	58	44	7

Table 3. Fish species composition and abundance by groundtruthing gear in the Hudson River during 2011 and 2012 (see Table 2 for details of sampling effort).

Common name	**Scientific name**	Groundtruthing Gear							
		Cast Net		Gill Net		Killitraps		Seine	
		2011	2012	2011	2012	2011	2012	2011	2012
Fish									
alewife	*Alosa pseudopharengus*							2	
striped anchovy	*Anchoa hepsetus*		1						
bay anchovy	*Anchoa mitchilli*							164	8
anchovy	*Anchoa sp.*								1
American eel	*Anguilla rostrata*					1			1
silver perch	*Bairdiella chrysoura*			11		1		3	1
Atlantic menhaden	*Brevoortia tyrannus*		27		27				17
mummichog	*Fundulus heteroclitus*		16			135	53	54	60
striped killifish	*Fundulus majalis*						15	2	32
skilletfish	*Gobiesox strumosus*							3	1
naked goby	*Gobiosoma bosc*					1			3
pinfish	*Lagodon rhomboides*							2	
spot	*Leiostomus xanthurus*		2		4			5	
bluegill	*Lepomis macrochirus*							1	
inland silverside	*Menidia beryllina*								2

Atlantic silverside	*Menidia menidia*	13					278	270
silverside	*Menidia sp.*		1				1	3
northern kingfish	*Menticirrhus saxatilis*						4	2
tomcod	*Microgadus tomcod*				1		1	
white perch	*Morone americana*						1	
striped bass	*Morone saxatilis*			1			34	31
	Morone sp.				1		18	3
grubby	*Myoxocephalus aeneus*						1	
white mullet	*Mugil curema*		7					3
oyster toadfish	*Opsanus tau*				1		2	1
yellow perch	*Perca flavescens*						1	
bluefish	*Pomatomus saltatrix*		1	4			1	8
northern searobin	*Prionotus carolinus*						1	1
striped searobin	*Prionotus evolans*		2					
winter flounder	*Pseudoplueronectes americanus*						30	4
lookdown	*Selene volmer*						5	
northern puffer	*Spheroides maculatus*							3
northern sennet	*Sphreana borealis*						4	
scup	*Stenotomus chrysops*							2
northern pipefish	*Syngnathus fuscus*					1	7	4
tautog	*Tautoga onitis*							2

	Trachinotus sp.				6	
Crab						
blue crab	*Callinectes sapidus*	3	4	3	153	57
green crab	*Carcinus maenus*					1
spider crab	*Limulus polyphemus*				1	

Table 4a. Fish category events by habitat as detected with DIDSON in the study area in 2011 and 2012. See Table 3 type for timing of sampling and effort.

	Beach		Bulkhead		Marsh		Riprap		Shallows	
Fish Category	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Benthic Fish	8	0.6	2	0.1	1	0.6	3	0.1	0	0
Crab	0	0	0	0	0	0	2	0.1	0	0
Large aggregation of large pelagic fish	0	0	0	0	0	0	1	0.05	0	0
Large aggregation of small pelagic fish	11	0.8	45	2.3	1	0.6	45	2.2	2	0.9
Large pelagic singleton	23	1.7	219	11.2	7	3.9	187	9.1	19	8.2
Large school of large pelagic fish	1	0.07	16	0.8	0	0	5	0.2	0	0
Large school of small pelagic fish	32	2.4	87	4.5	0	0	88	4.3	0	0
Small aggregation of large pelagic fish	0	0	8	0.4	0	0	1	0.05	0	0
Small aggregation of small pelagic fish	44	3.3	73	3.7	2	1.1	71	3.4	5	2.1
Small pelagic singletons	849	63.4	1019	52.3	147	82.1	1199	58.1	174	74.7
Small school of large pelagic fish	1	0.07	71	3.6	0	0	40	1.9	1	0.4
Small school of small pelagic fish	369	27.6	408	20.9	21	11.7	423	20.5	32	13.7
TOTAL	1338		1948		179		2065		233	

Table 4b. Fish abundance by category for all fish in each habitat type as detected with DIDSON in the study area in 2011 and 2012. See Table 3 for timing of sampling and effort.

	Beach		Bulkhead		Marsh		Riprap		Shallows	
Fish Category	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Benthic Fish	9	0.08	2	0.004	1	0.2	2	0.005	0	0
Crab	0	0	0	0	0	0	2	0.005	0	0
Large aggregation of large pelagic fish	0	0	0	0	0	0	152	0.4	0	0
Large aggregation of small pelagic fish	1409	12.4	21676	46.5	196	30.0	18018	42.9	572	51.2
Large pelagic singleton	31	0.3	308	0.6	8	1.2	266	0.6	21	1.9
Large school of large pelagic fish	62	0.5	2314	5.0	0	0	340	0.8	0	0
Large school of small pelagic fish	3170	27.9	13337	28.6	0	0	15062	35.9	0	0
Small aggregation of large pelagic fish	0	0	157	0.3	0	0	4	0.01	0	0
Small aggregation of small pelagic fish	615	5.4	823	1.8	8	1.2	1044	2.5	101	9.0
Small pelagic singletons	1184	10.4	1475	3.2	207	31.7	1717	4.1	238	21.3
Small school of large pelagic fish	9	0.08	987	2.1	0	0	404	1.0	6	0.5
Small school of small pelagic fish	4889	43.0	5533	11.9	234	35.8	4990	11.9	180	16.1
TOTAL	11378		46612		654		42001		1118	

Table 5. Fish abundance by category for all fish as detected with DIDSON at the oyster reef sites for 2011 and 2012.

	Governor’s Island		Soundview	
Fish Category	Number	Percent	Number	Percent
Benthic fish	0	0	2	0.4
Large aggregation of small pelagic fish	53	2.7	0	0
Large pelagic fish	1	0.05	6	1.3
Large school of small pelagic fish	1556	79.5	61	12.9
Small aggregation of small pelagic fish	47	2.4	0	0
Small pelagic singletons	69	3.5	49	10.4
Small school of large pelagic fish	0	0	6	1.3
Small school of small pelagic fish	232	11.8	348	73.6
TOTALS	1958		473	

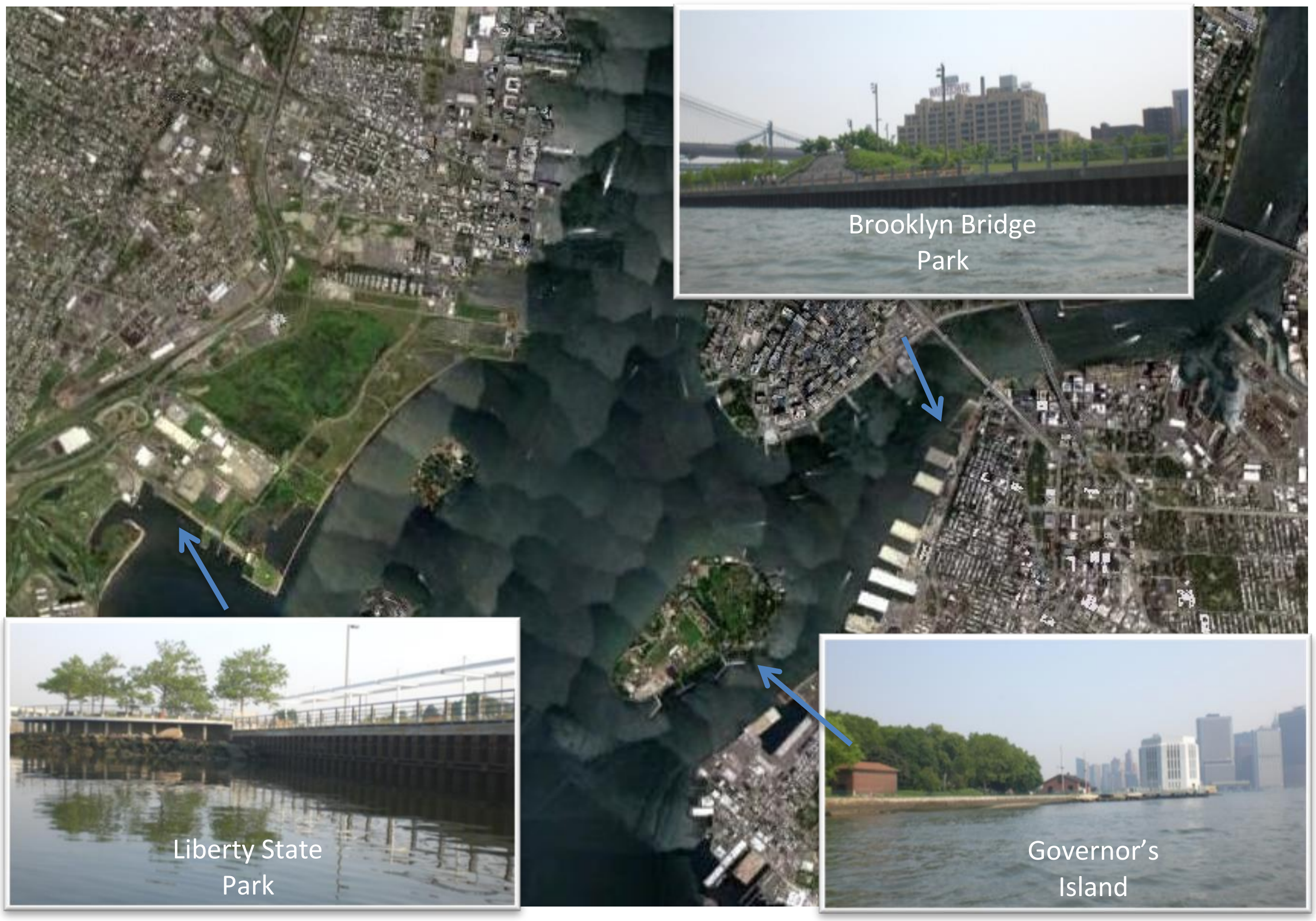


Figure 1. Study sites in upper New York Harbor. See Table 1 for details for each site.

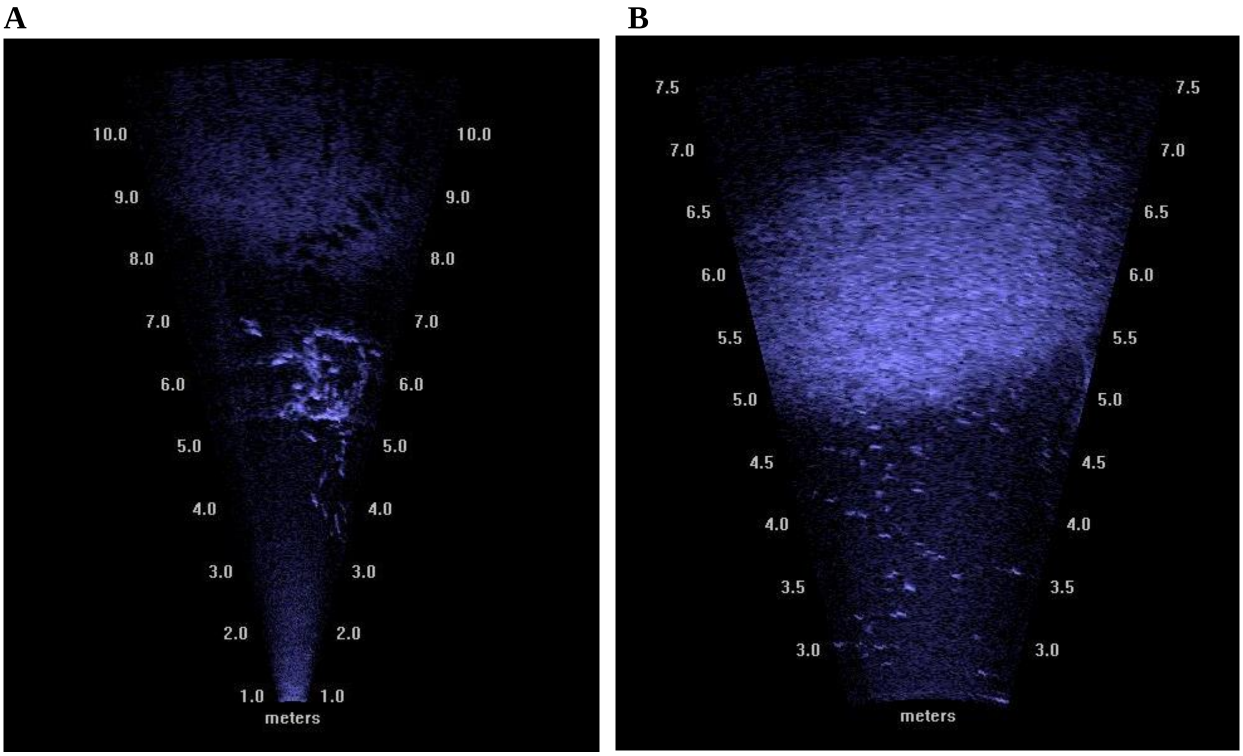


Figure 2. DIDSON images of a menhaden school (A) and a small fish aggregation (B).

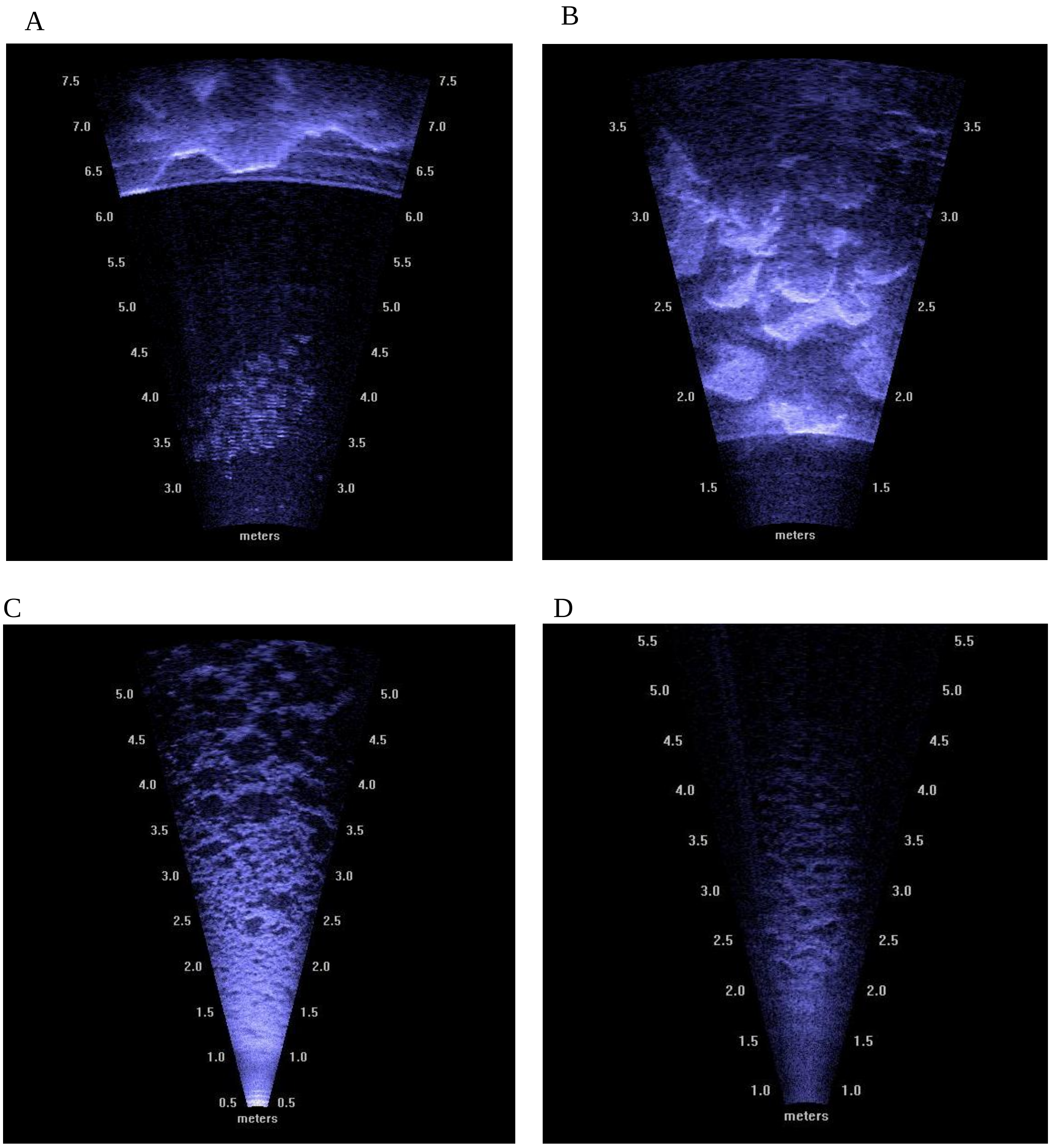


Figure 3. DIDSON images of various shoreline types including corrugated bulkhead (A), riprap boulders (B), sand and sediment mixture of the beach with biogenic depressions in subtrate (C), and sediment along the marsh with biogenic depressions (D).

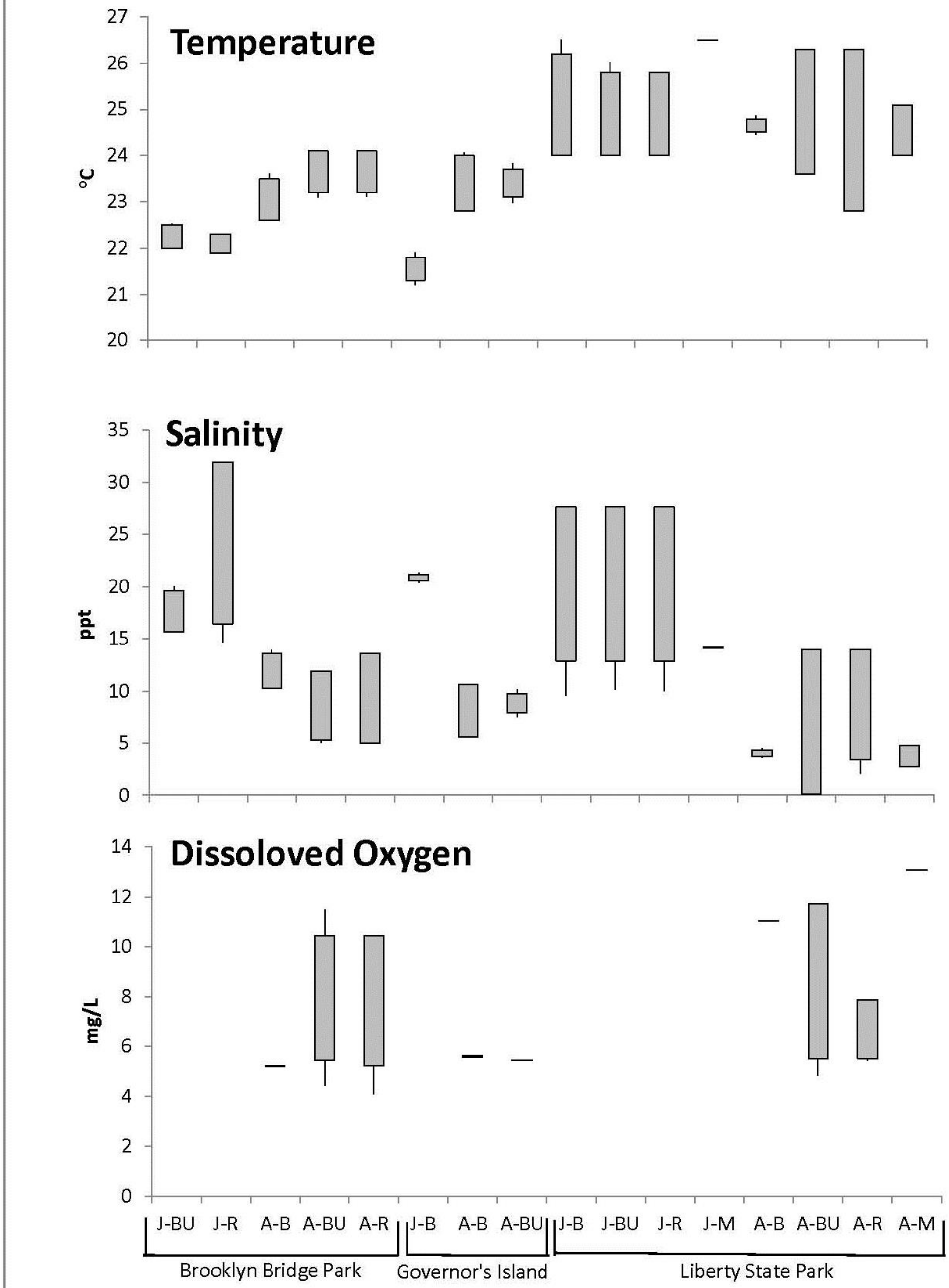


Figure 4. Environmental variable ranges (box ends) with standard deviation (bars) by habitat and site location for summer of 2011. J=June, A=August, BU= Bulkhead, B= Beach, R=Riprap, and M=Marsh.

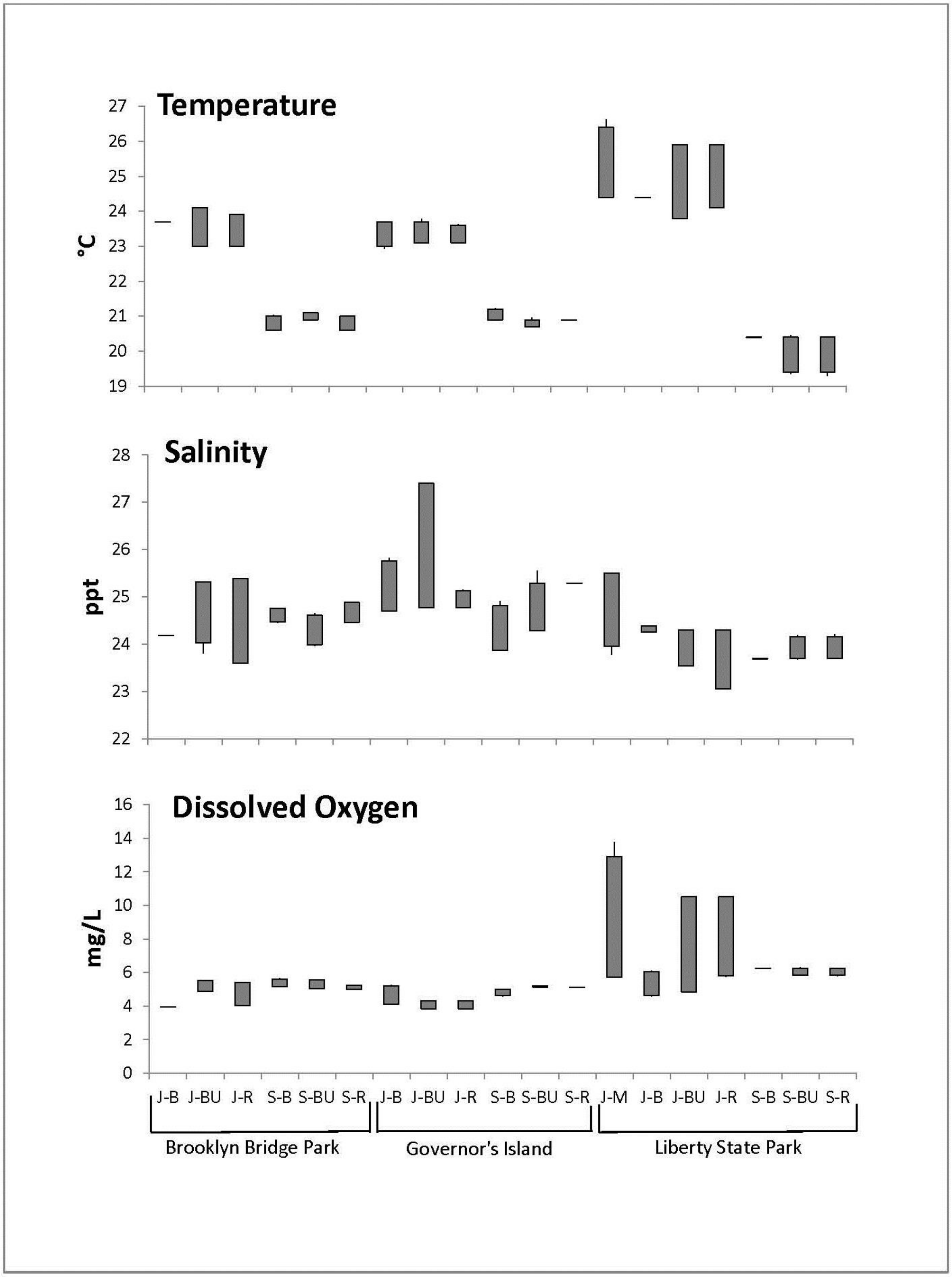


Figure 5. Environmental variable ranges with standard deviation by habitat and site location for summer of 2012. J=July, S=September, BU= Bulkhead, B= Beach, R=Riprap, and M=Marsh.

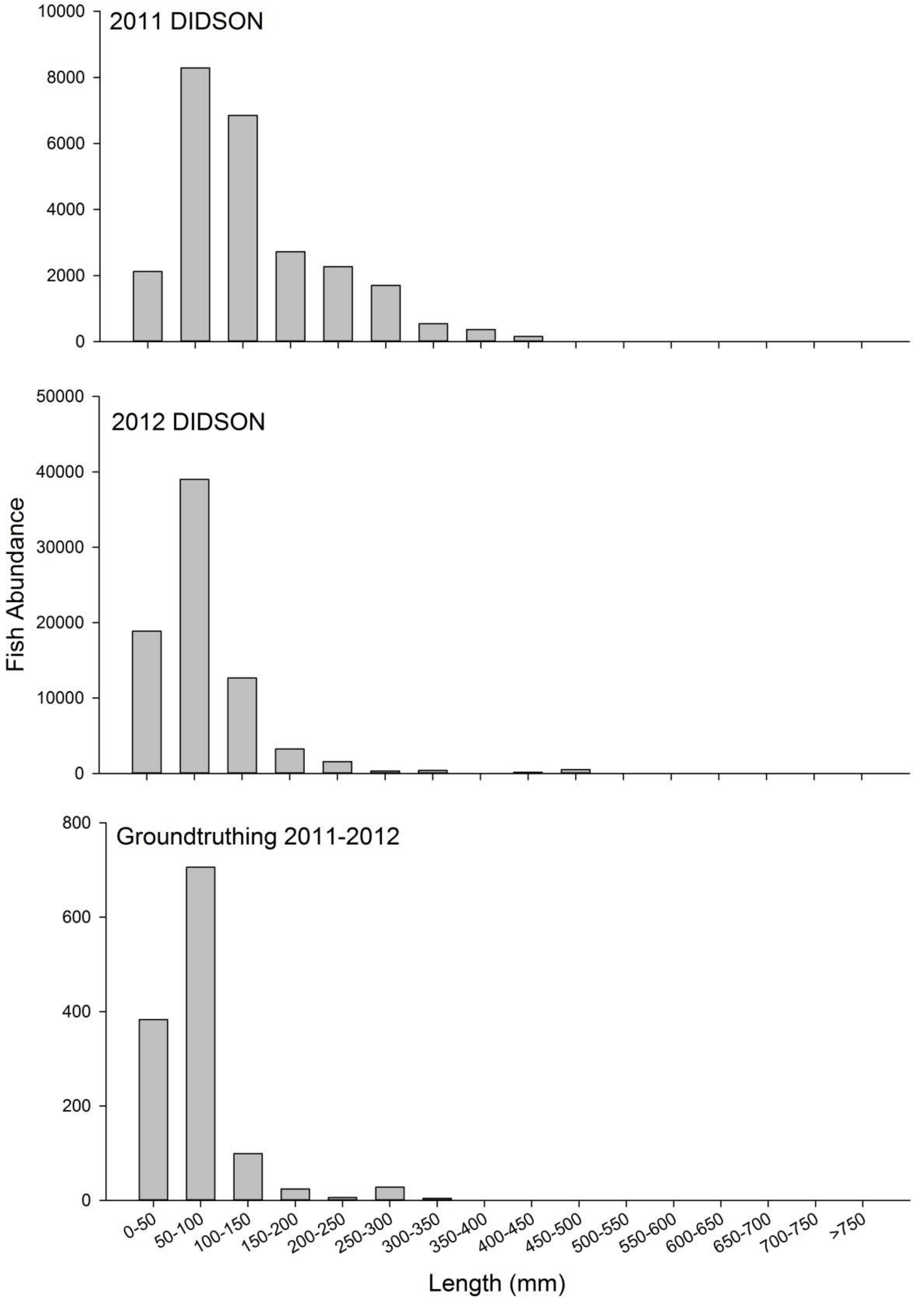


Figure 6. The length frequency distribution of abundance of fish for both DIDSON files and groundtruthing for 2011 and 2012. X-axis values reflect actual size range, although rare larger fish are not apparent on the scale of this y-axis.

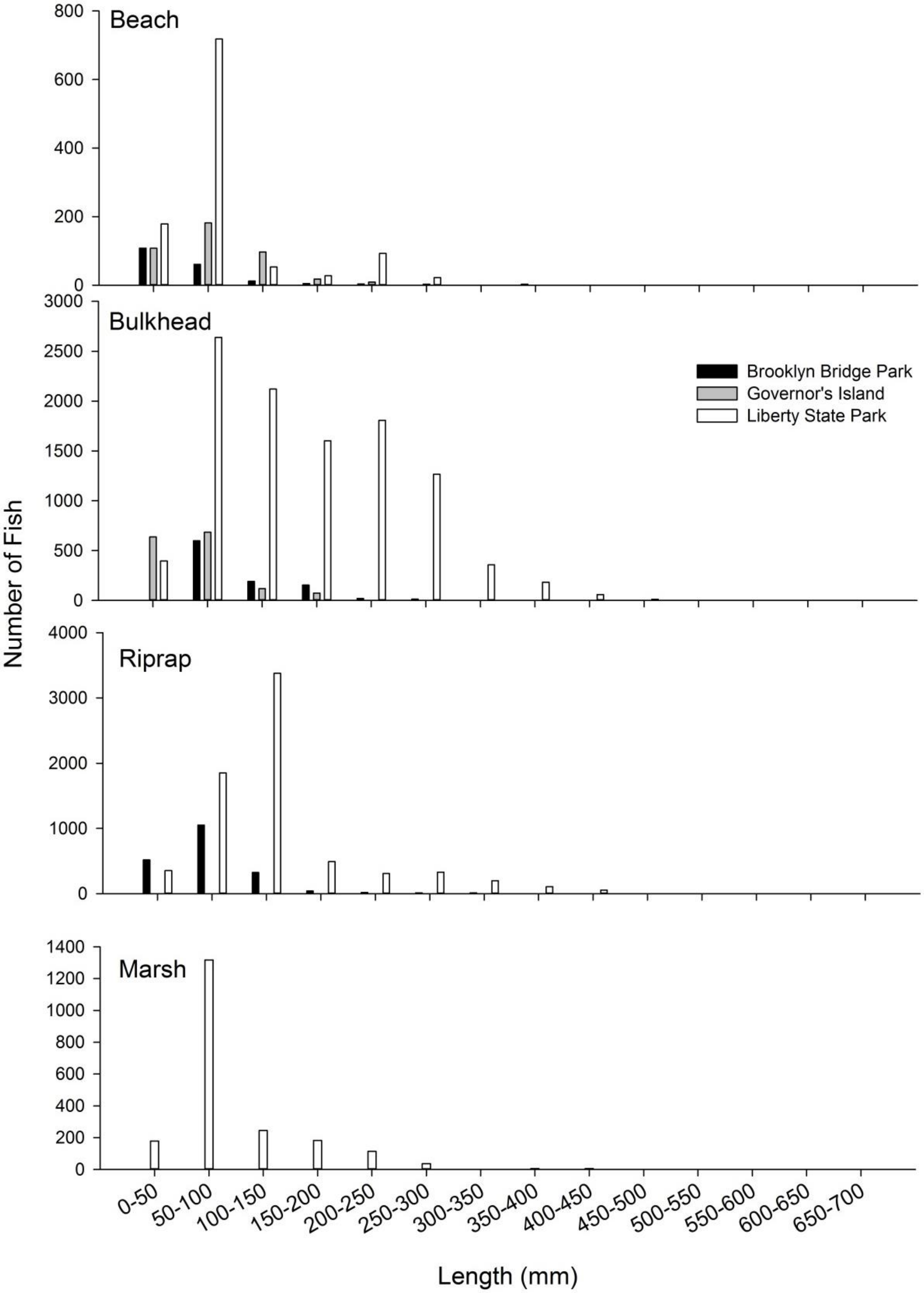


Figure 7. The length frequency of fish that occurred at each habitat in the study area based on DIDSON images during 2011. X-axis values reflect actual size range, although rare larger fish are not apparent on the scale of this y-axis.

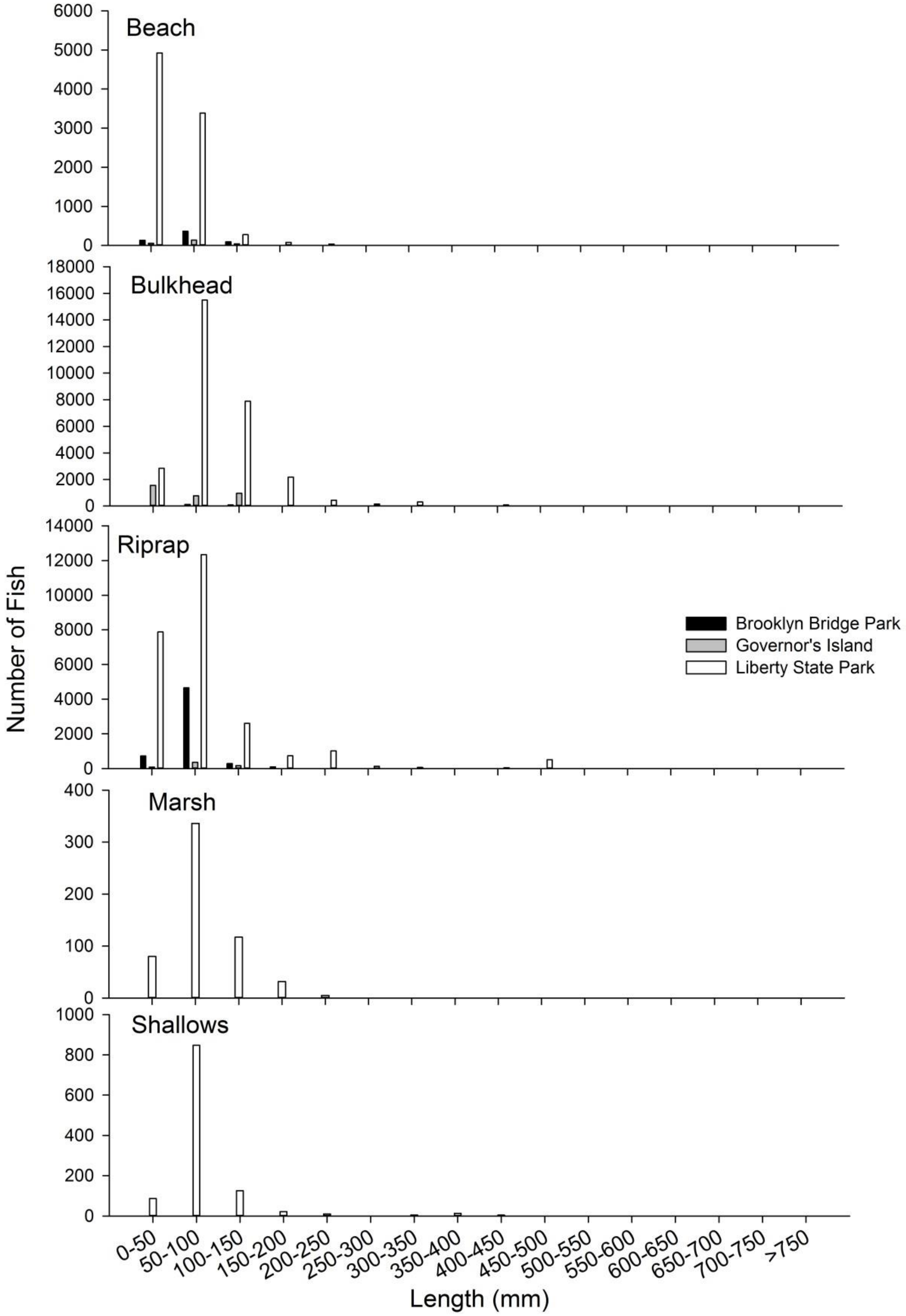


Figure 8. The length frequency of fish that occurred at each habitat in the study area based on DIDSON images during 2012. X-axis values reflect actual size range, although rare larger fish are not apparent on the scale of this y-axis.

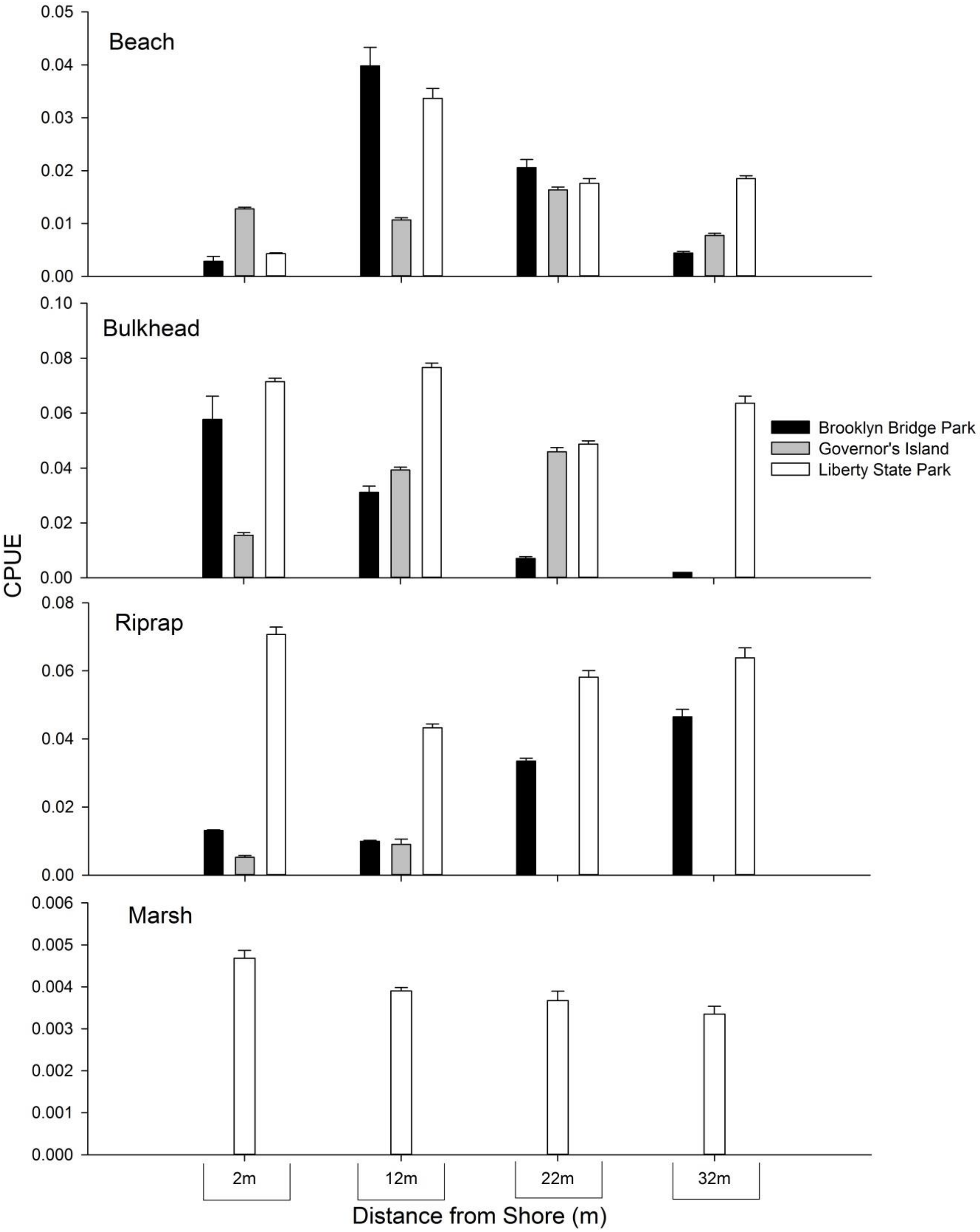


Figure 9. The abundance of fish that occurred relative to the distance from shore at each habitat and location in the study area for 2011.

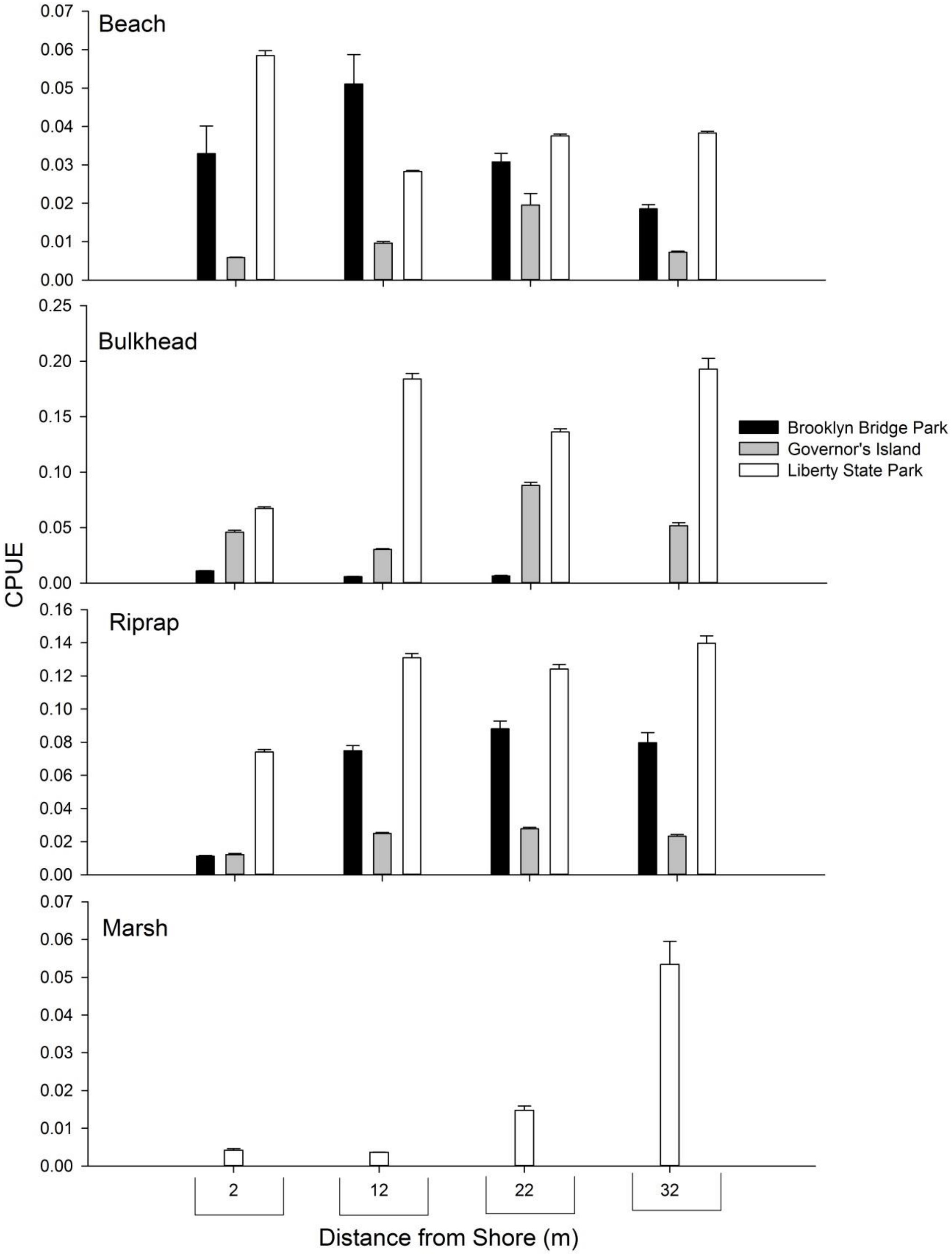


Figure 10. . The abundance of fish that occurred relative to the distance from shore at each habitat and location in the study area for 2012.

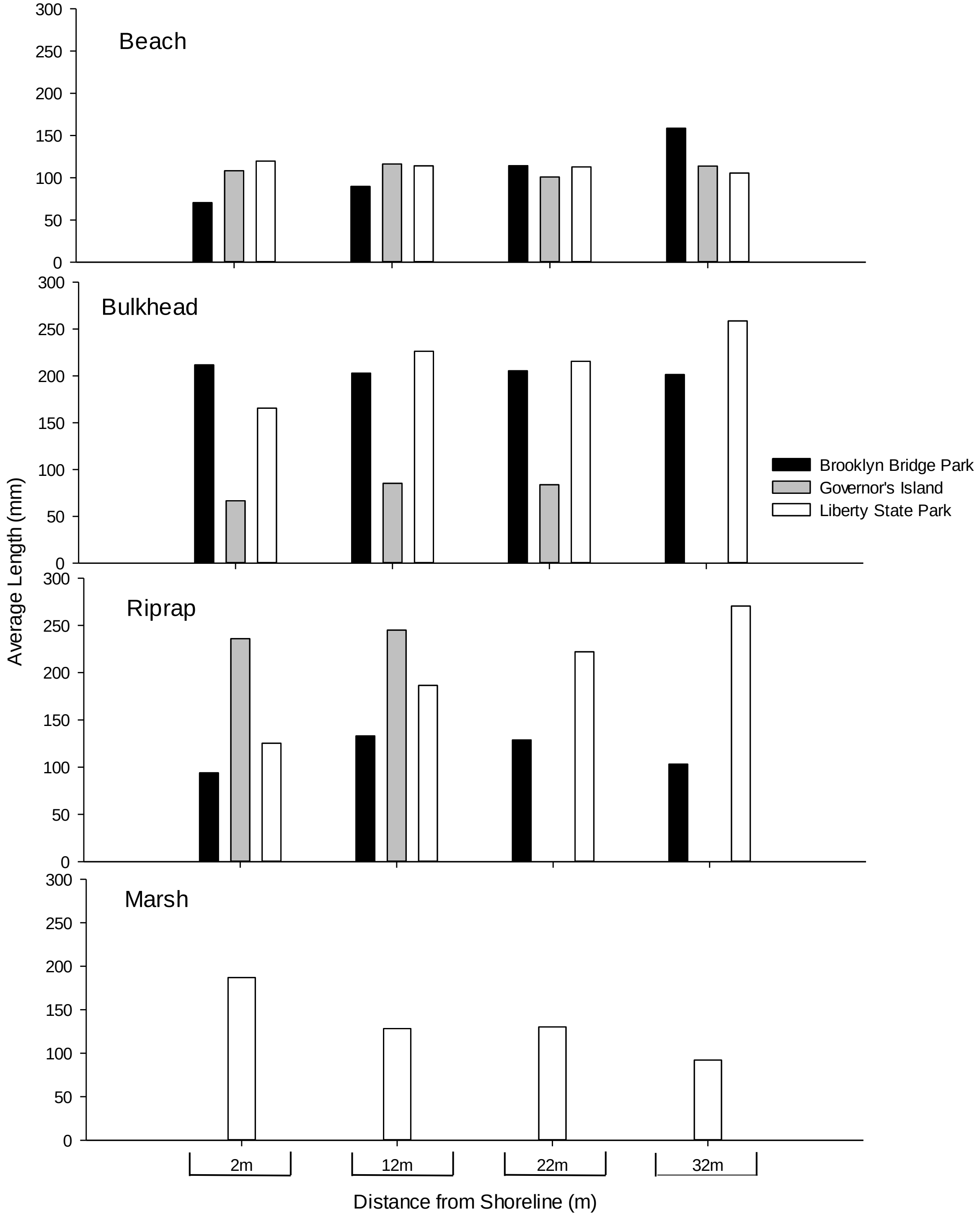


Figure 11. Average length of fishes relative to the distance from the shore and each habitat and location in the study area for 2011.

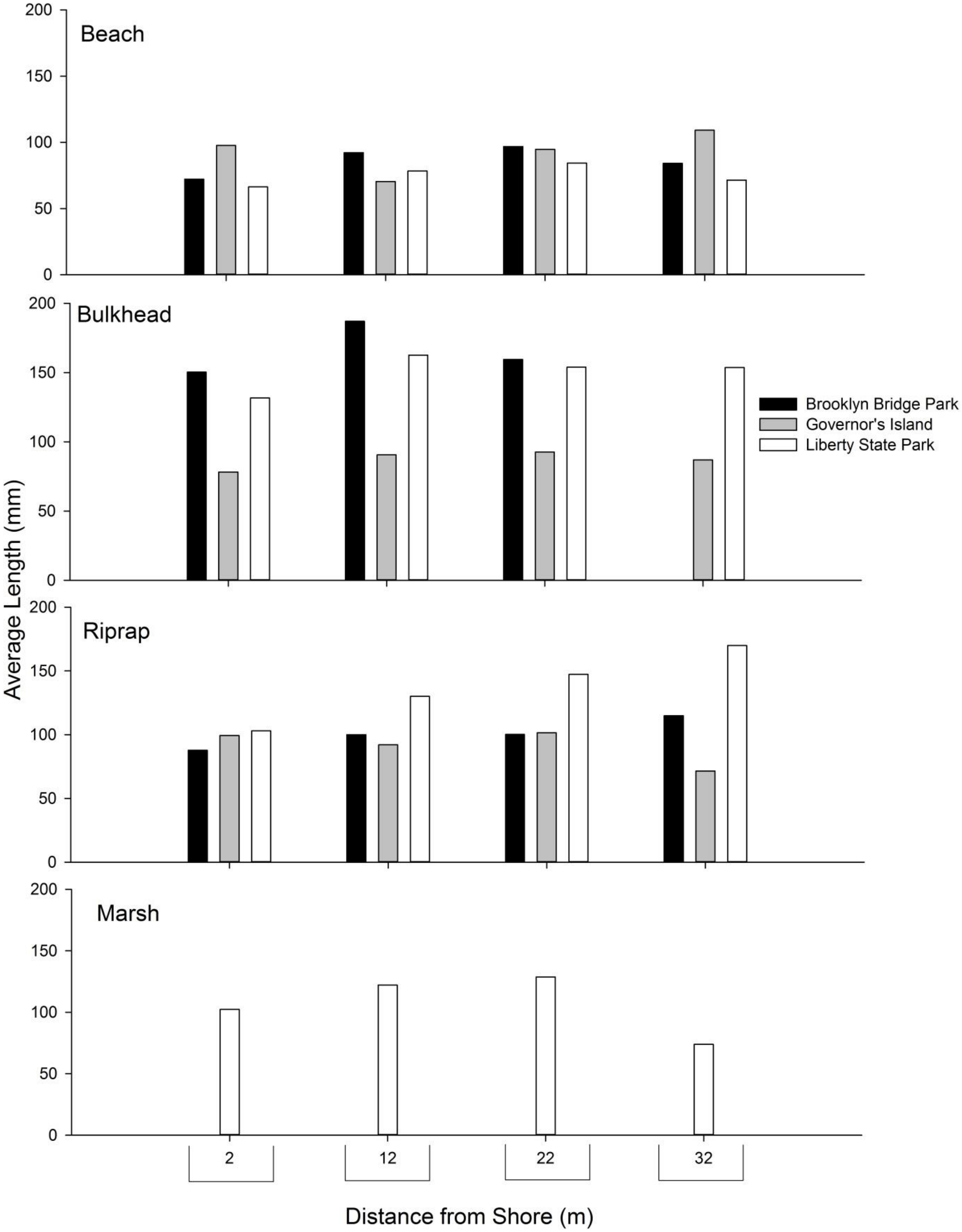


Figure 12. Average length of fishes relative to the distance from the shore and each habitat and location in the study area for 2012.

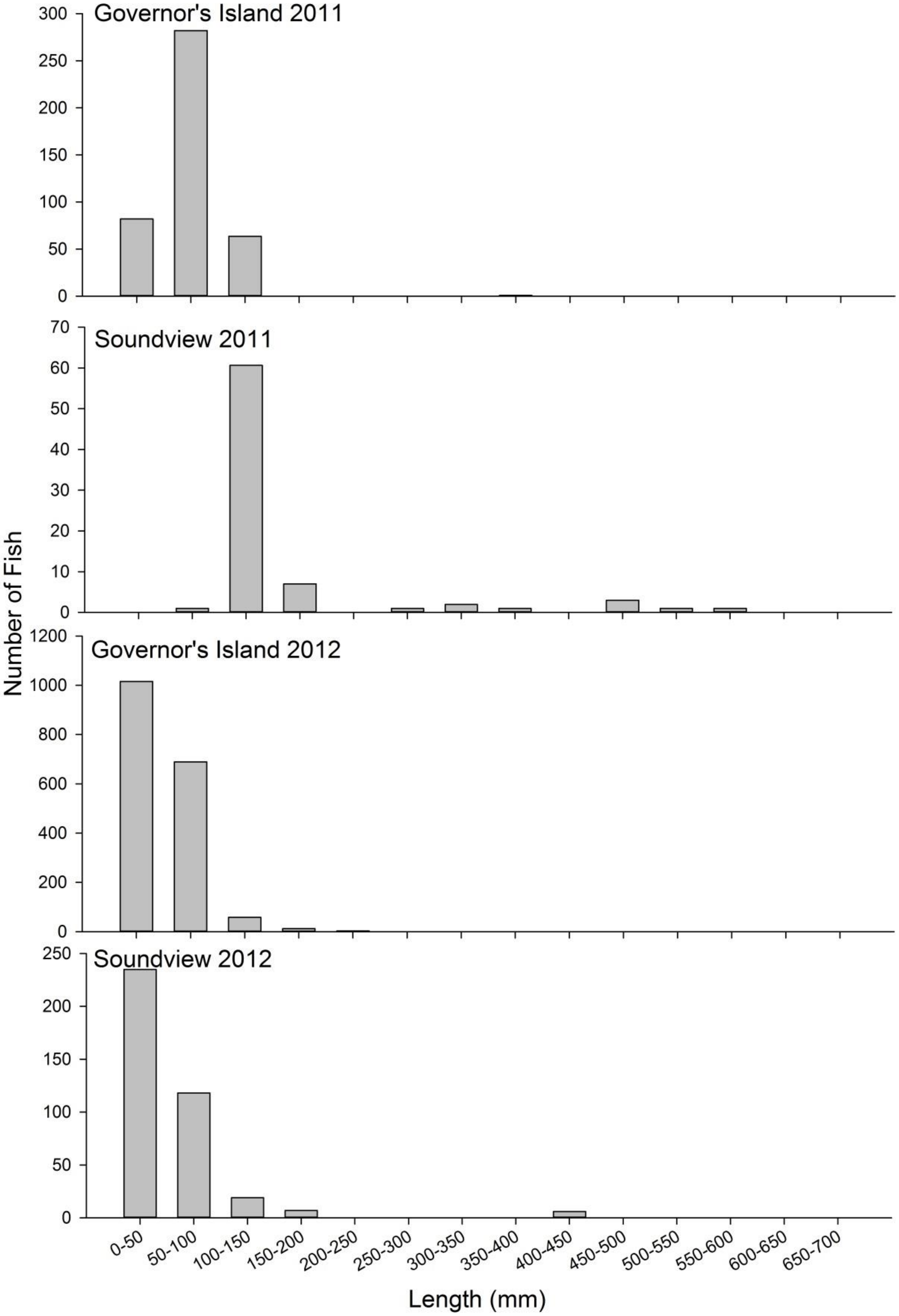


Figure 13. The length frequency distribution of fishes that occurred at the two oyster reef sites in both 2011 and 2012.

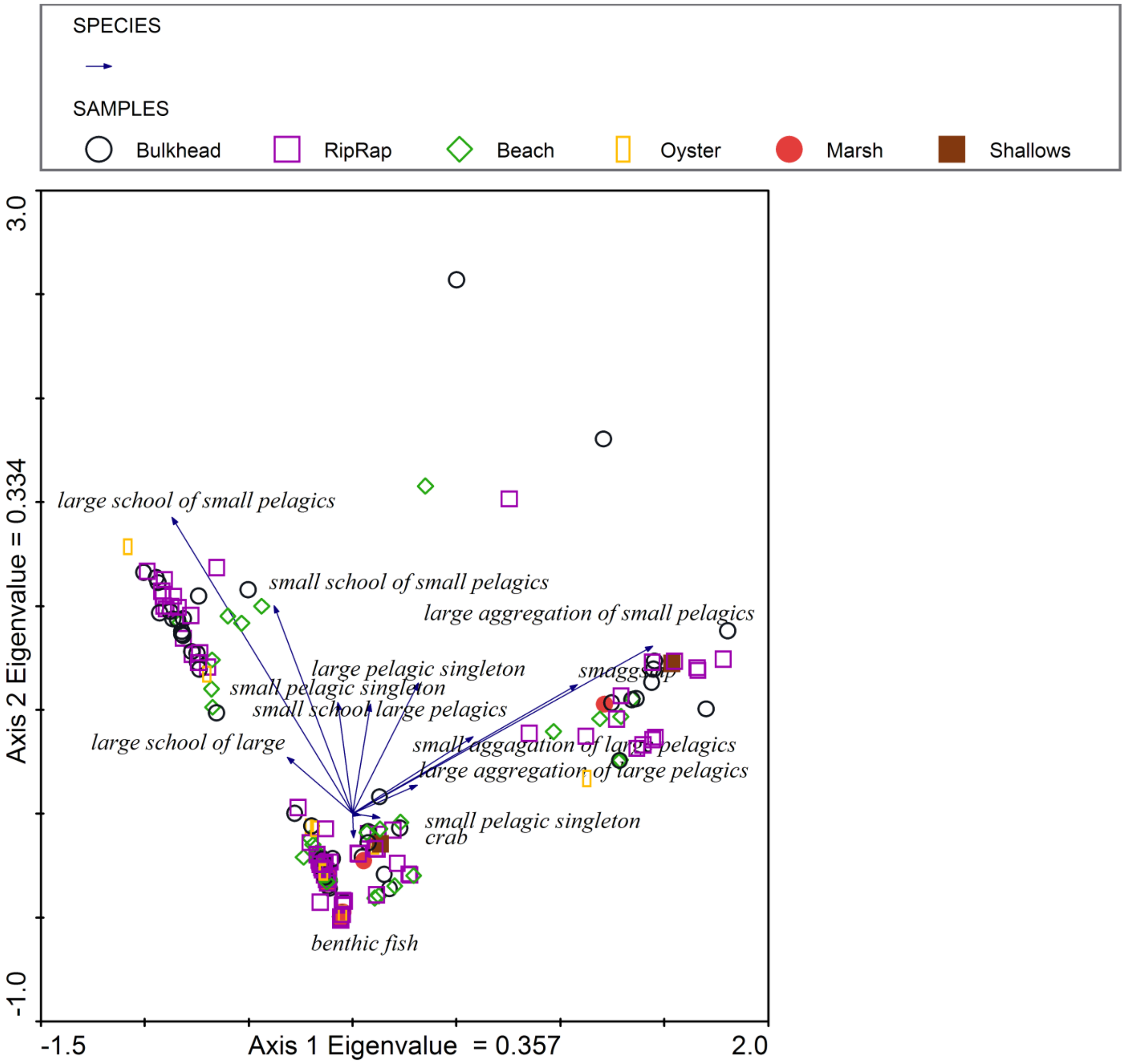


Figure 14 A. Biplot of sample amplitude along principle components 1 and 2. Plotted samples are averages of all transects at a particular habitat at a particular location across years, months, and shoreline distance, but not across diurnal period. Inter sample distance in the plot reflects the likelihood that they contain similar abundances of fish in the various classes, Samples coordinates in coenospace are coded by the type of shoreline (or other structure) sampled, but the analysis was blind to those categories so that the trends are latent. Vectors point in the direction of increasing abundance trend for a particular class of fish through the sample space. The length of the vector denotes the strength of the gradient in determining the sample distribution; short vectors do not necessarily indicate low abundance but also indicate ubiquitous high abundance, as in the case of “small pelagic singleton”. The angle between vector pairs is their pairwise correlation coefficient.

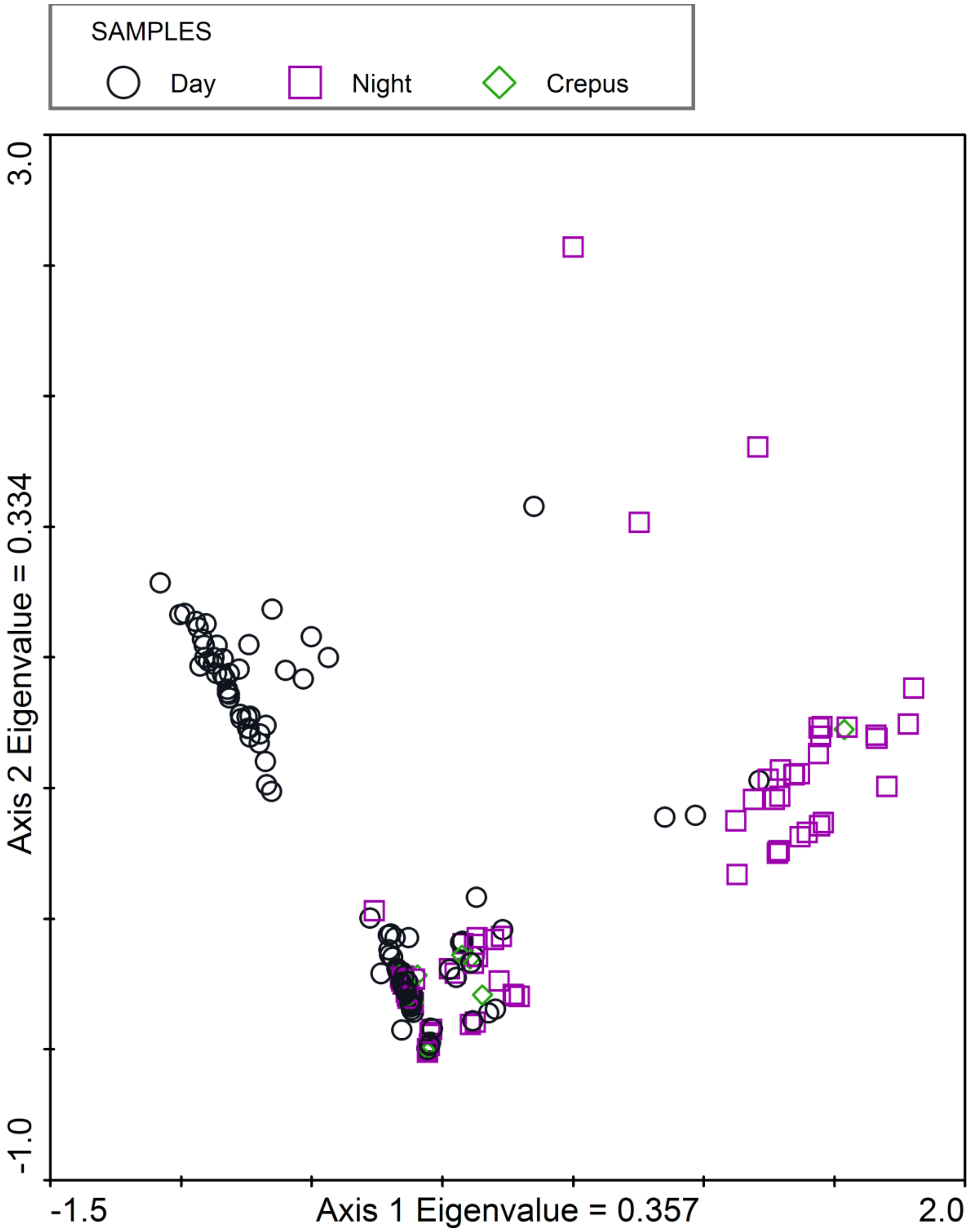


Figure 14 B. The distribution of samples as in 14 A, but coded by the diurnal period in which they were made. Class vectors are removed for easier viewing but the same gradients exist.

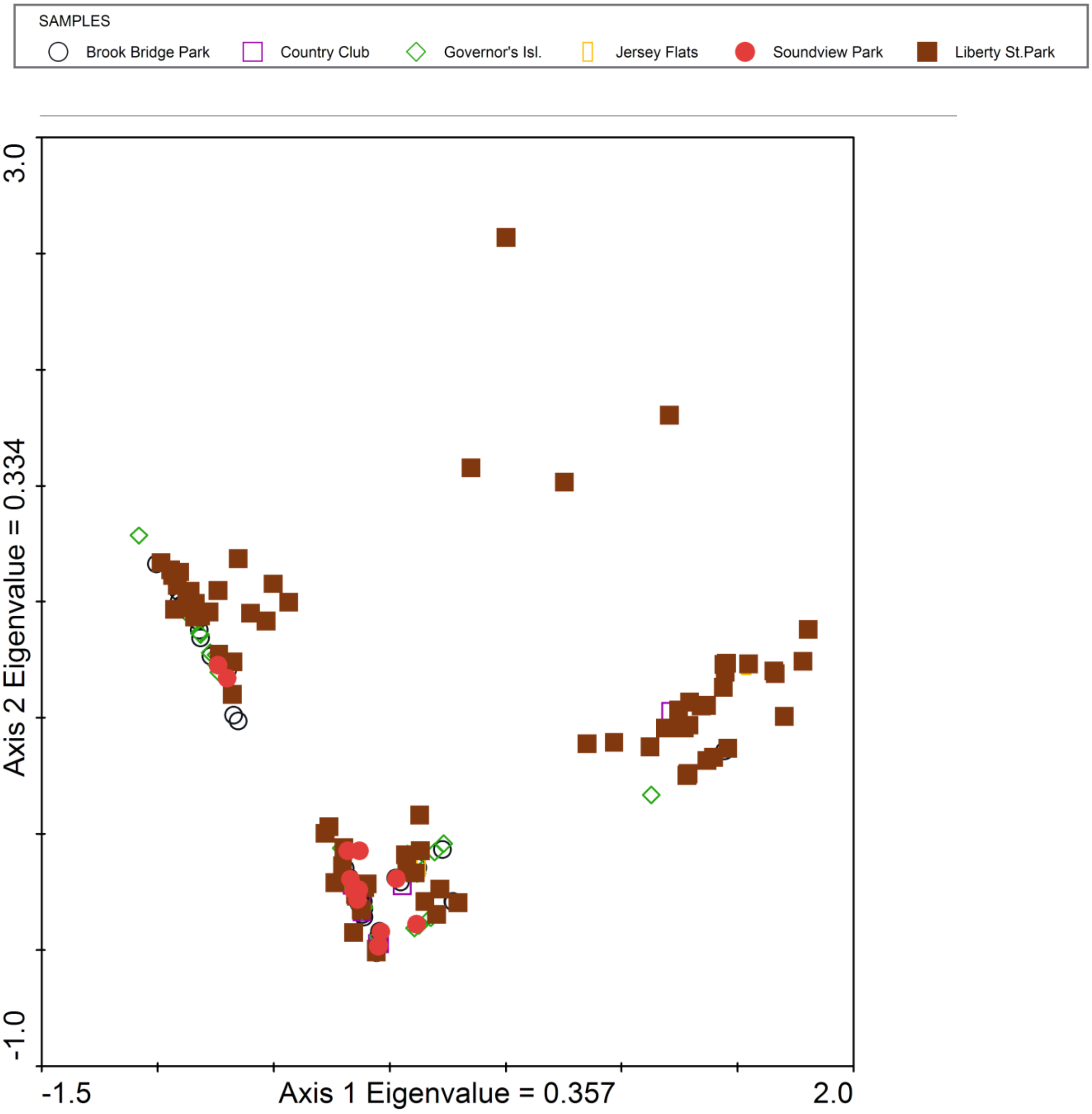


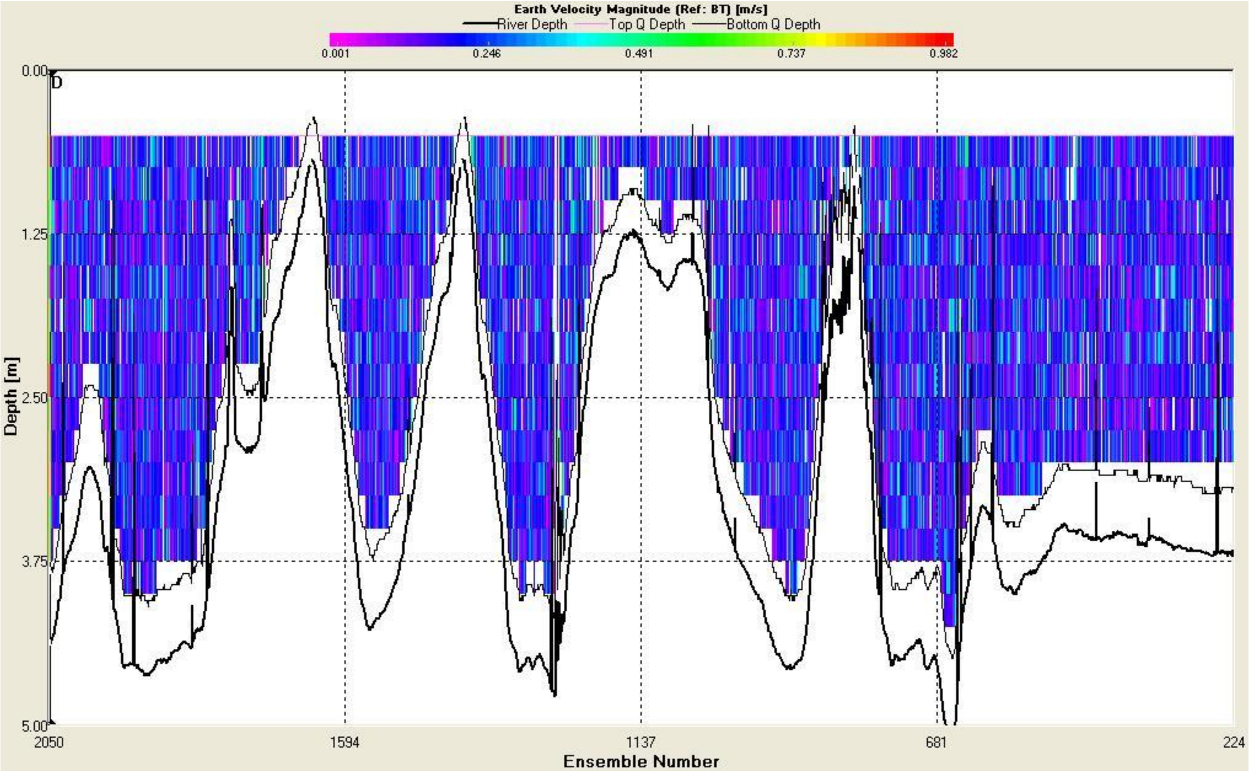
Figure 14 C. The distribution of samples as in 14 A, but coded by the location in which they were made. Class vectors are removed for easier viewing but the same gradients exist.

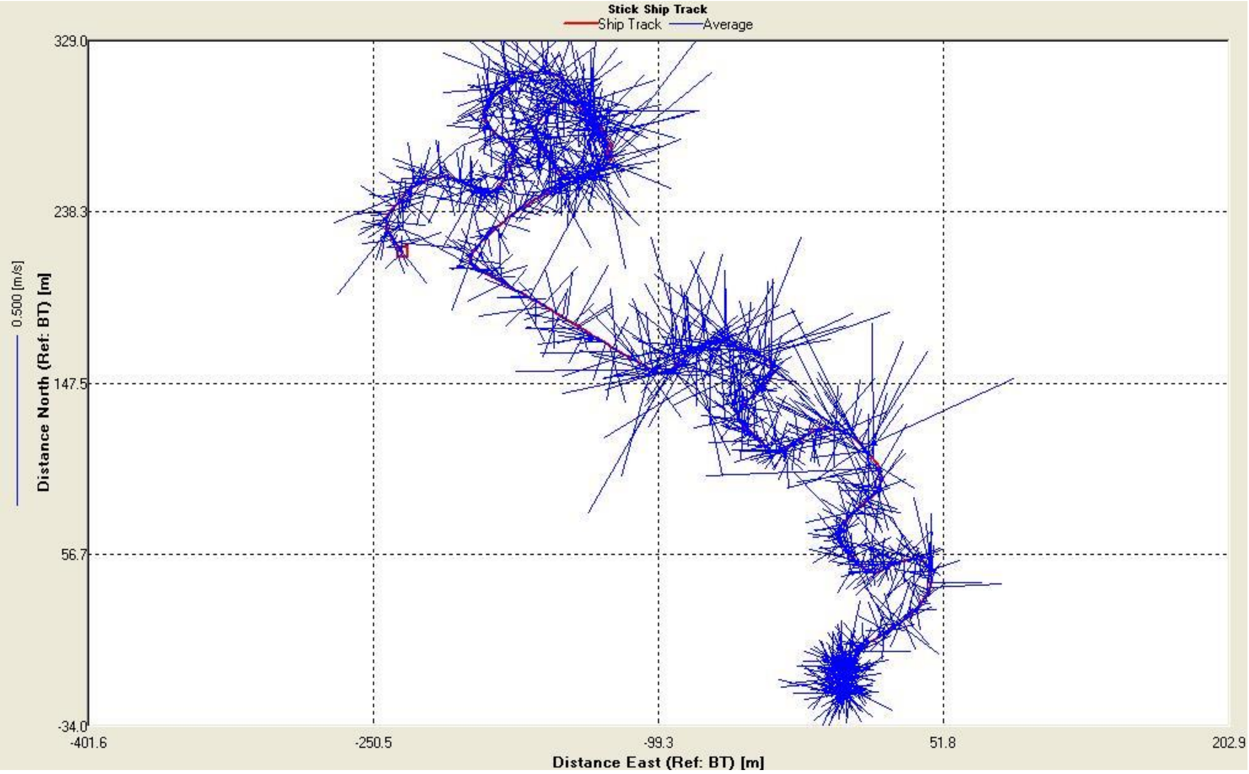
Appendix

Acoustic Doppler Current Profile (ADCP) at study Sites in the New York Harbor, East River, and Soundview Park Study sites.

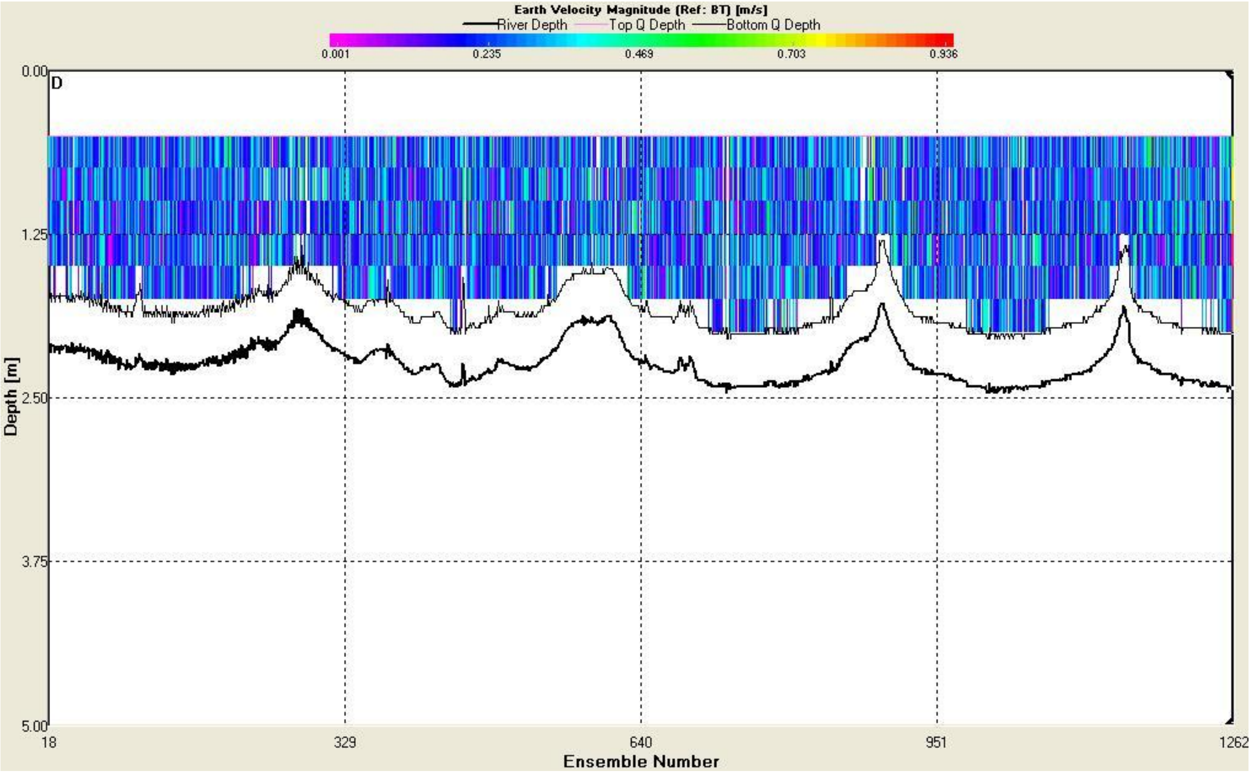
Profiles were constructed by an ADCP attached to a skiff at the water line. An attempt was made to enclose a section of water at each study site by returning to the starting point after a loop, sometimes with internal transects, in order to facilitate subsequent mass transport calculations and to examine eddy structures and shear in both x and y directions, but this was not always possible or necessary. Each sampling event shows a cross section of the linearalized transect showing change of flow relative to depth (upper panel) and the Eularian flow field as vectors (blue) pointing in the direction of flow along the transect (red line) with magnitude proportional to strength of the flow.

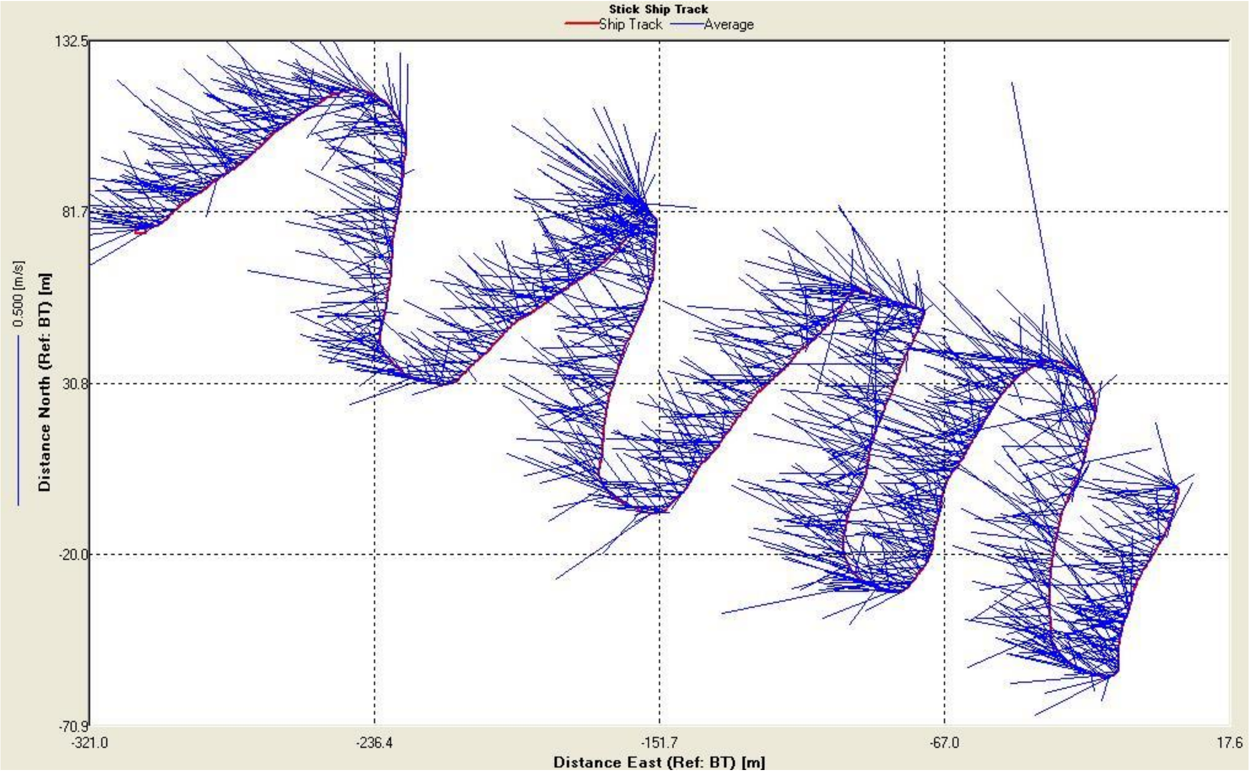
Transect 003 – Liberty State Park boat Ramp and bulkhead



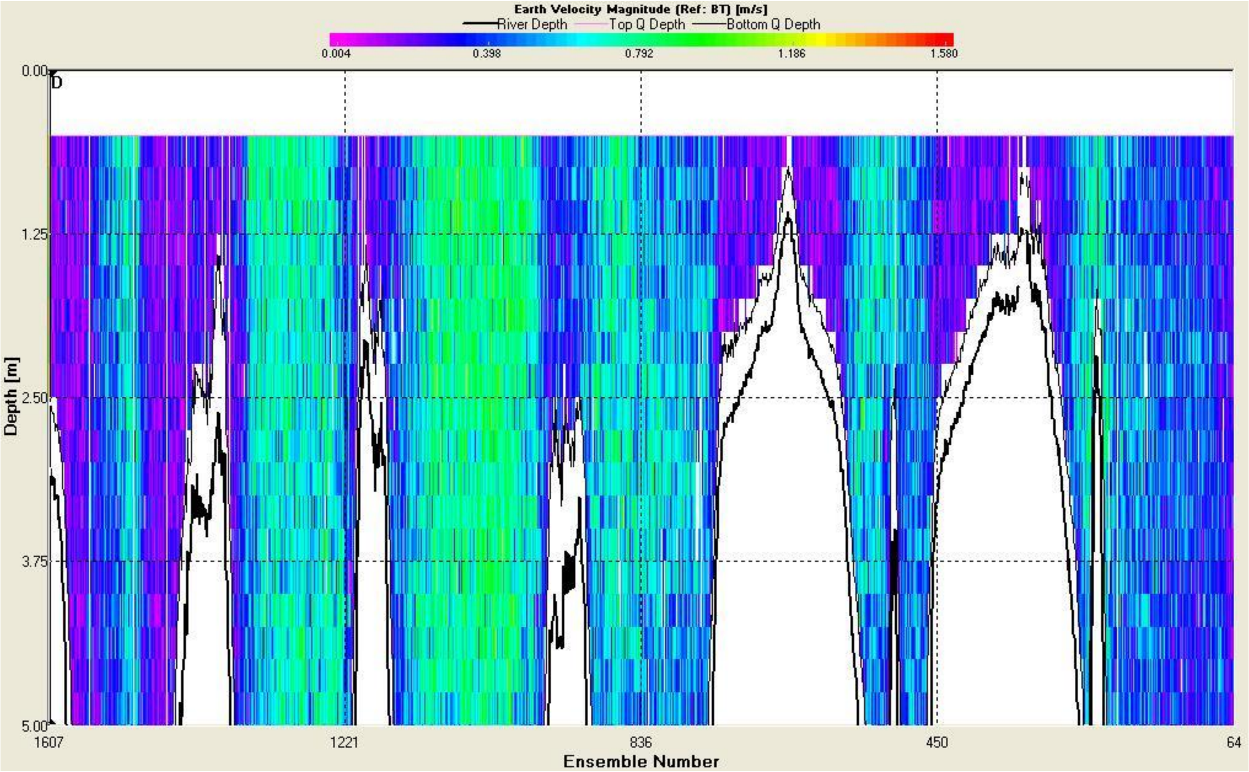


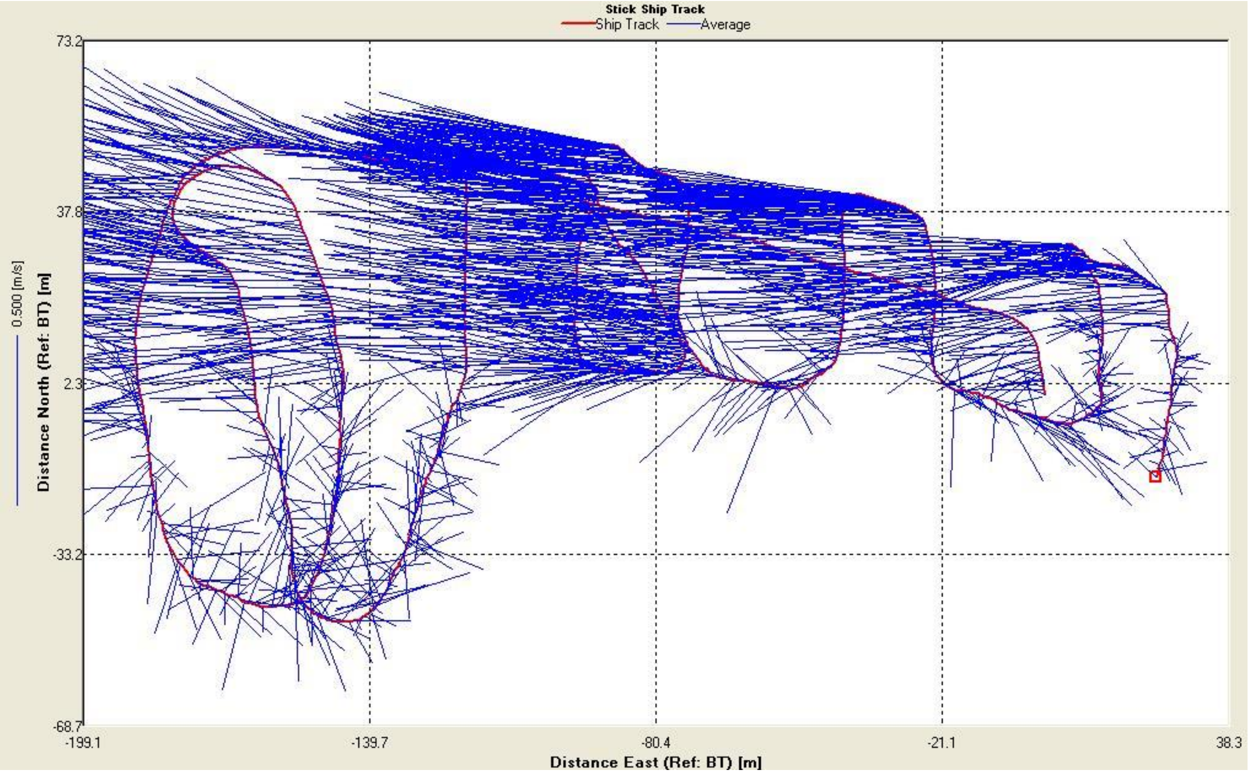
Transect 004 –Liberty State Park northside shoreline bulkhead



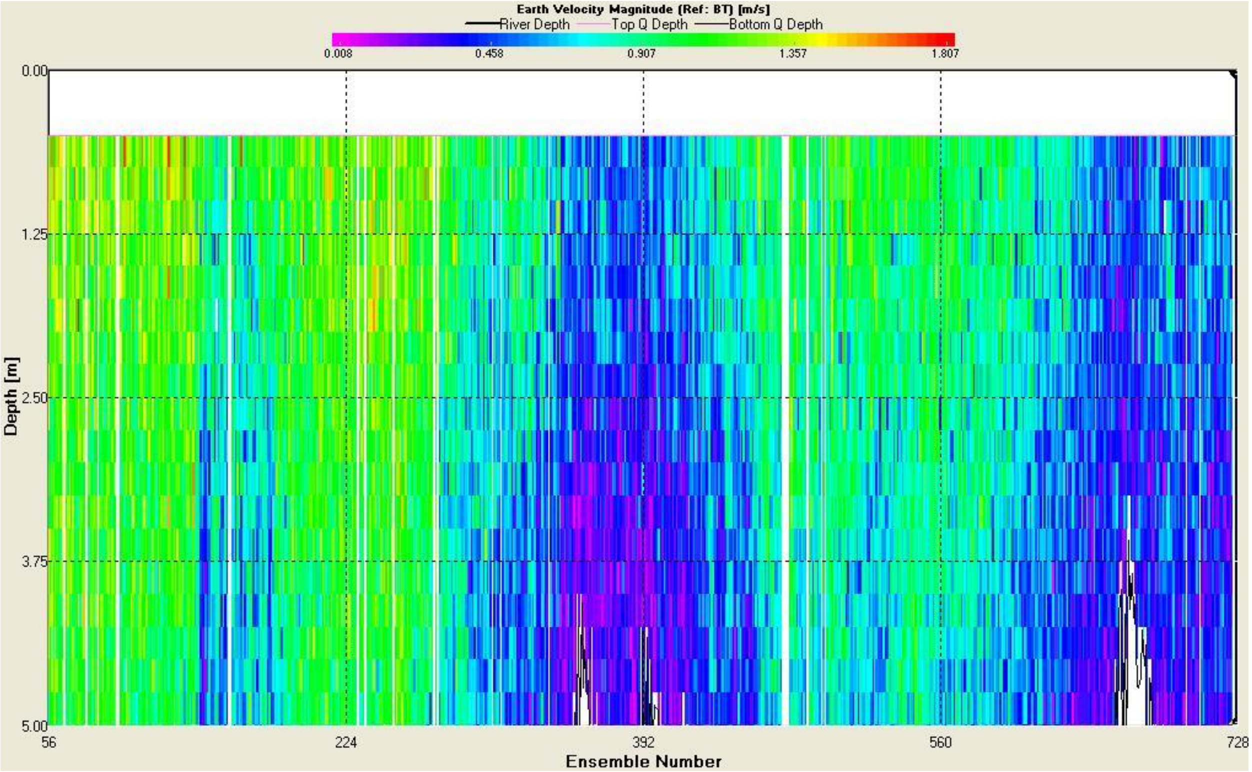


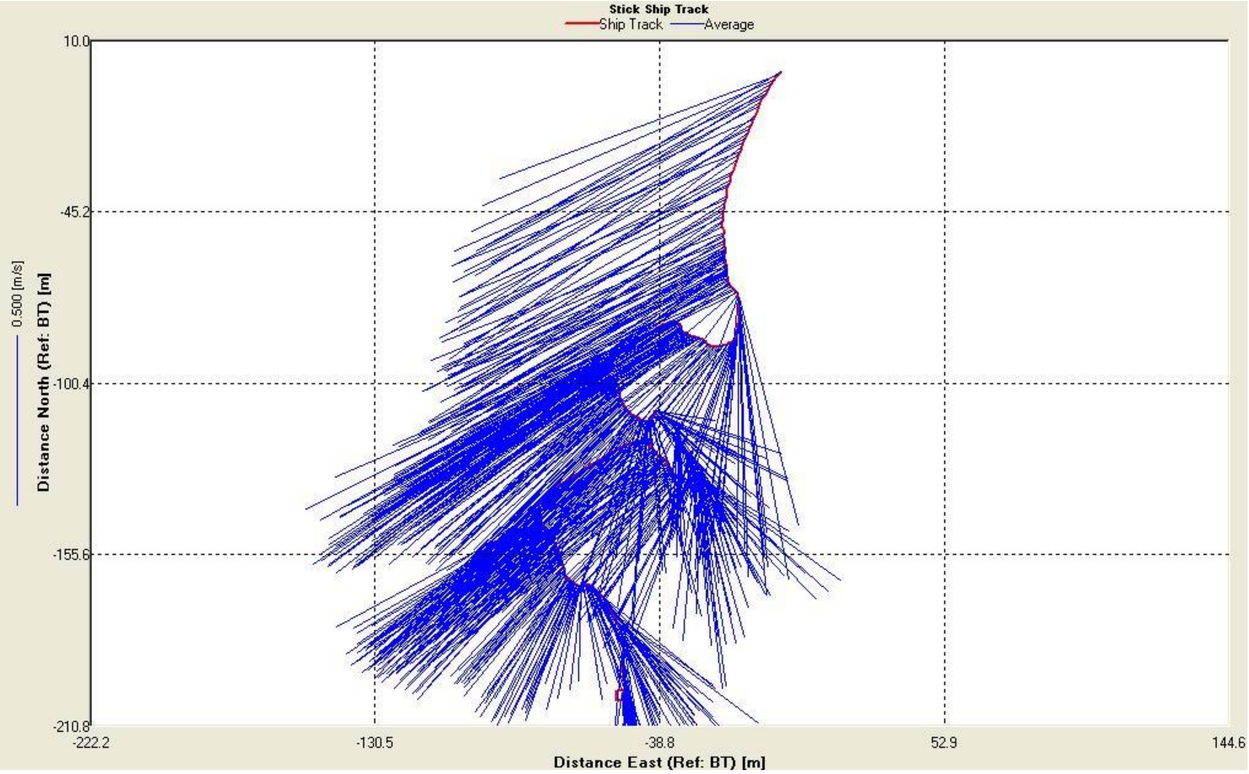
Transect 005 – Brooklyn Bridge Park and cove (beach) North (Manhattan Bridge) Riprap



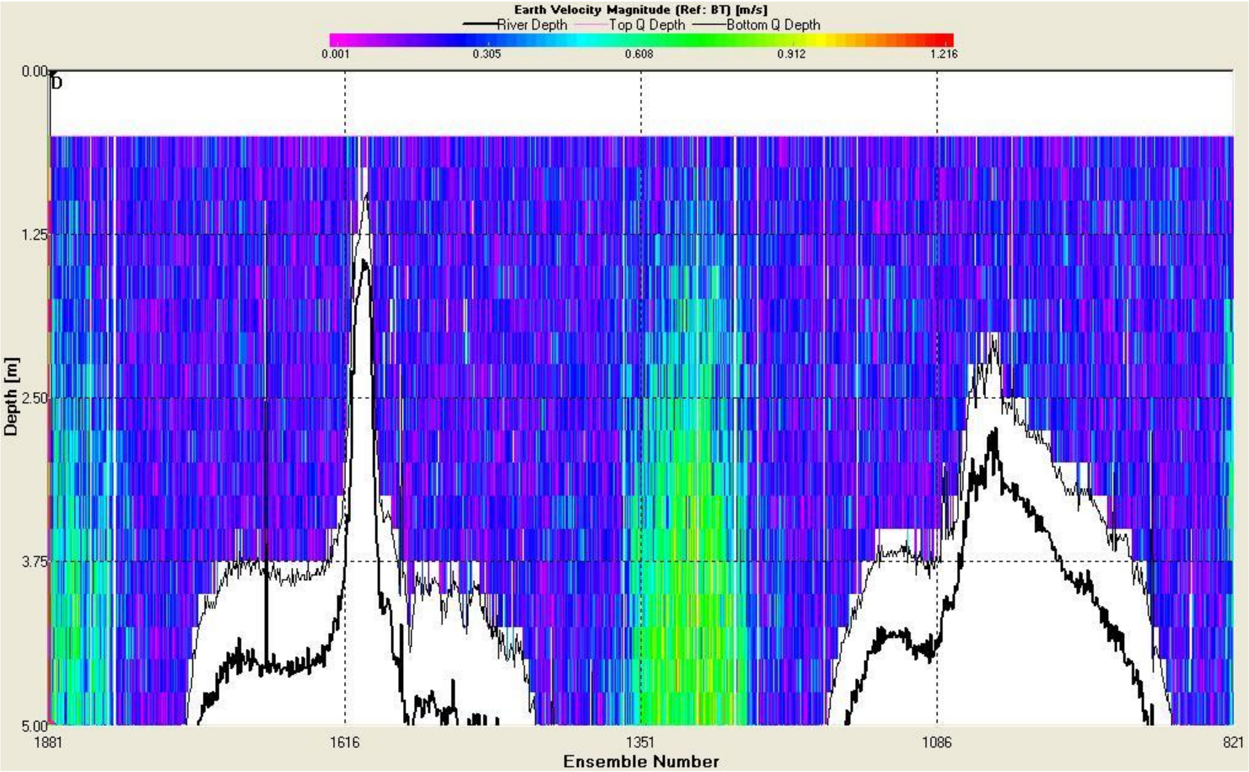


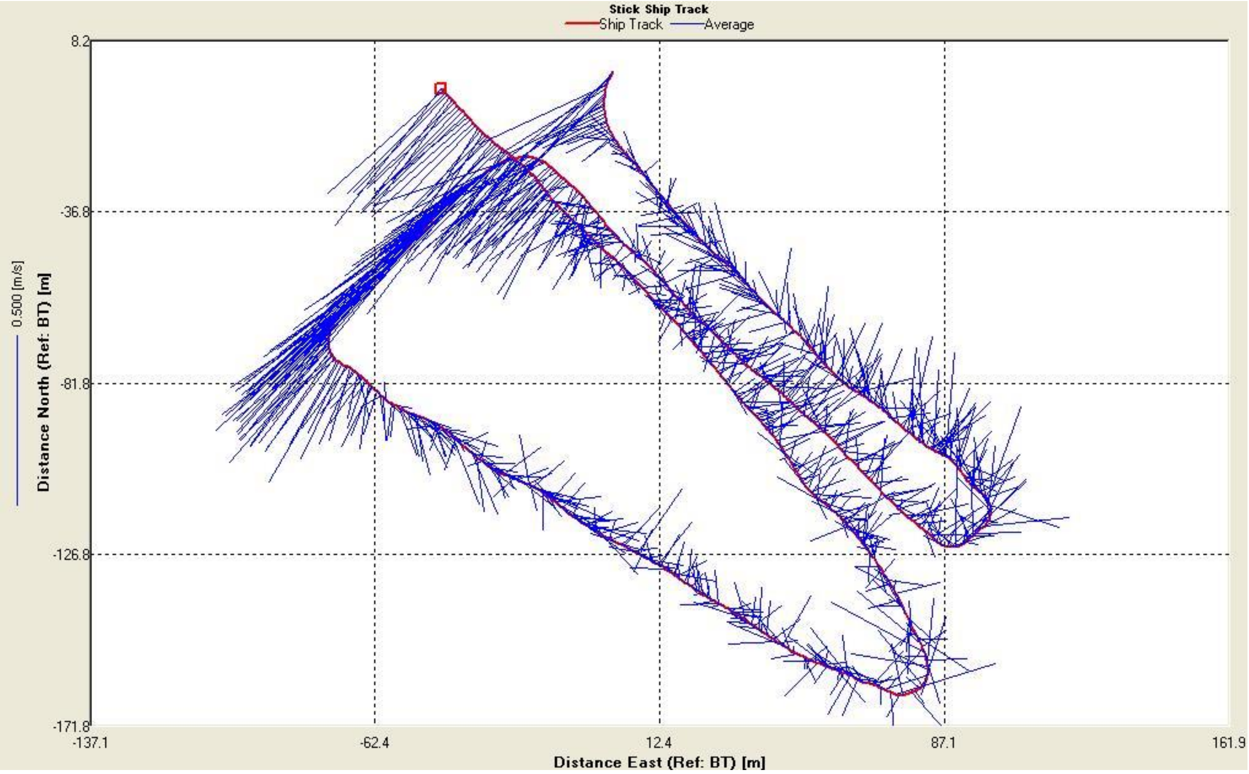
Transect 006 - Brooklyn Bridge Park Pier 1 bulkhead



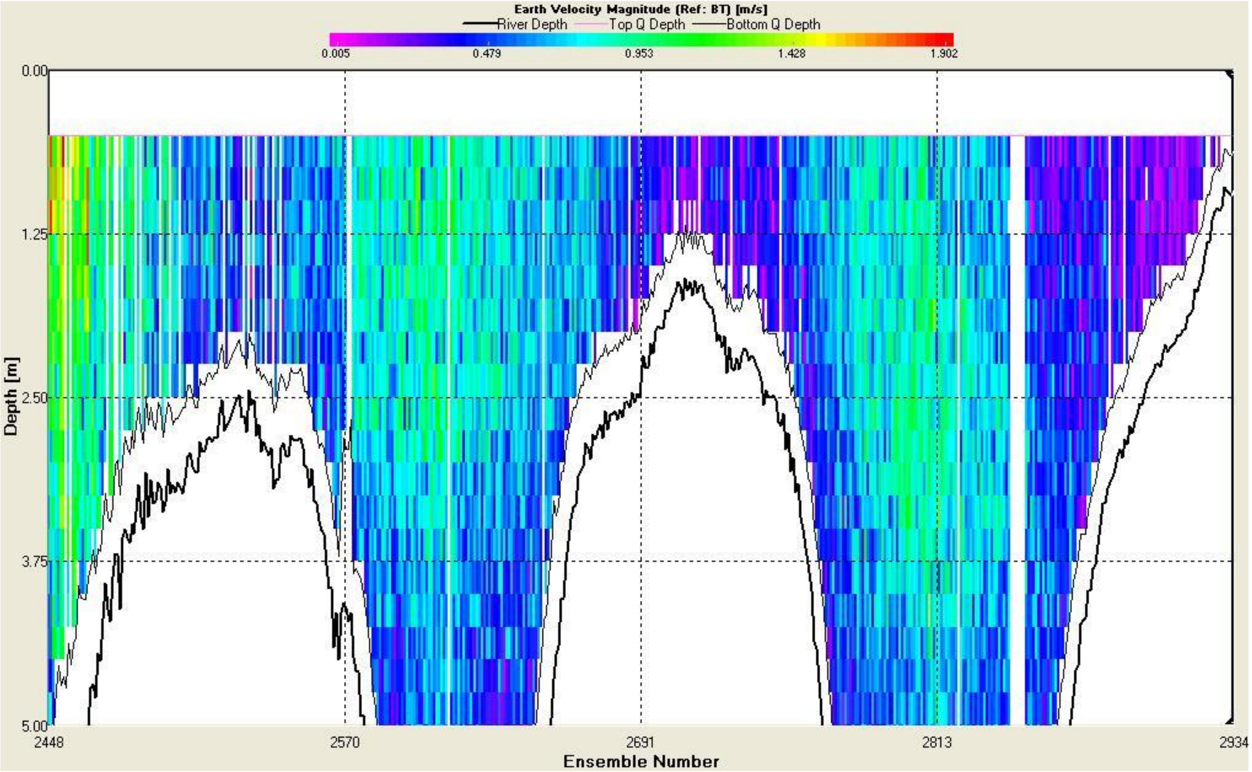


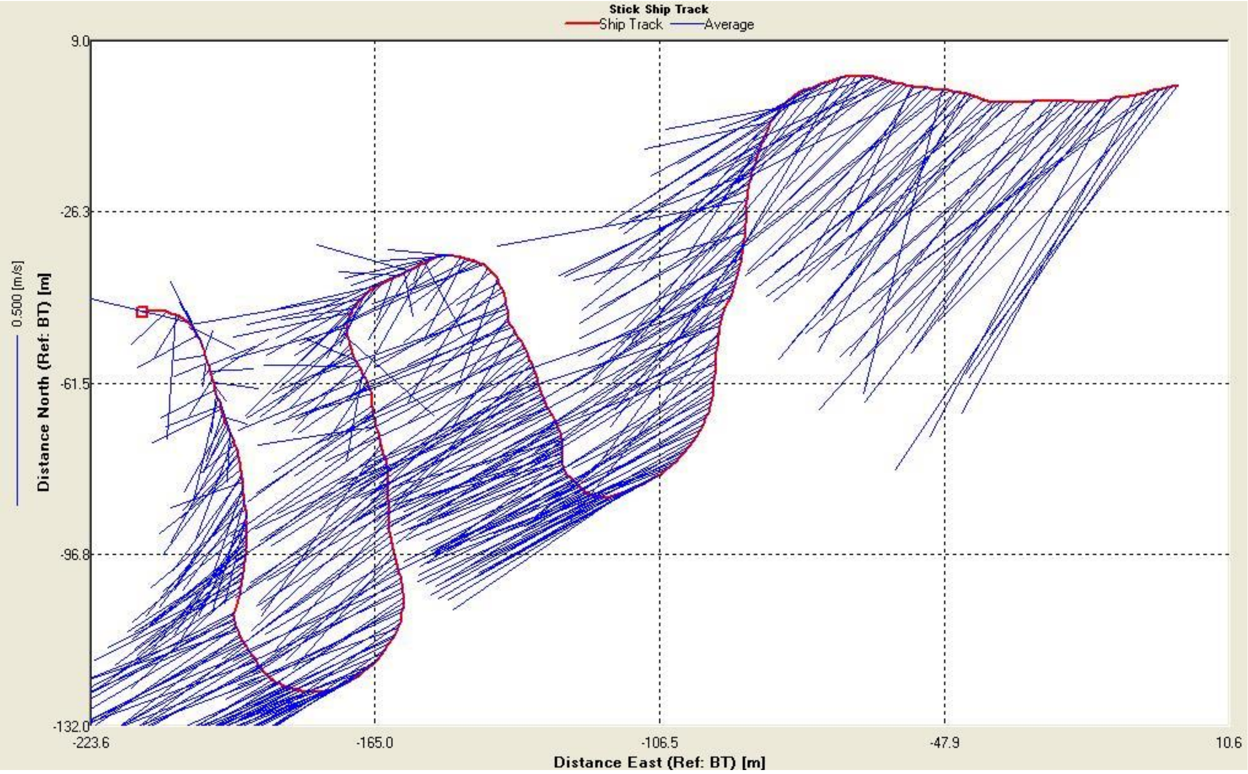
Transect 007 Brooklyn Bridge Park Pier 1-2 basin (barge site)



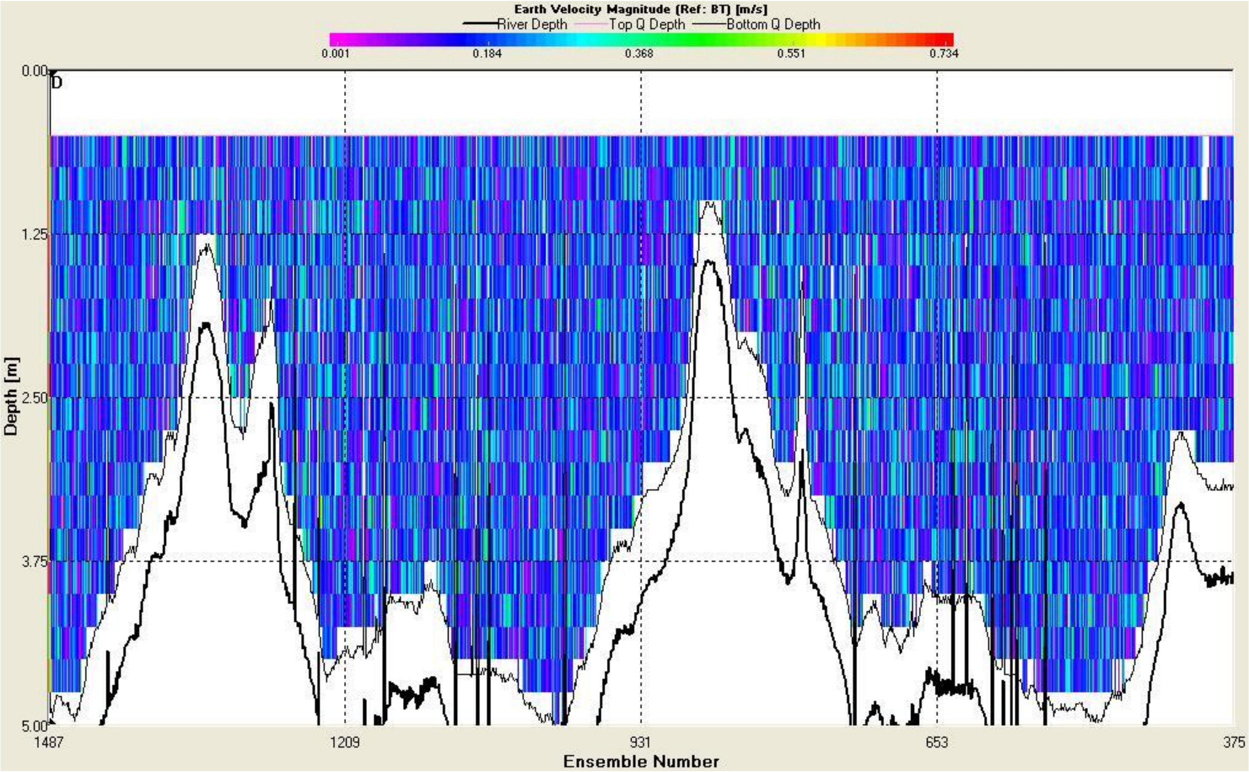


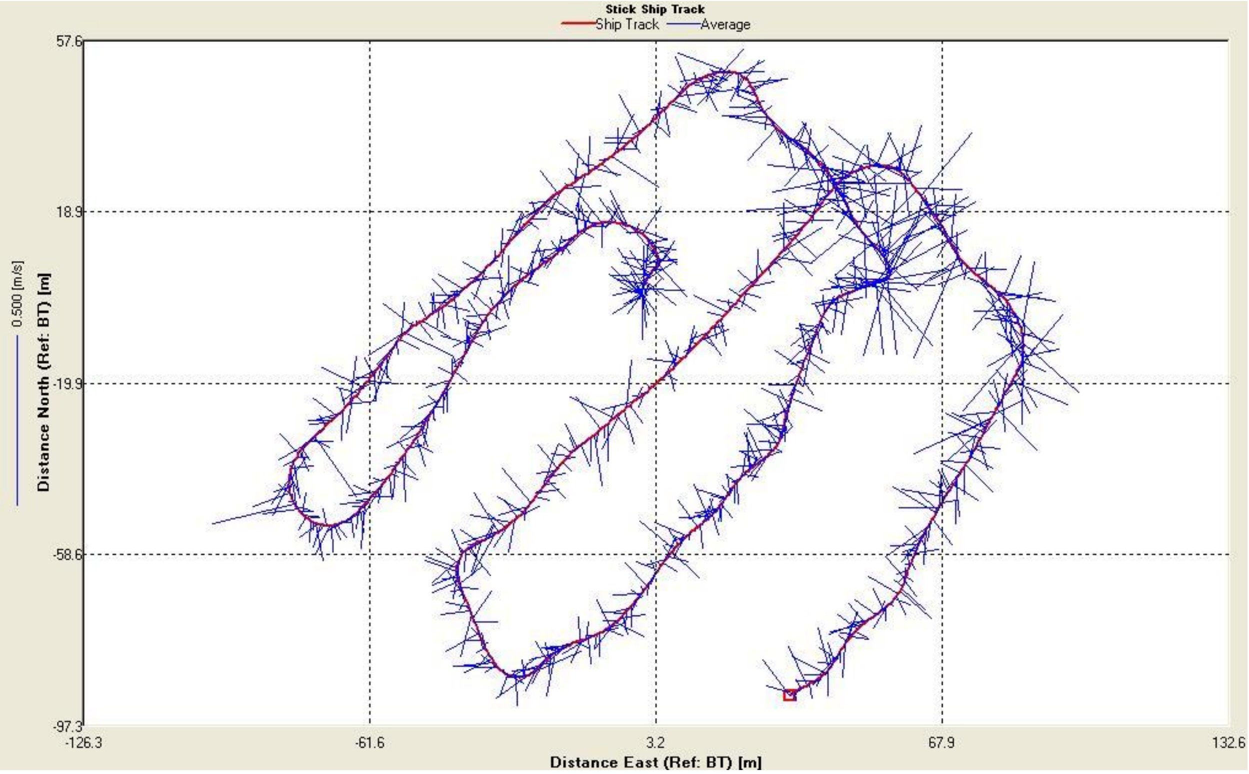
Transect 008 – Governor's Island beach and Oyster reef



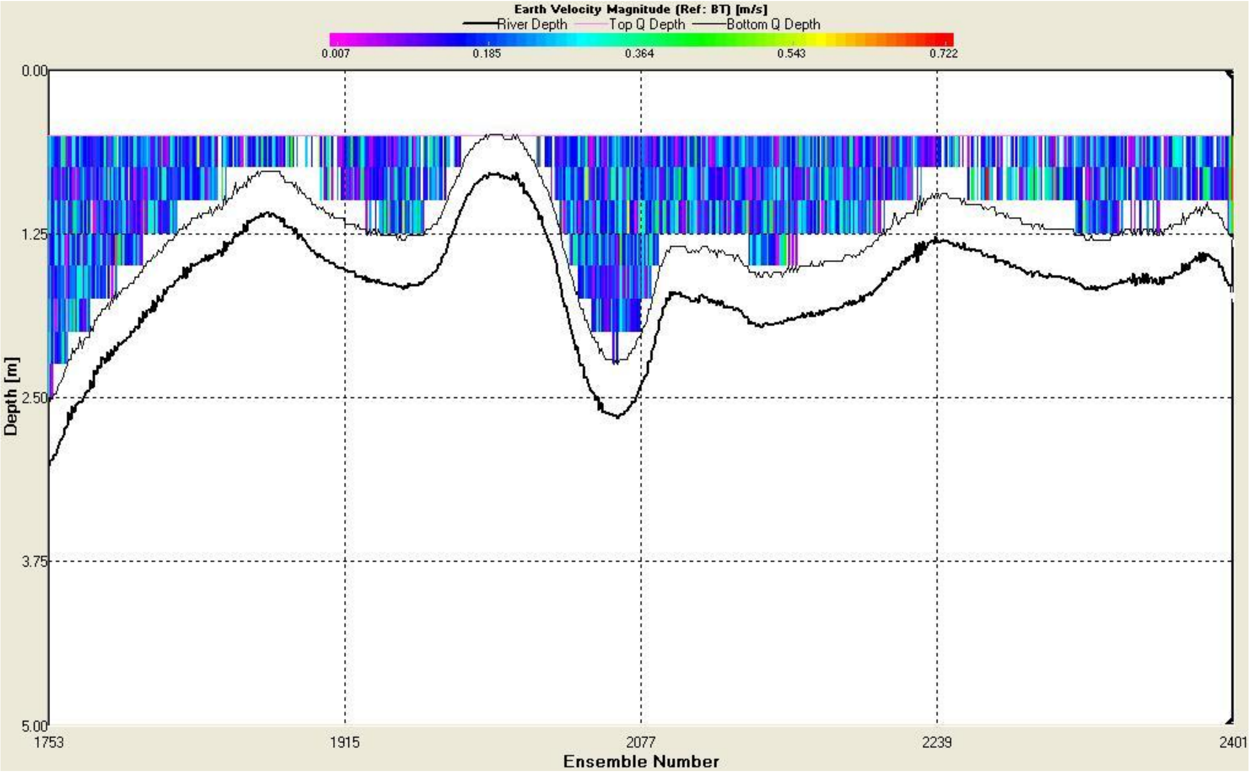


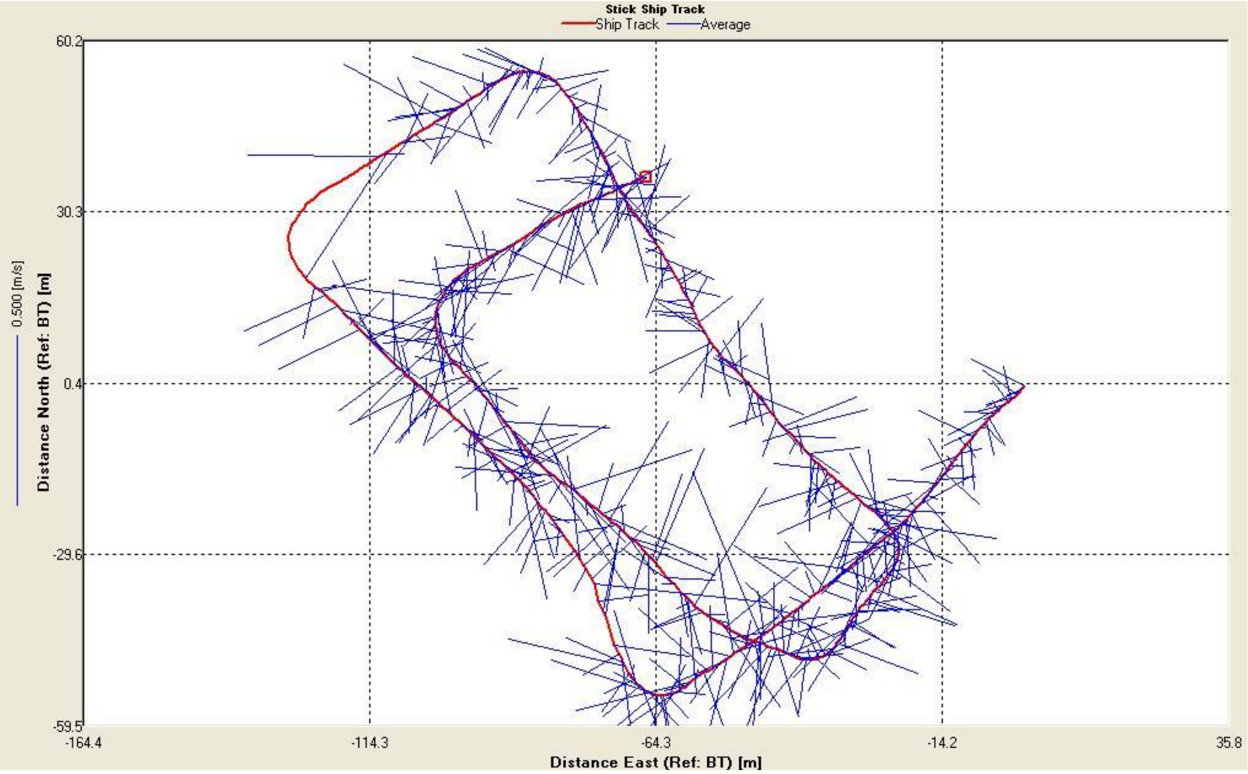
Transect 009 - Liberty State Park boat basin, NJ



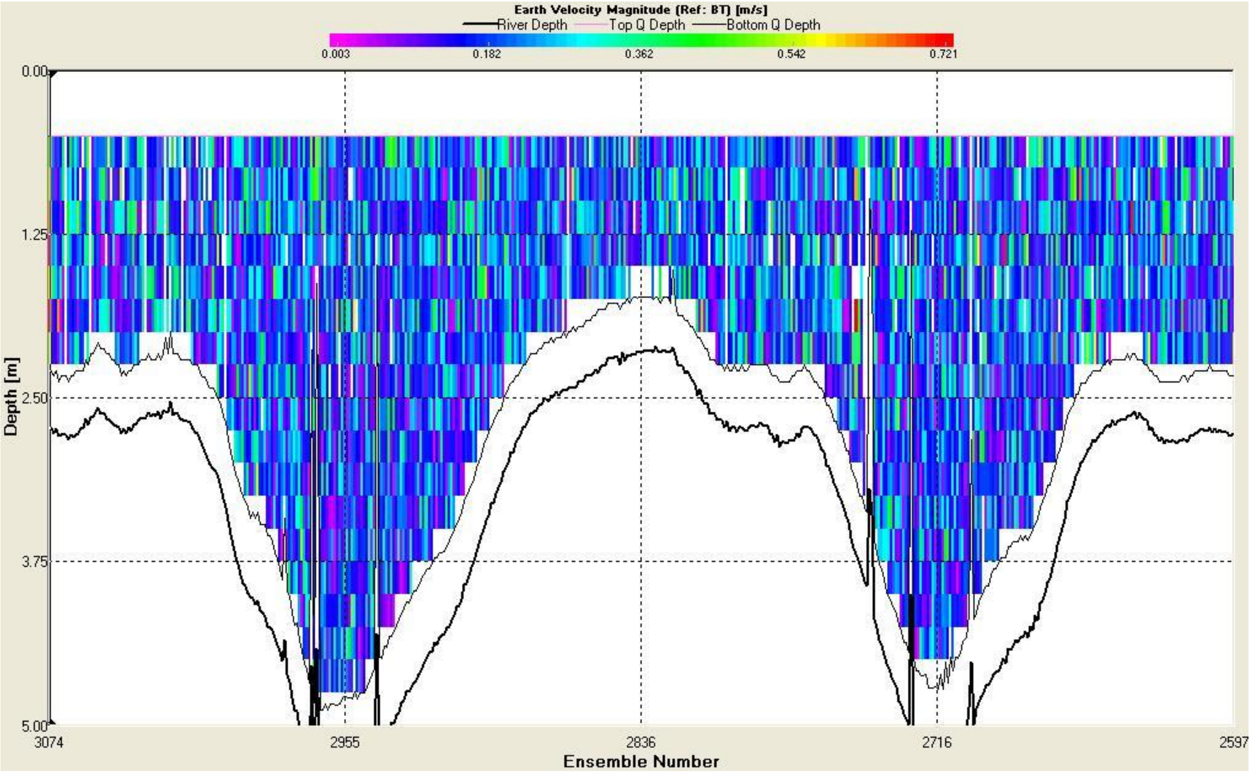


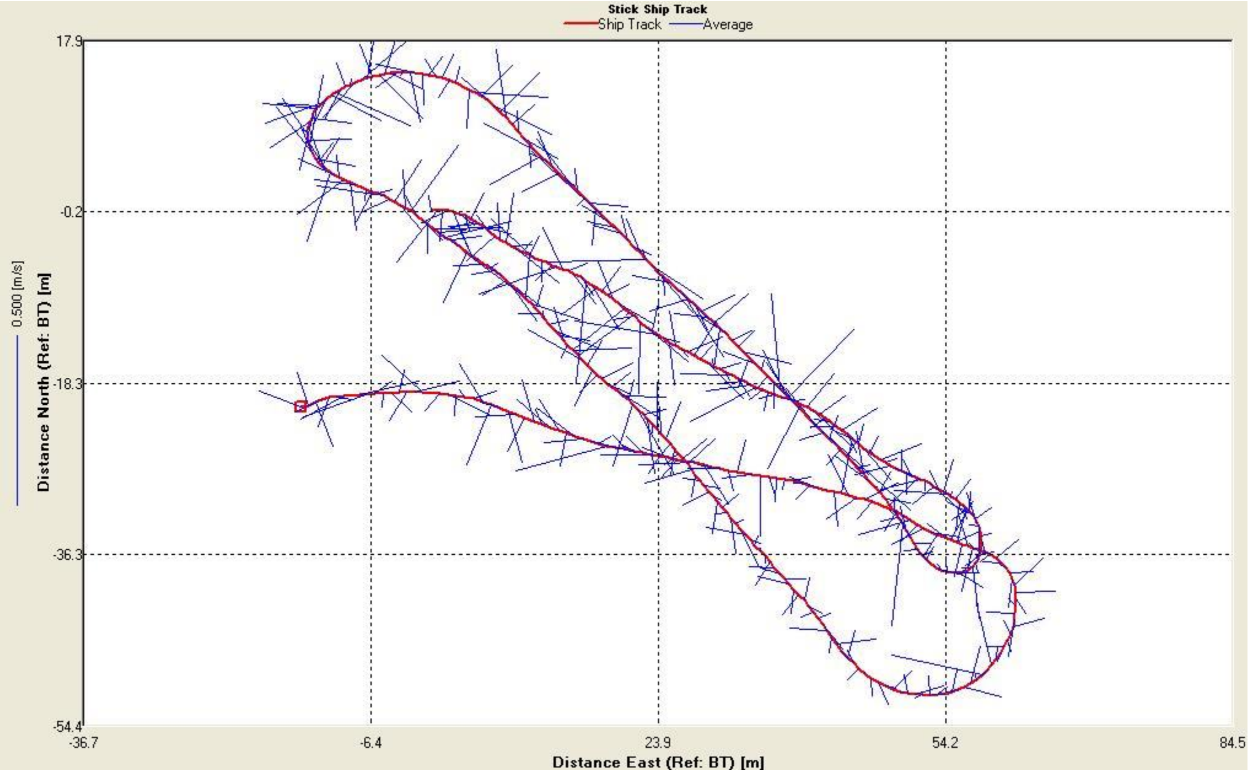
Transect 010 – Naturalized Beach, Liberty State Park boat basin



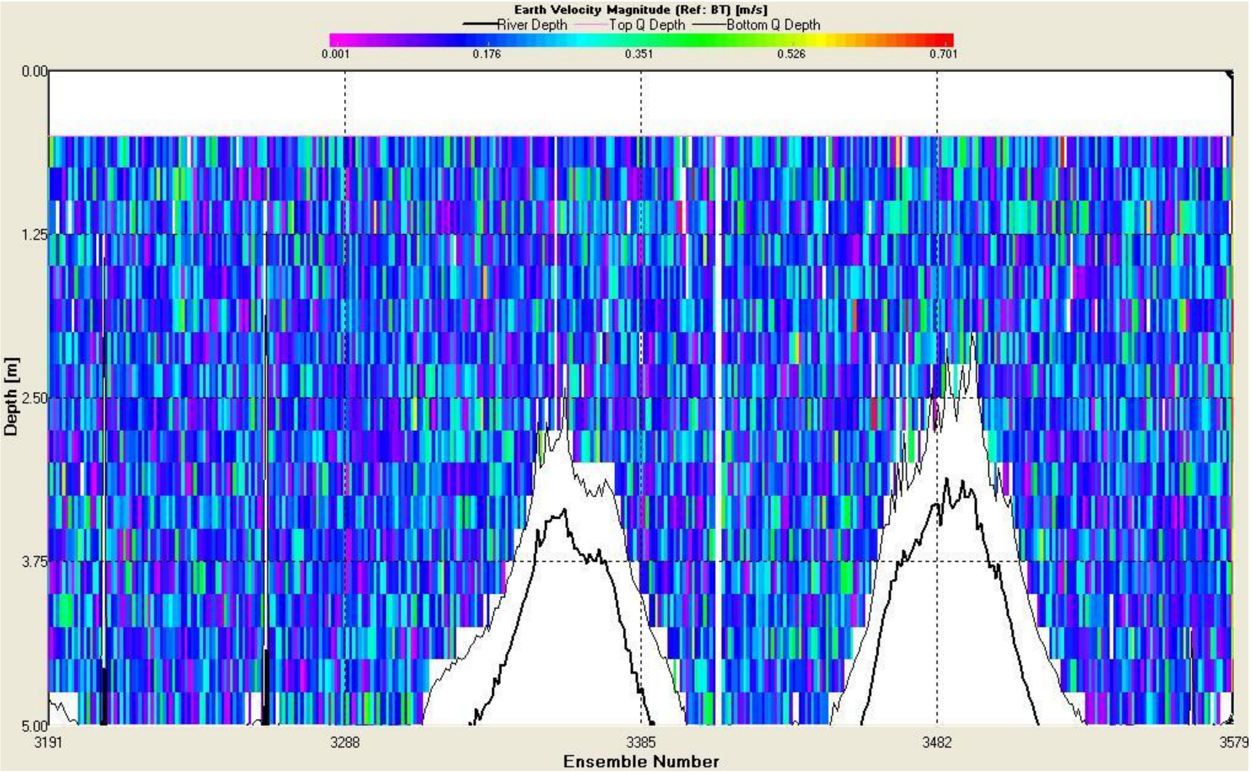


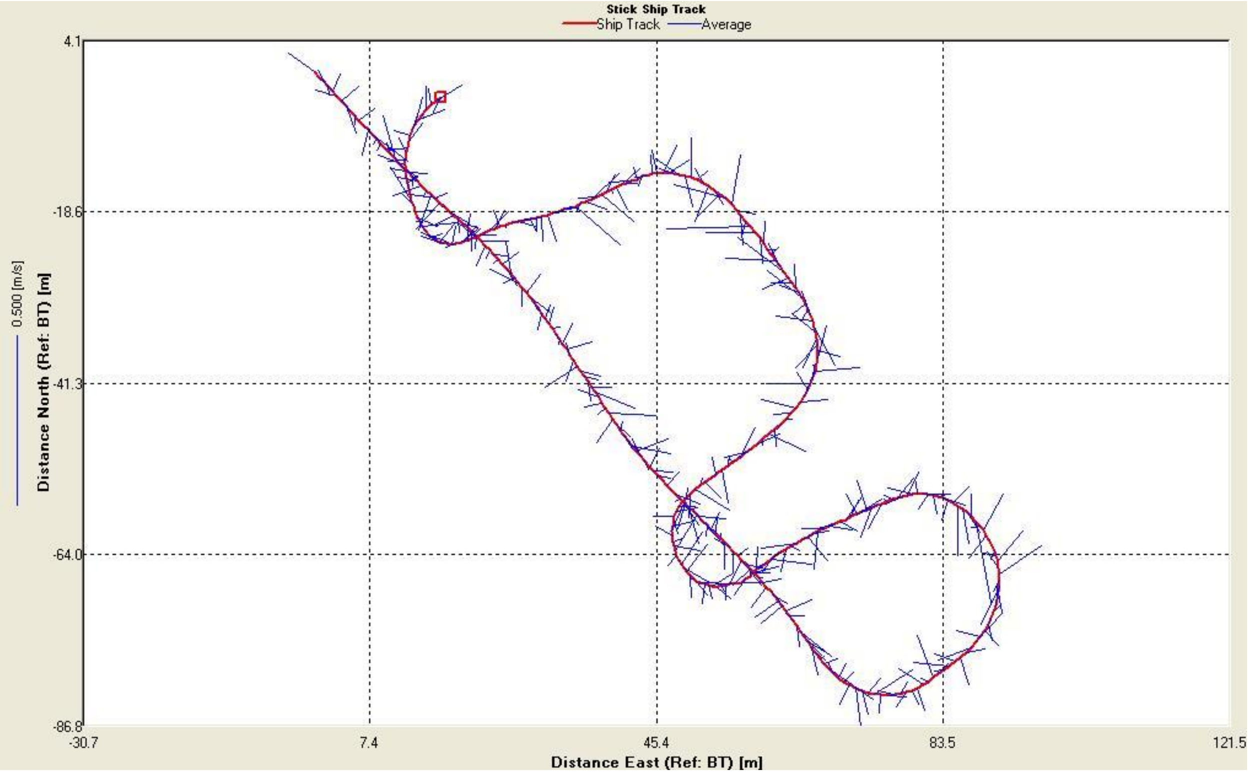
Transect 011 - Liberty State Park boat basin, NJ North side Bulkhead.



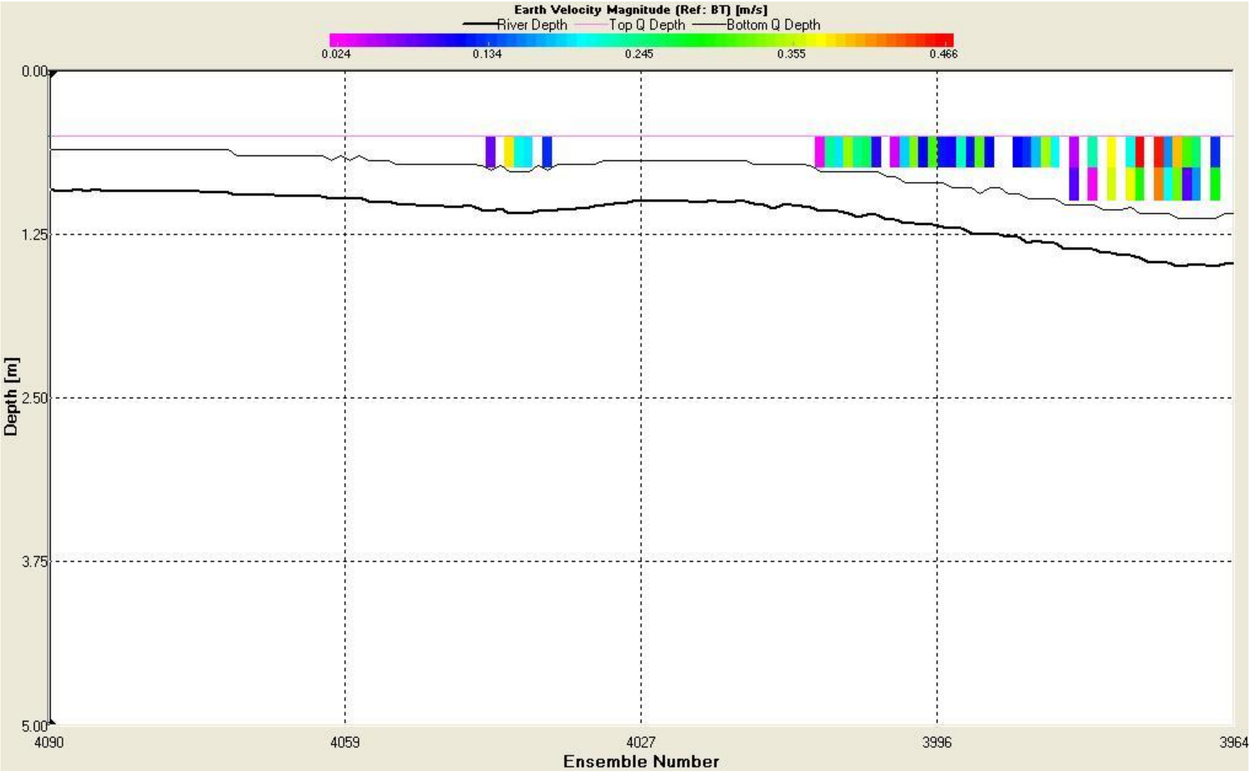


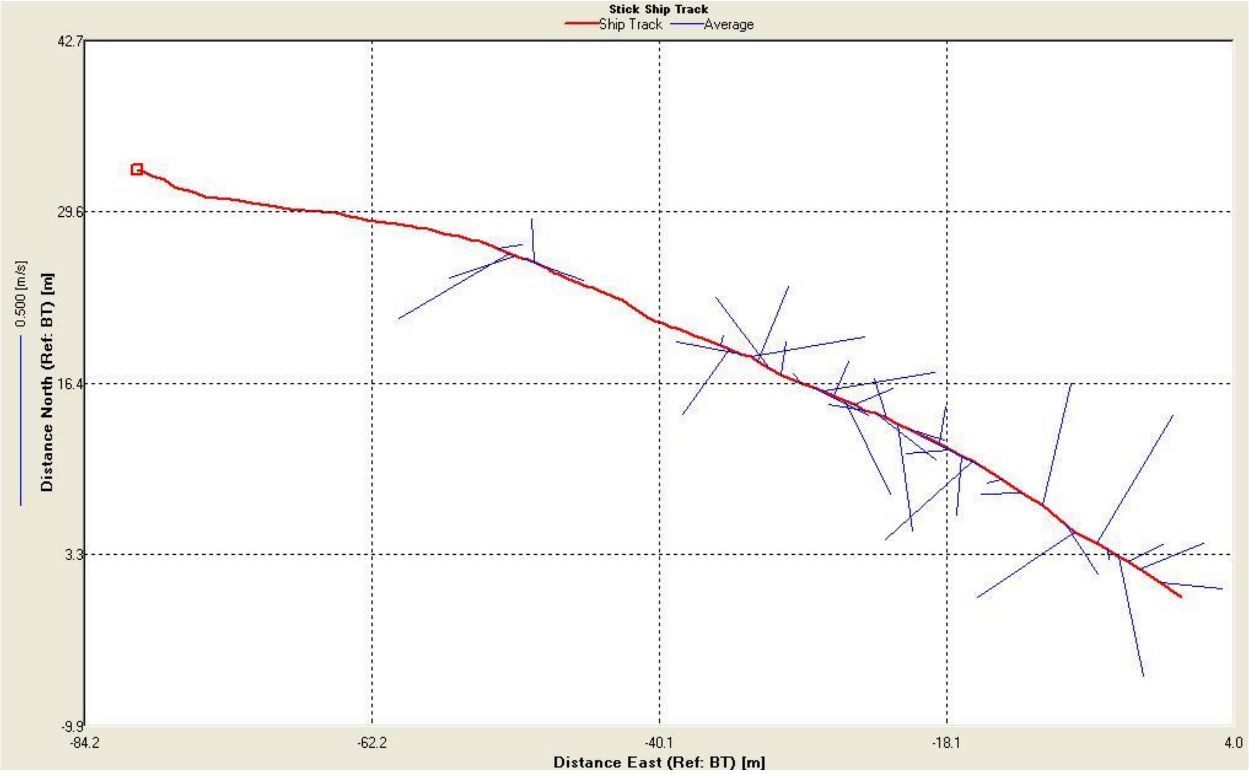
Transect 012 Liberty State Park boat basin, NJ North side large Riprap



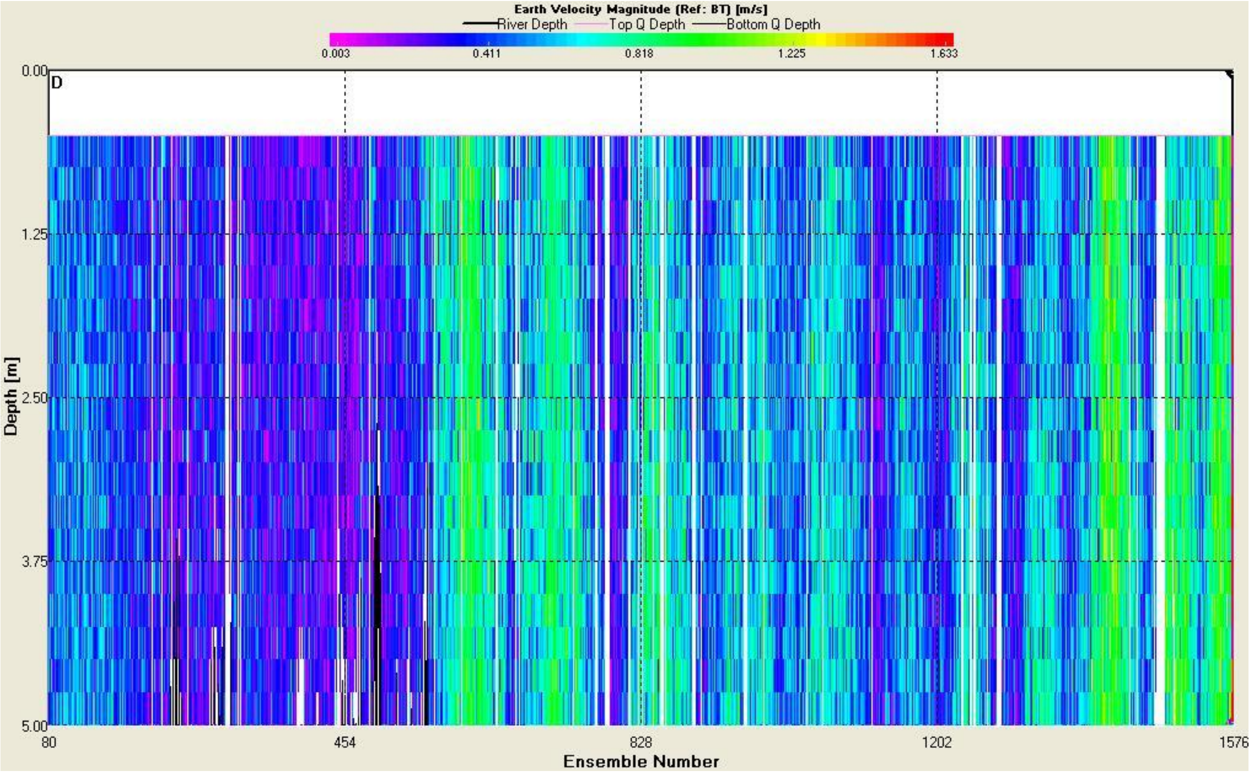


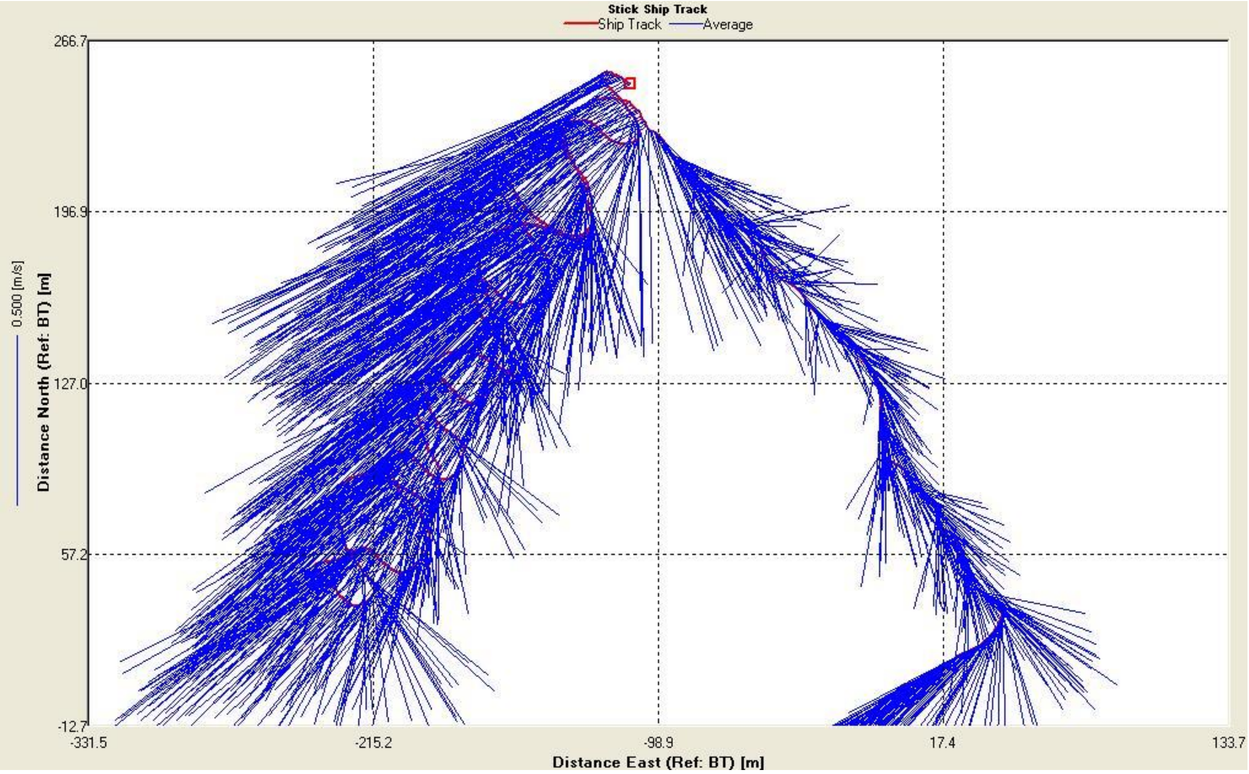
Transect 013



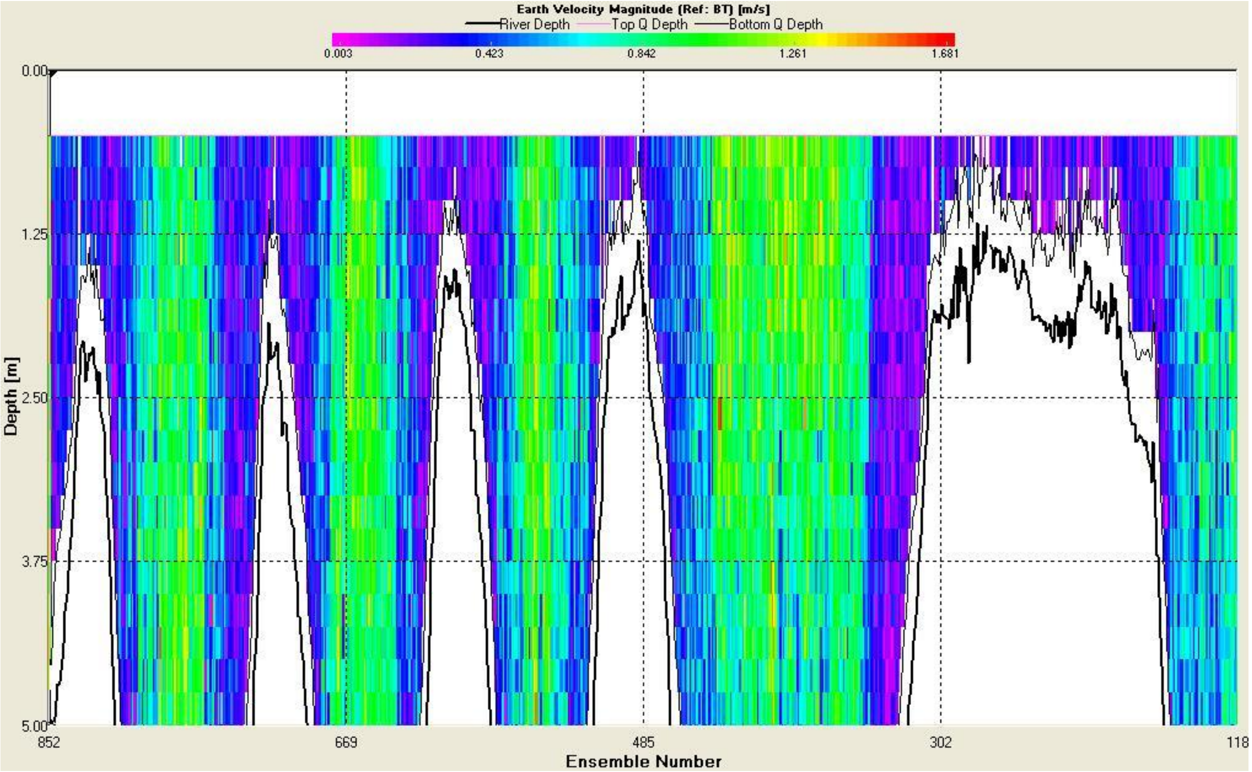


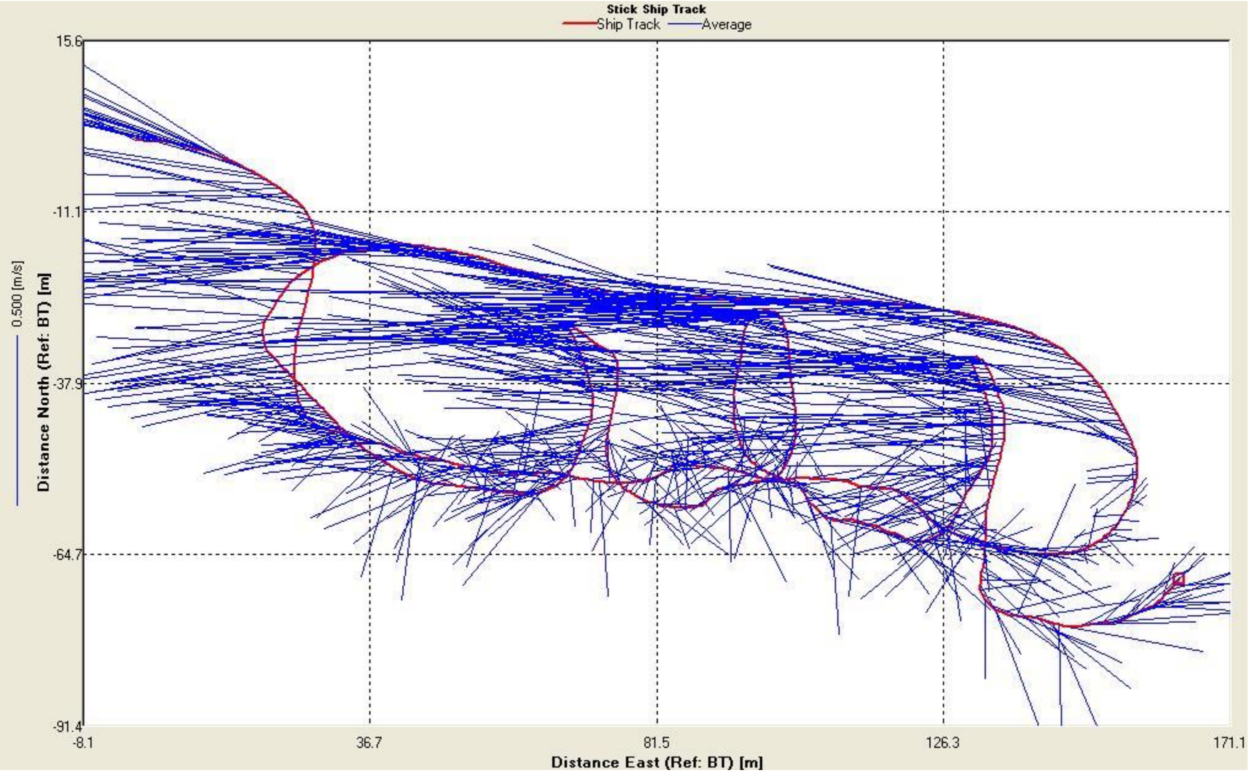
Transect 014 – Brooklyn Bridge Park Pier 1 bulkhead



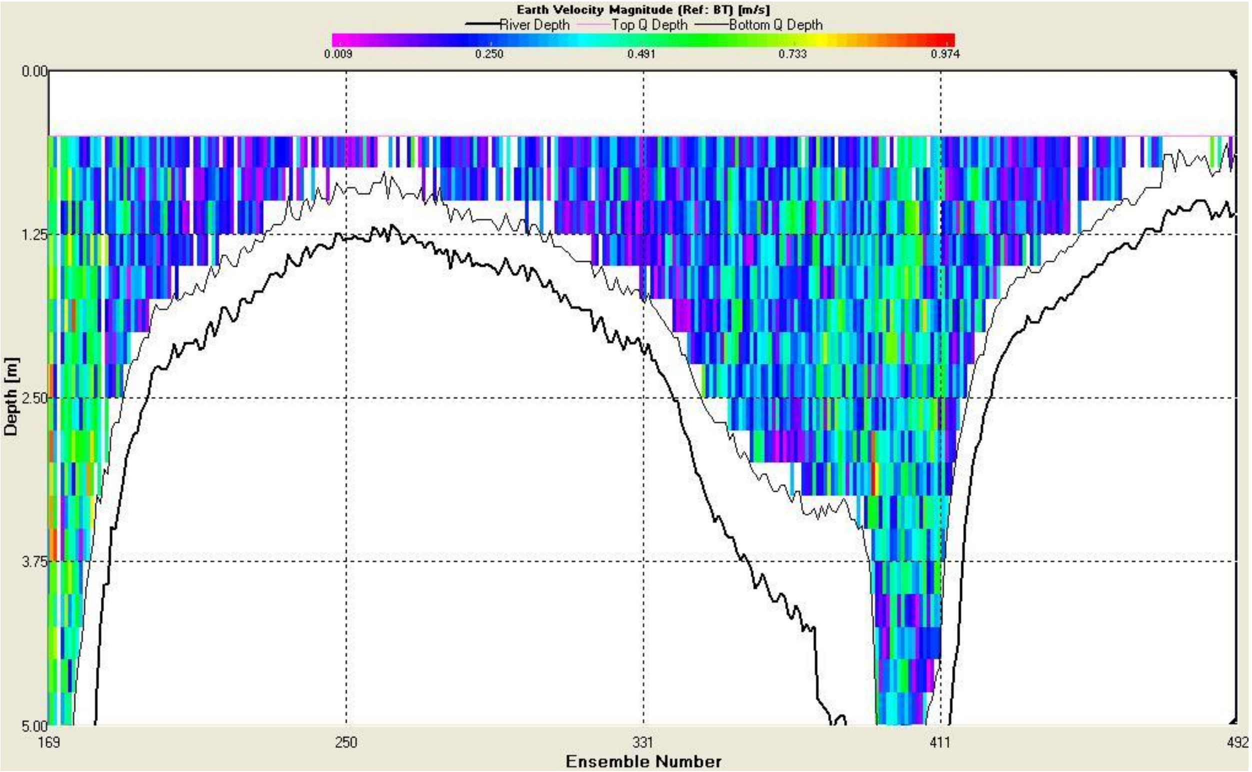


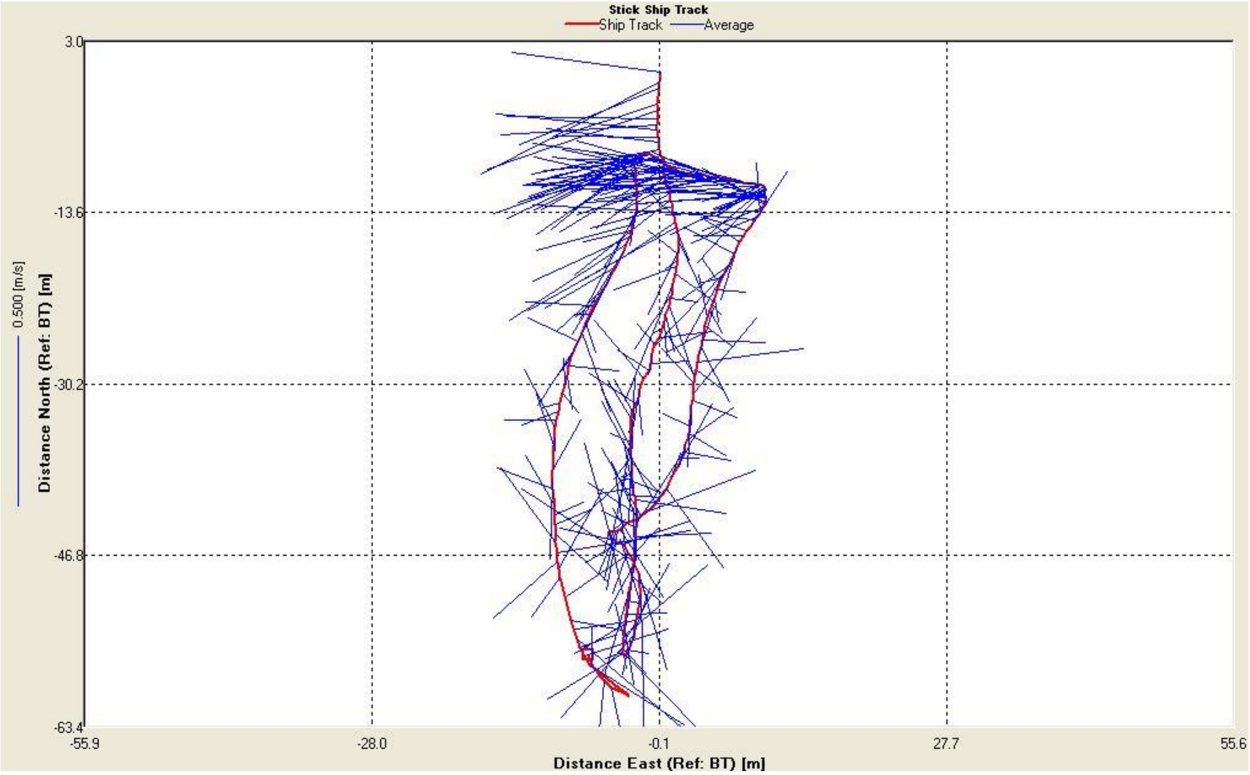
Transect 015 - Brooklyn Bridge Park North End (Manhattan Bridge) Riprap



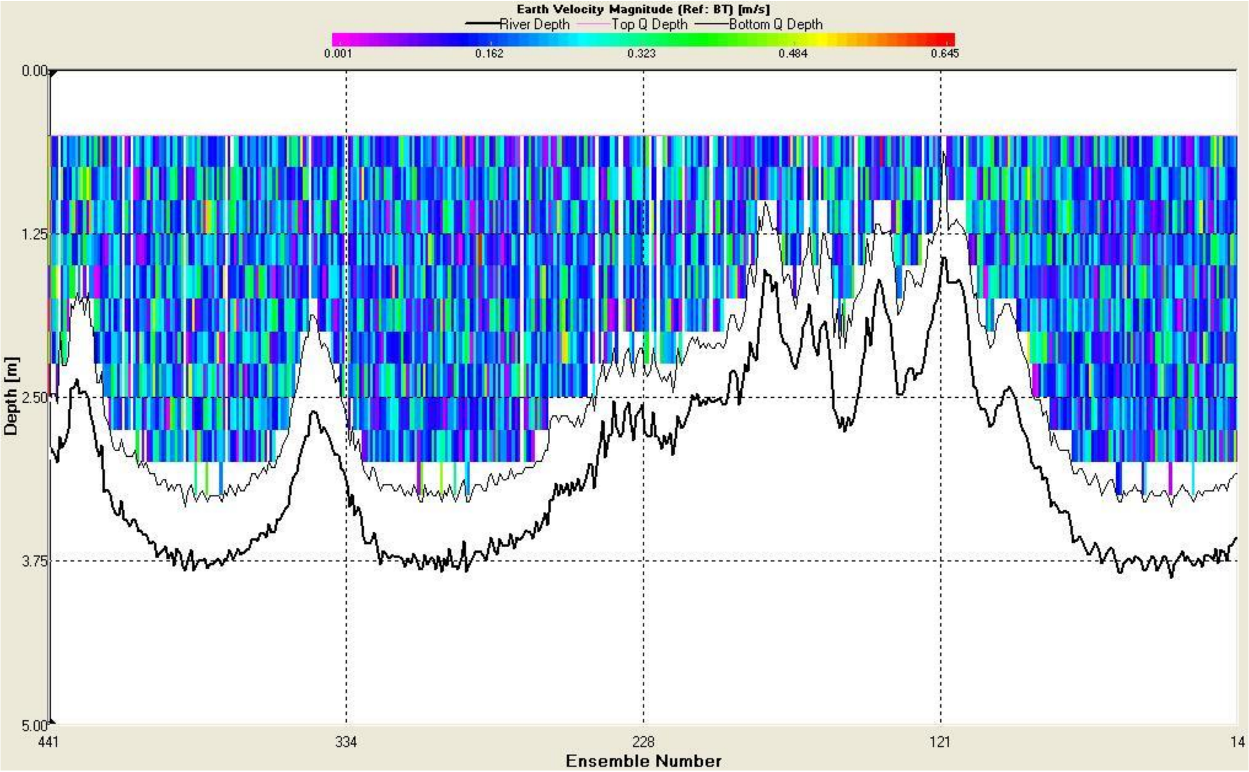


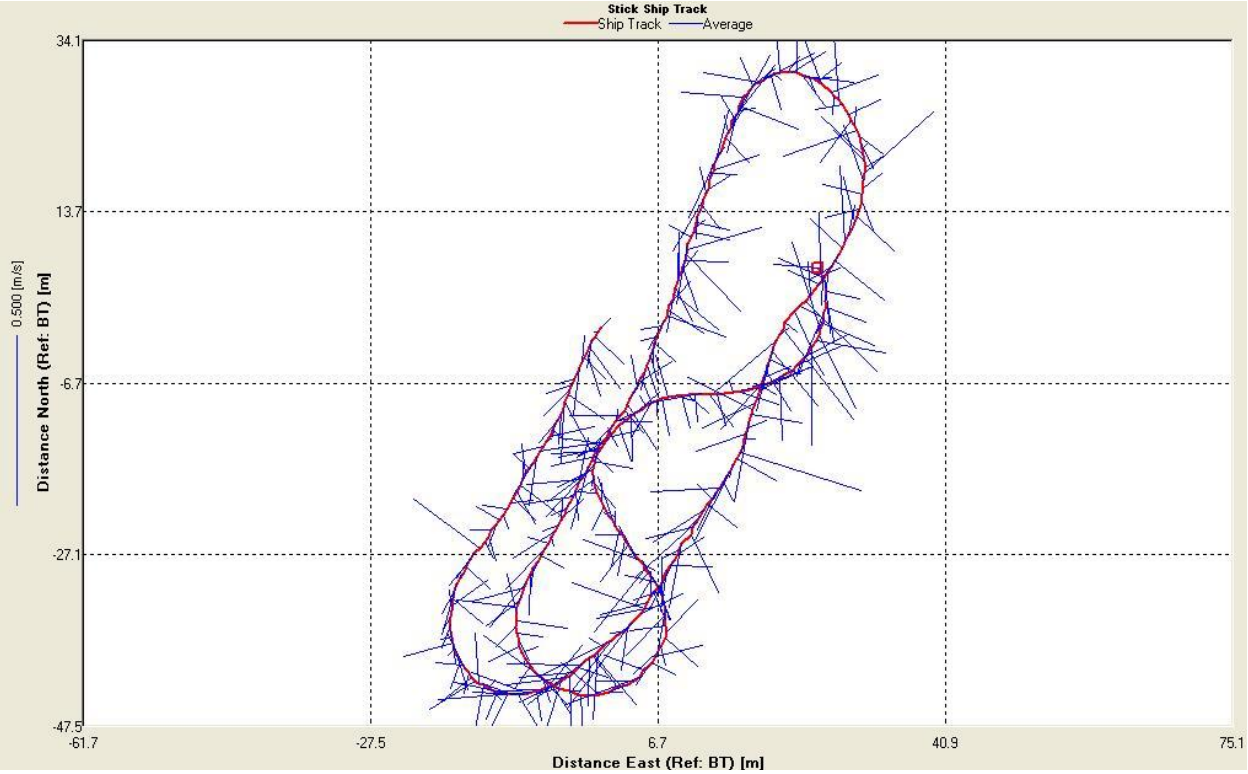
Transect 016 - Brooklyn Bridge Park Nortth (Manhattan Bridge) beach



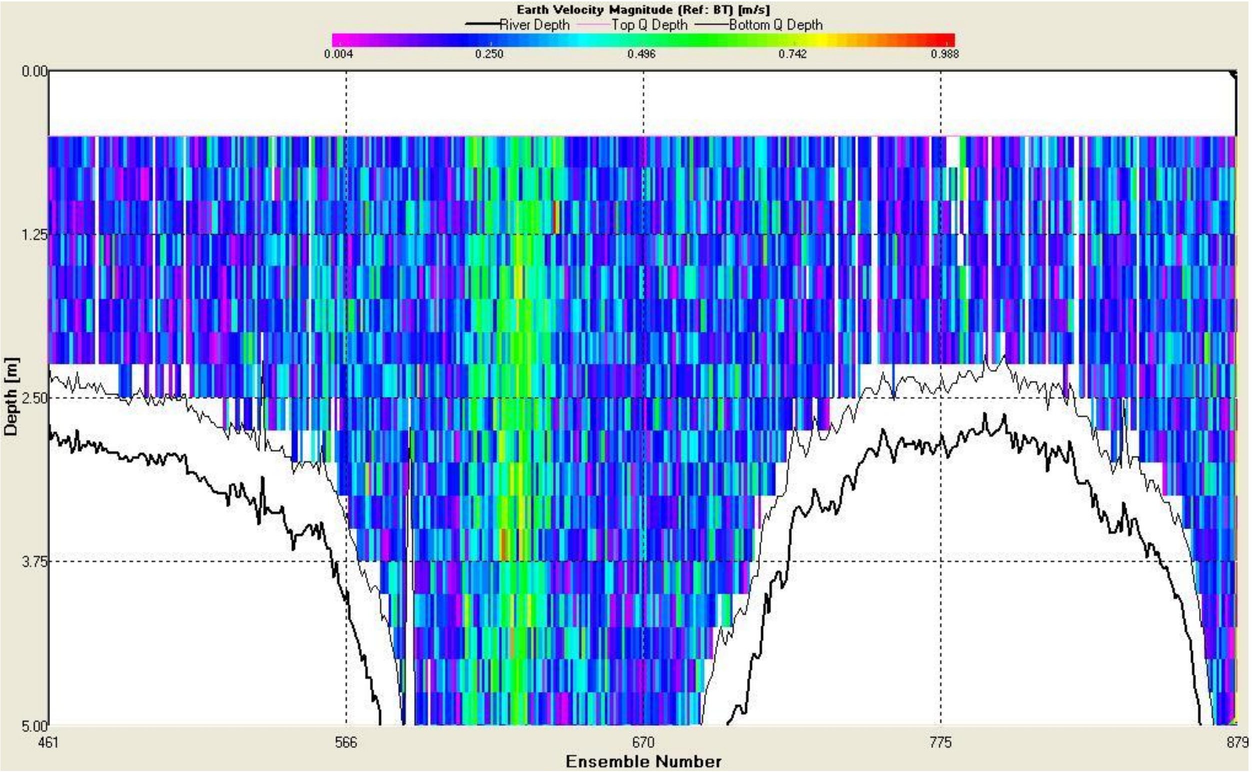


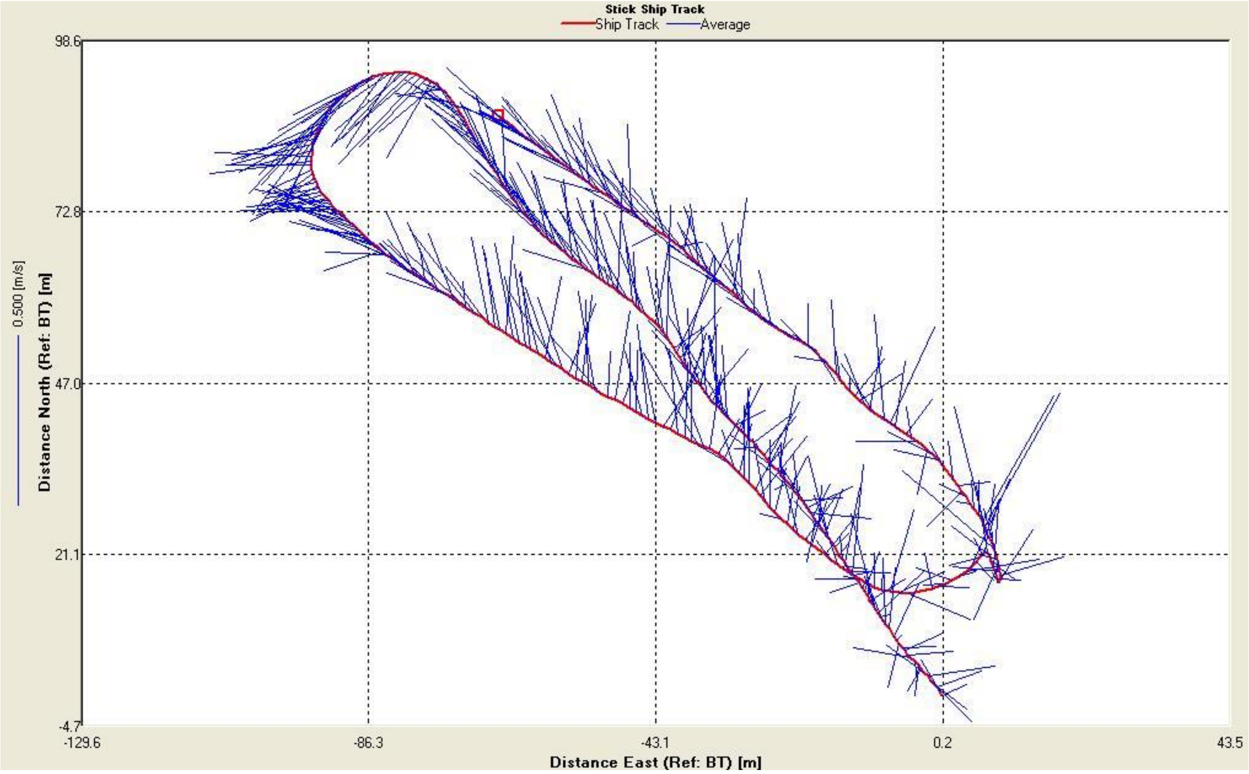
Transect 017 – Brooklyn Bridge Park South Pier 2 basin Riprap



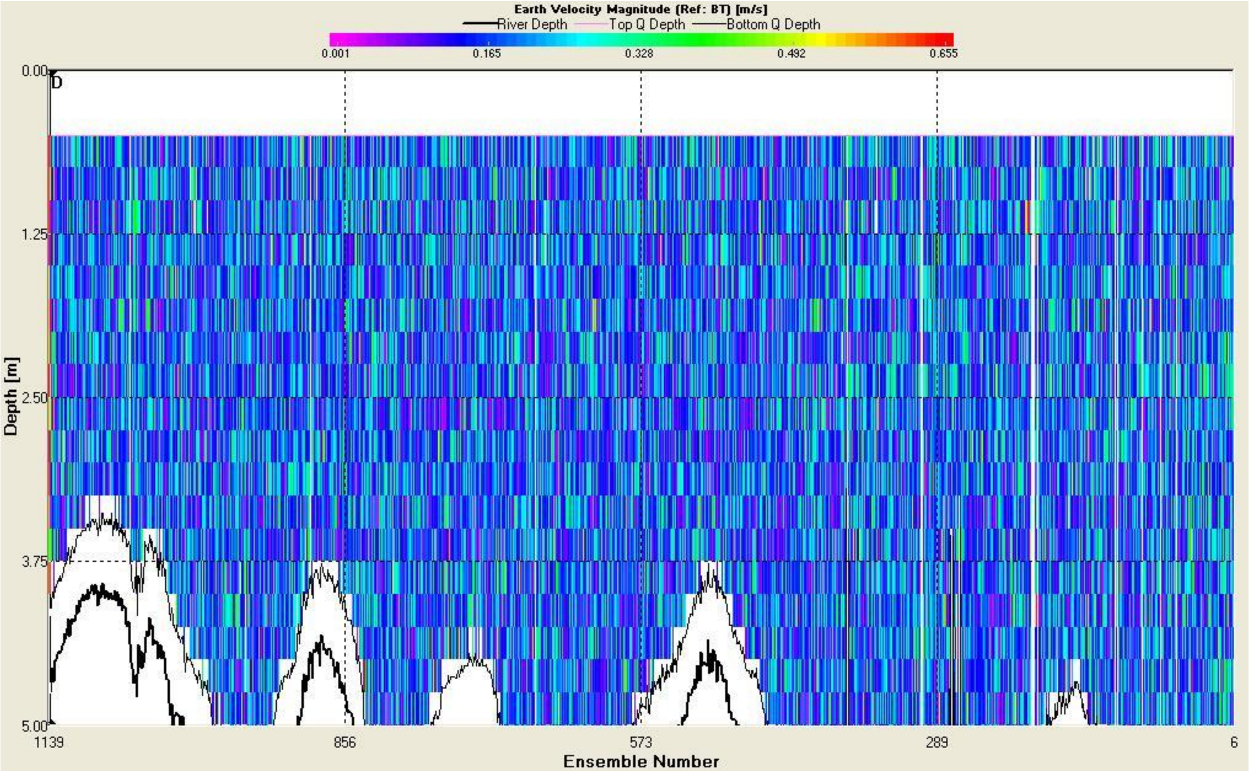


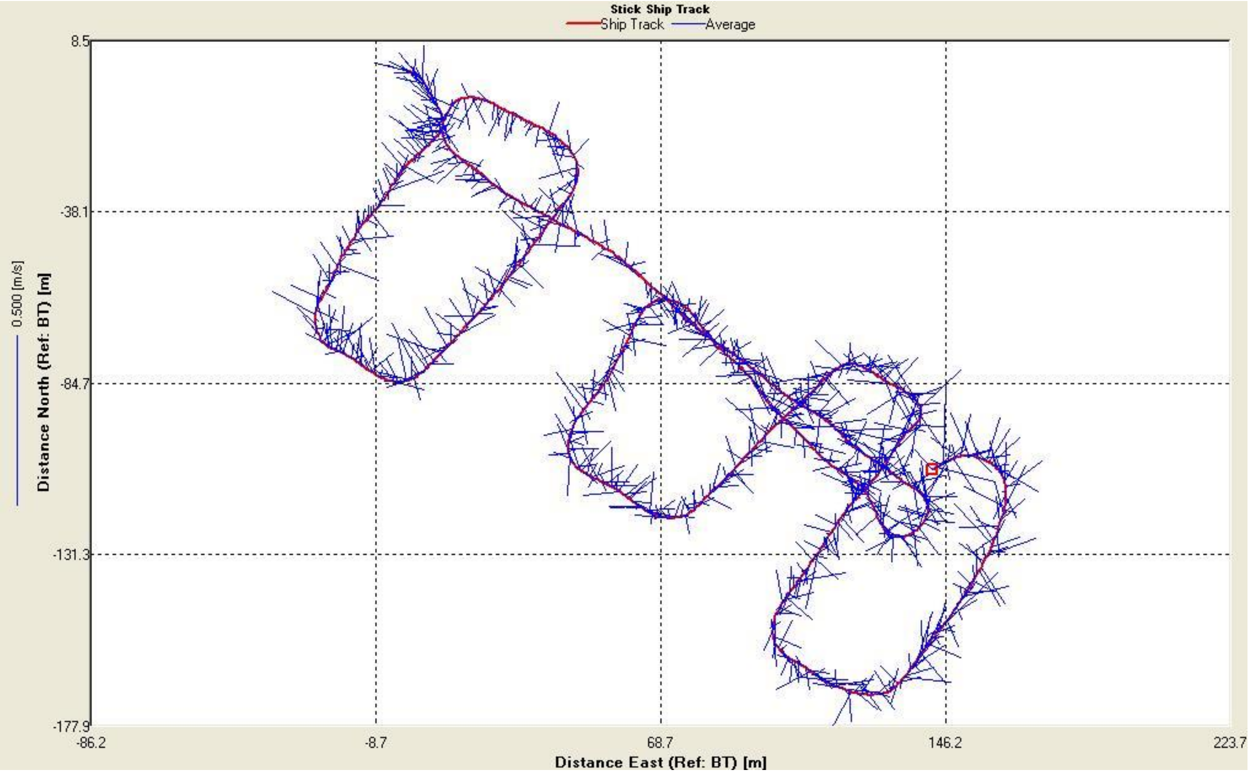
Transect 018 - Brooklyn Bridge Park South Pier 2 basin (open water)



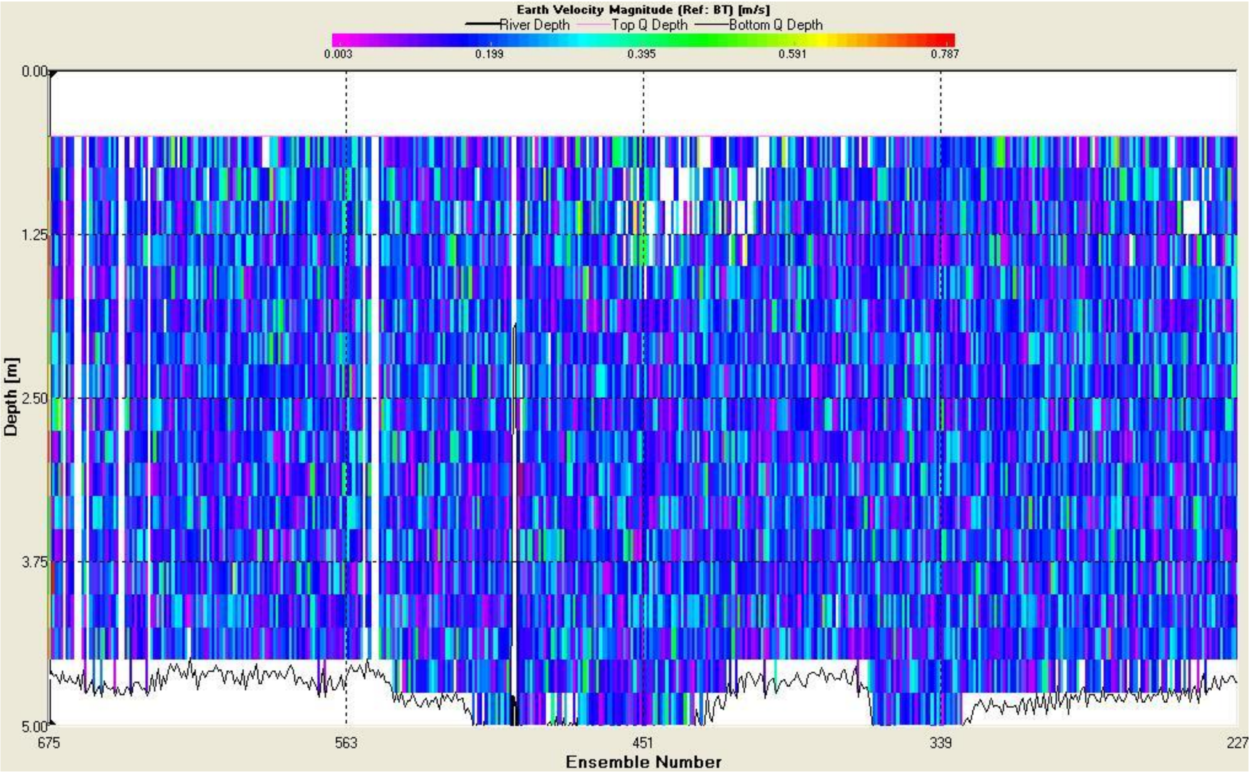


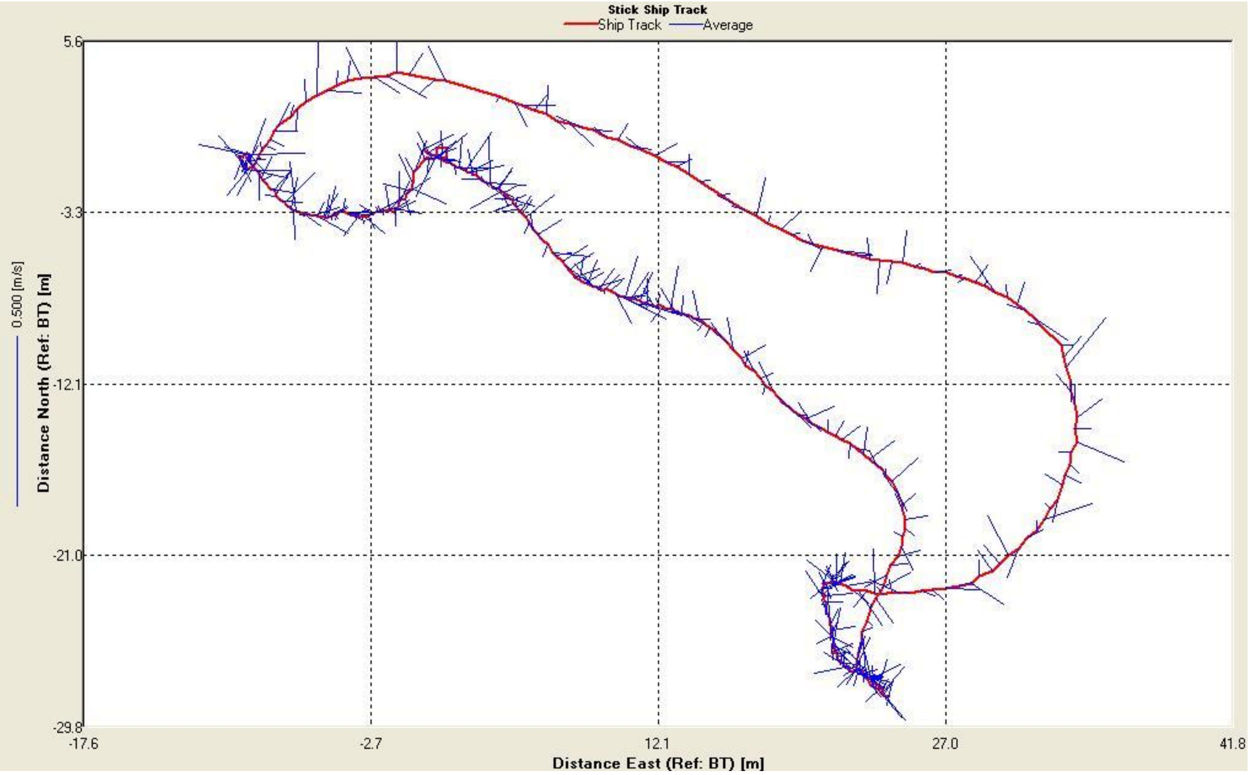
Transect 019 – Brooklyn Bridge Park Pier 6 (Barge Mooring)



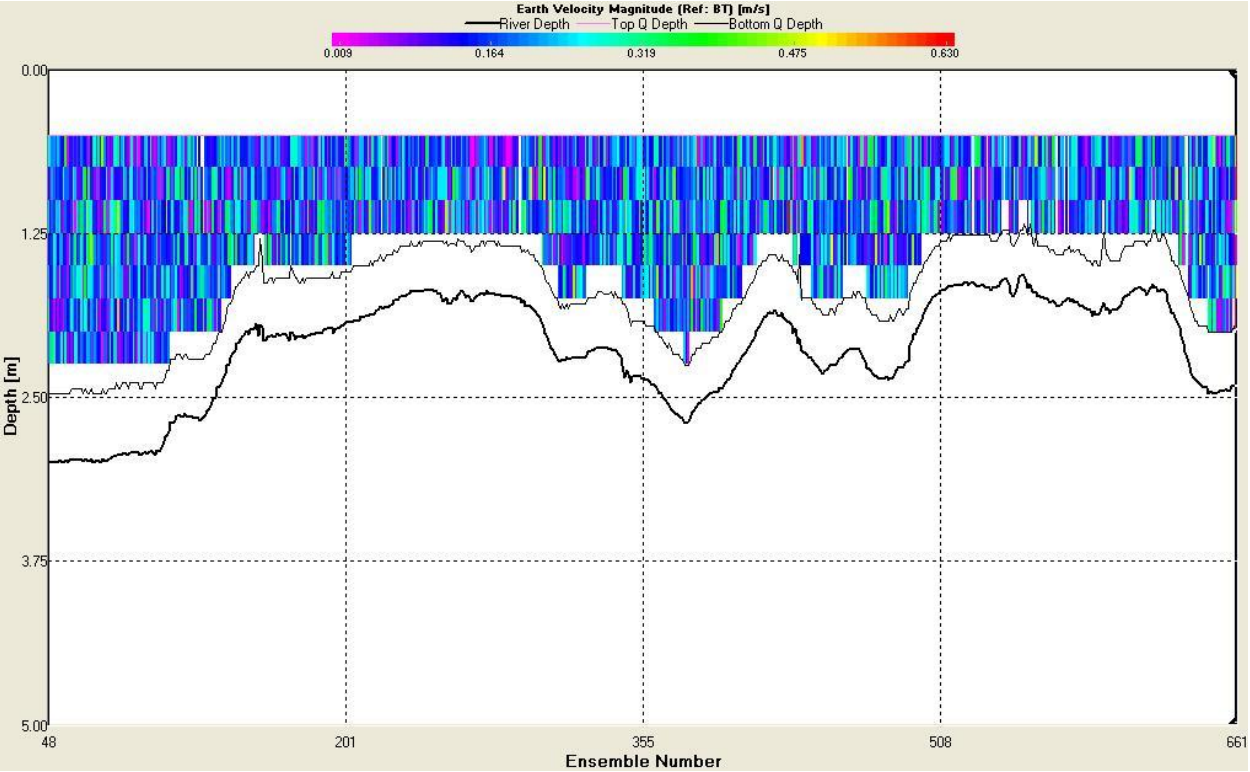


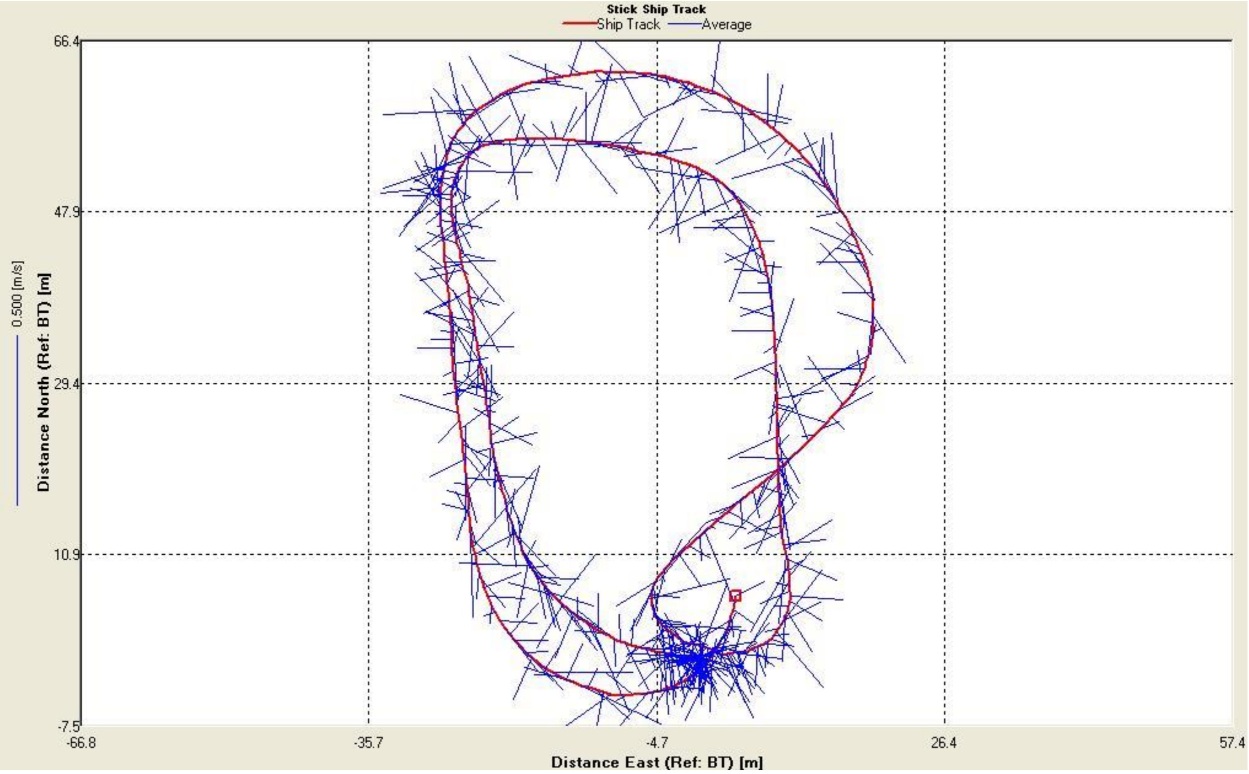
Transect 021 - Brooklyn Bridge Park Pier 6 (Barge Mooring)



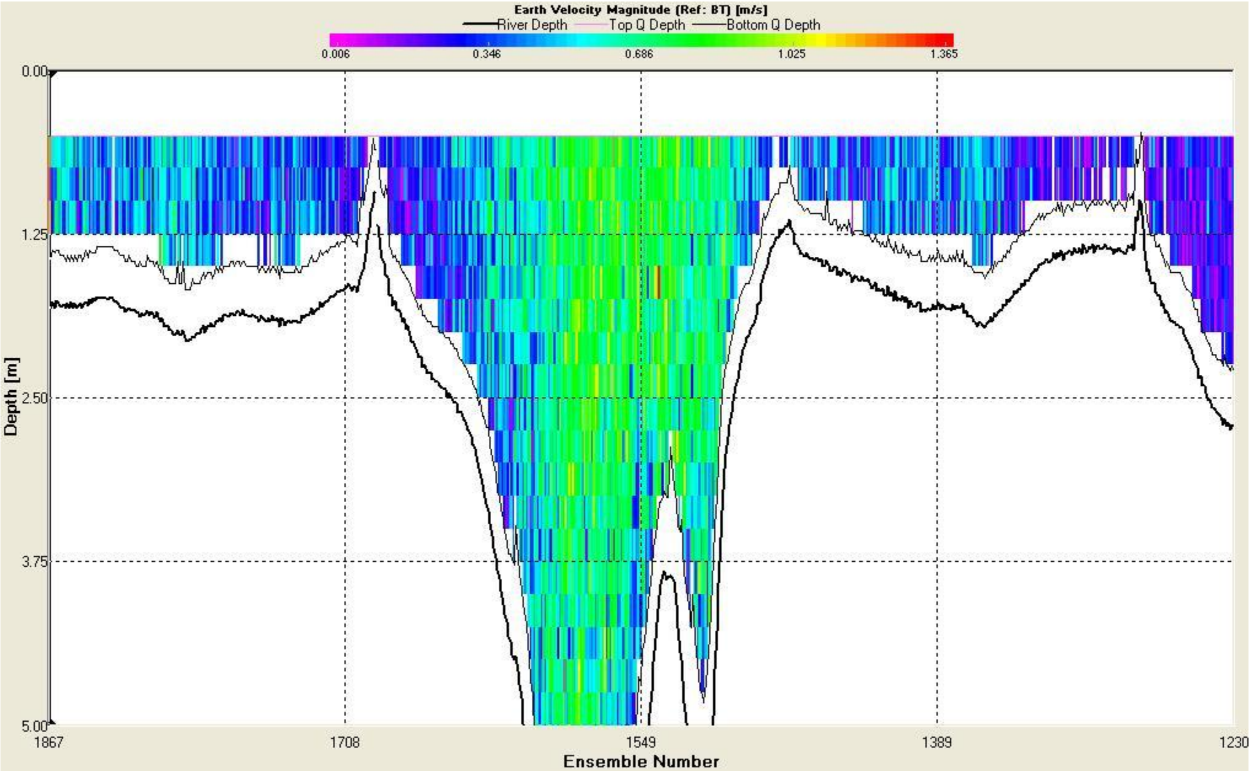


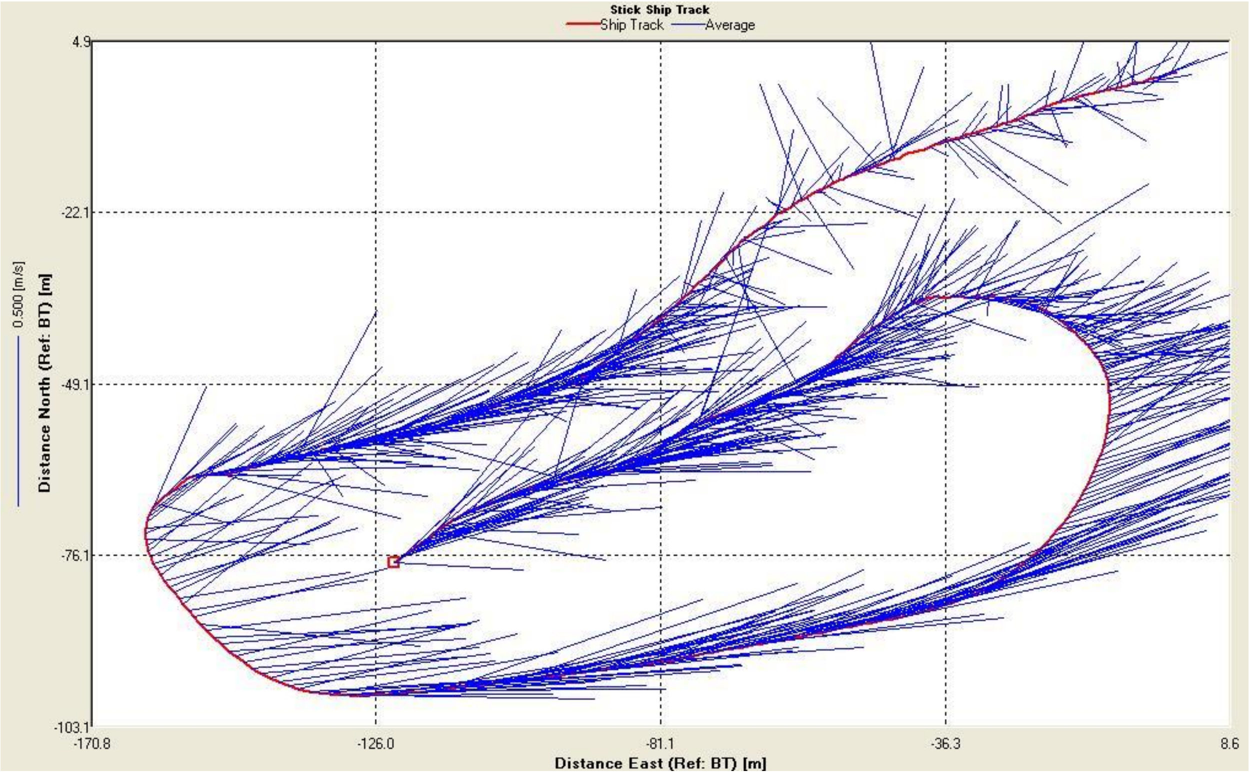
Transect 022 – Governor's Island Boat Basin



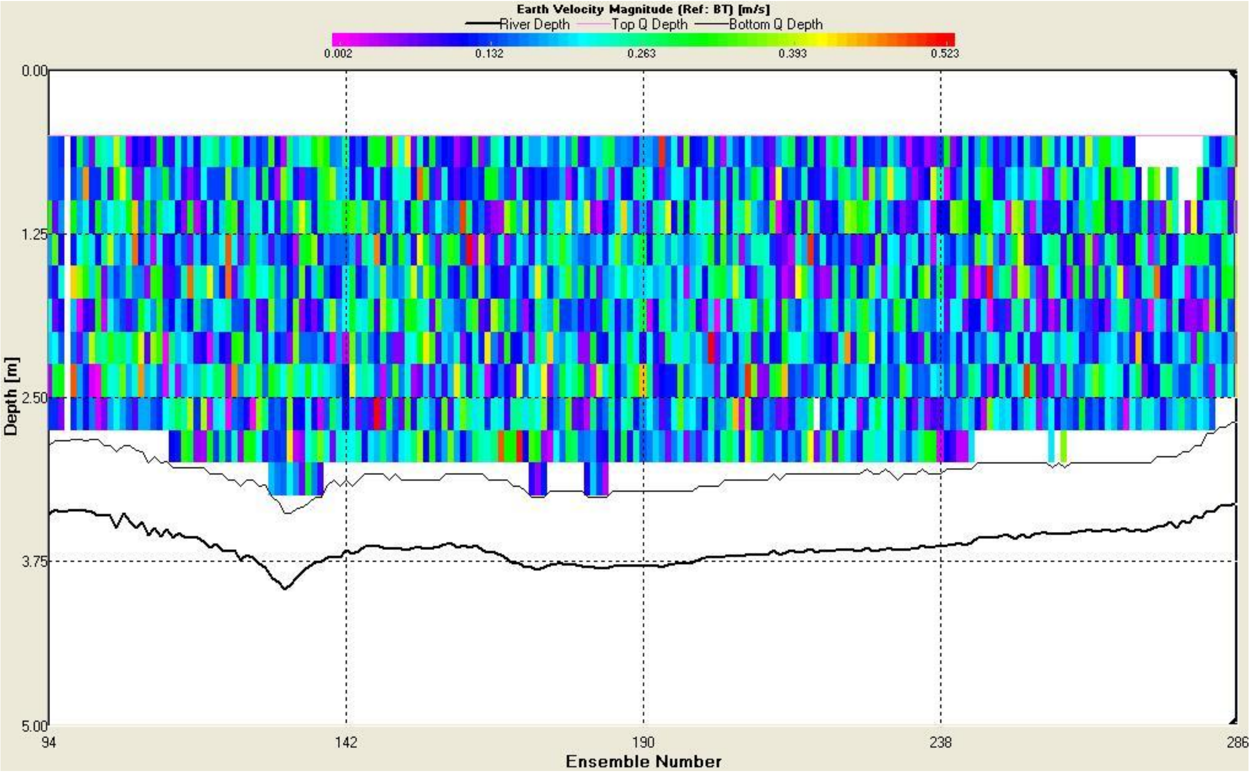


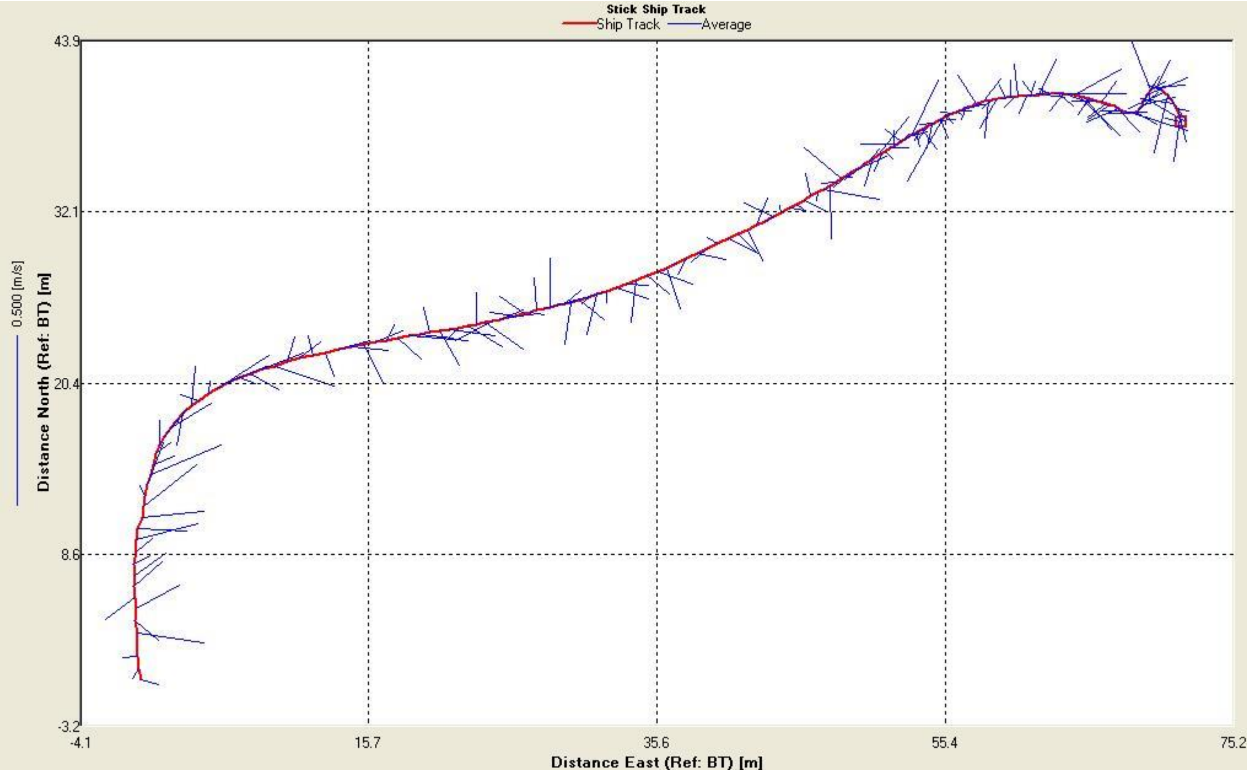
Transect 023 - Governor’s Island Beach and oyster reef



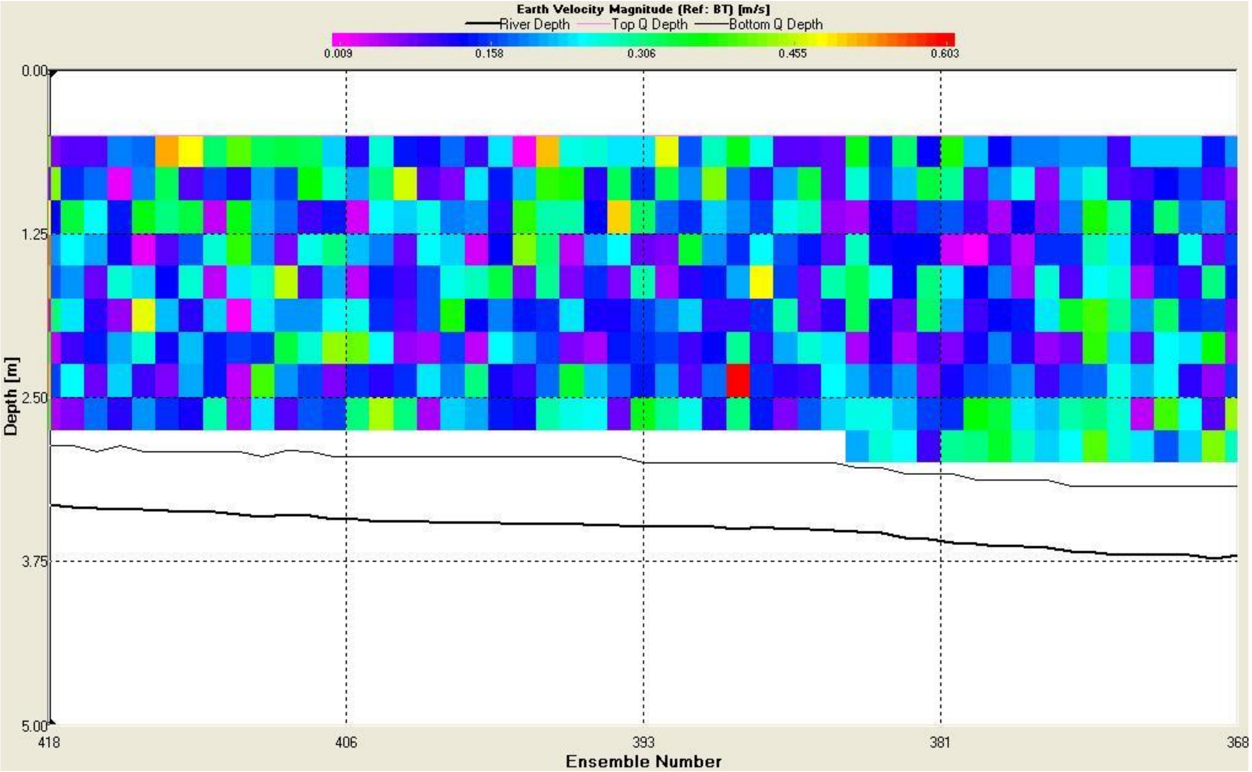


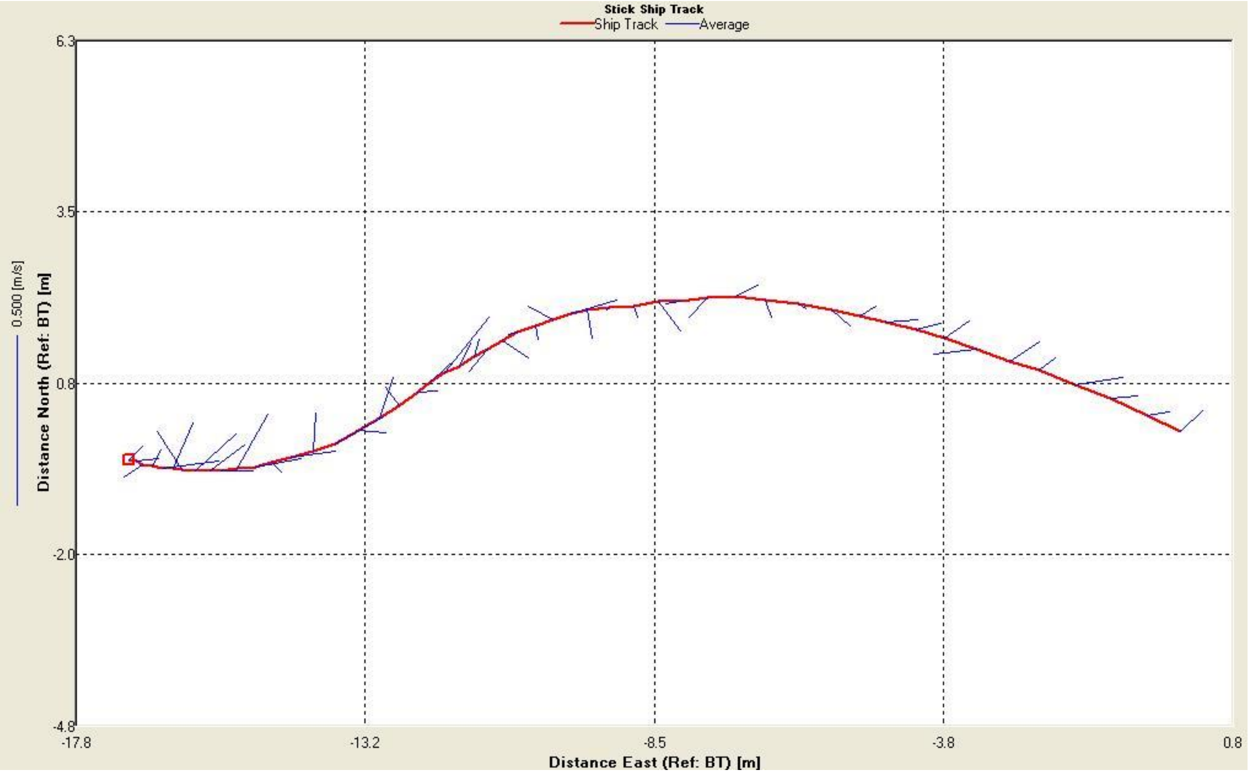
Transect 024 - Red Hook Barge Mooring



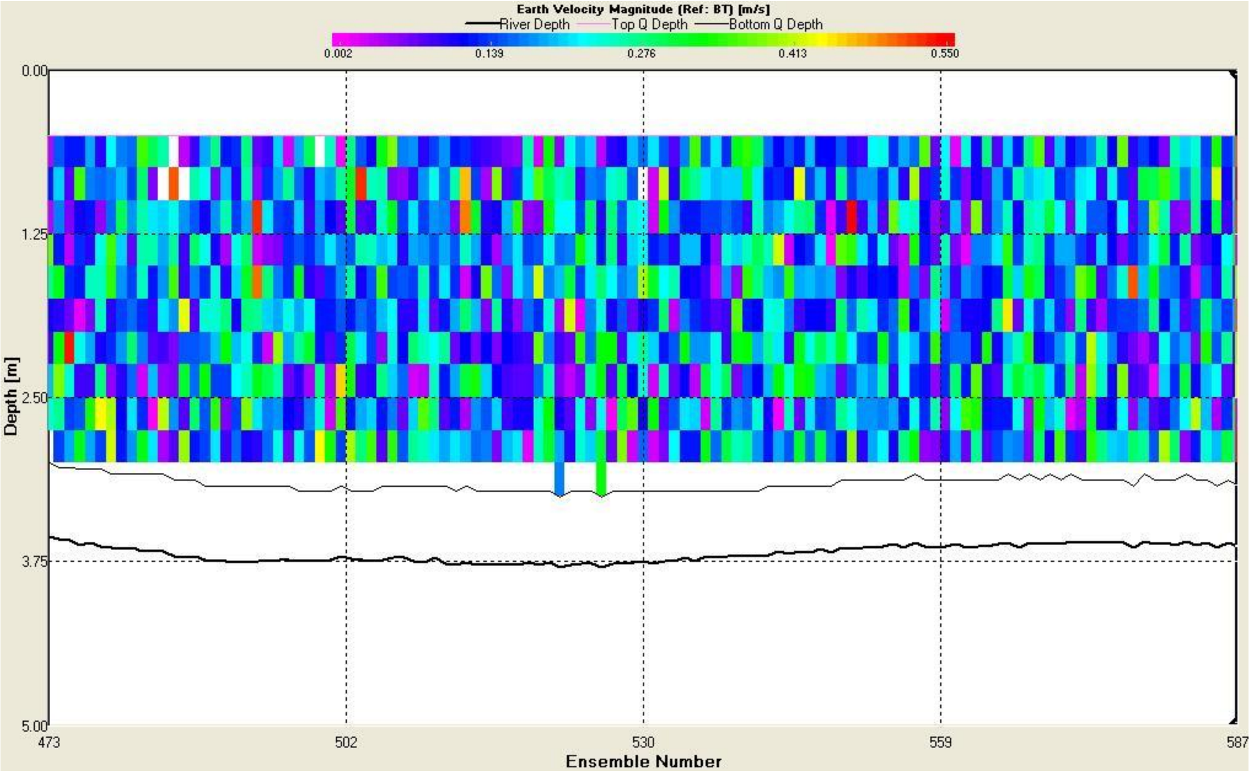


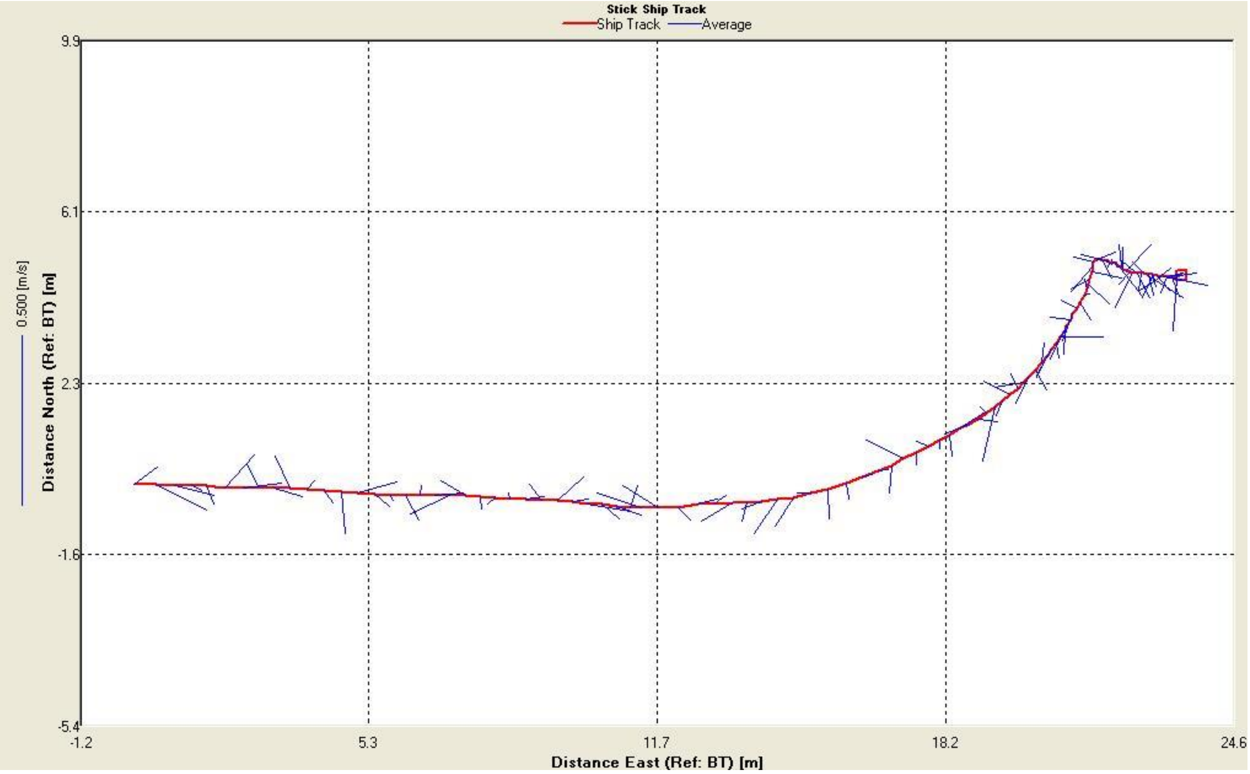
Transect 025 - Red Hook Barge Mooring



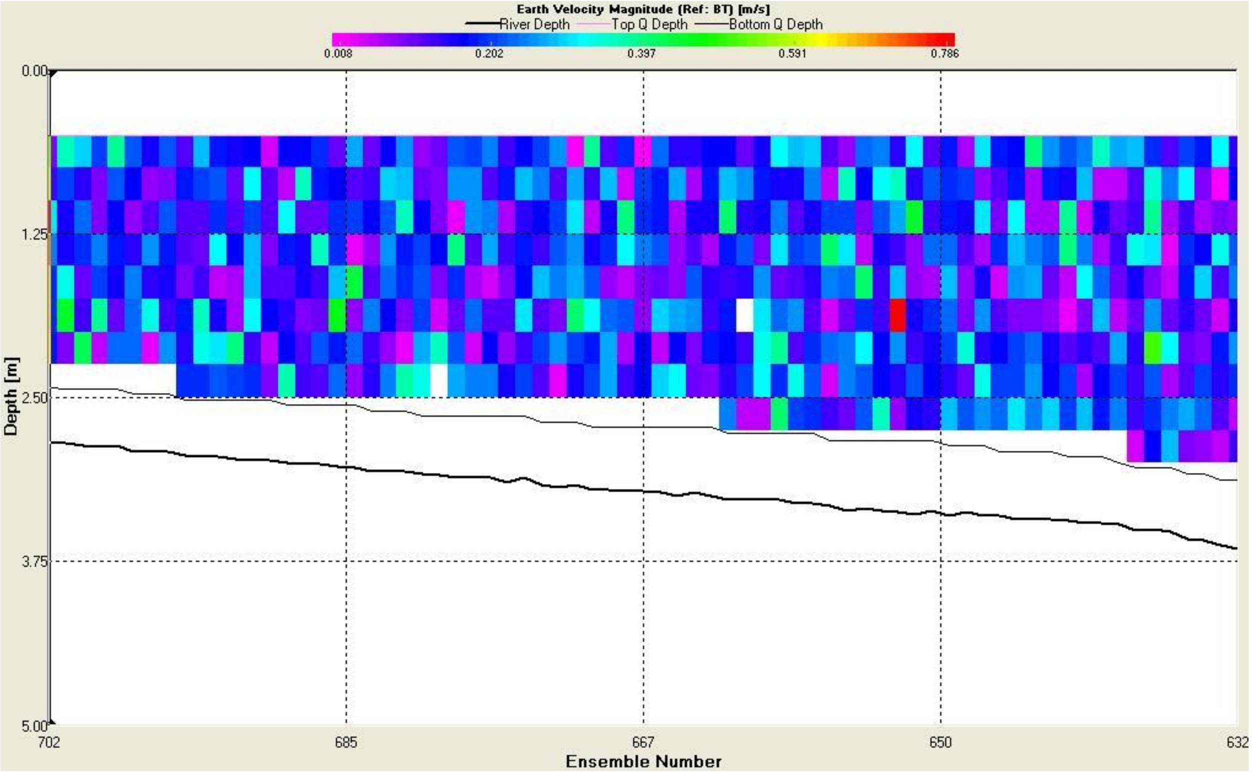


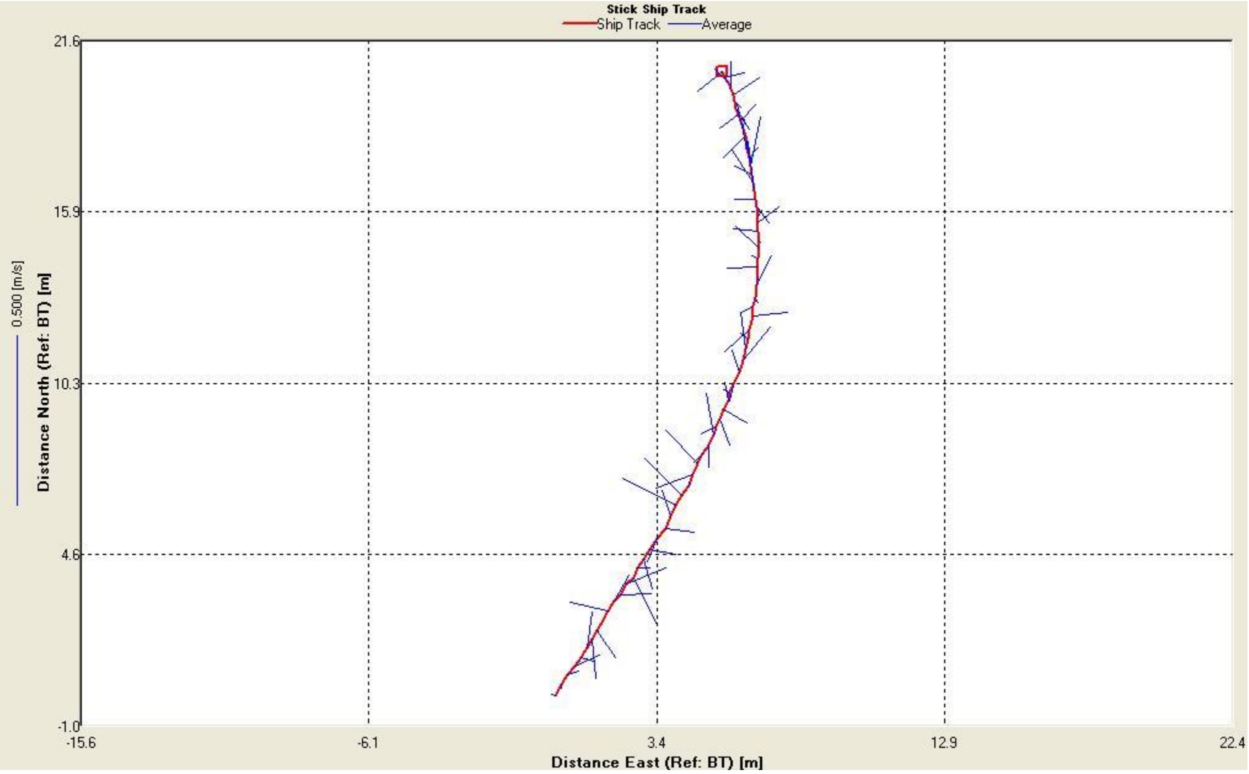
Transect 026 - Red Hook Barge Mooring





Transect 027 - Red Hook Barge Mooring





Transect 028 – Soundview Park Riprap and oyster reef