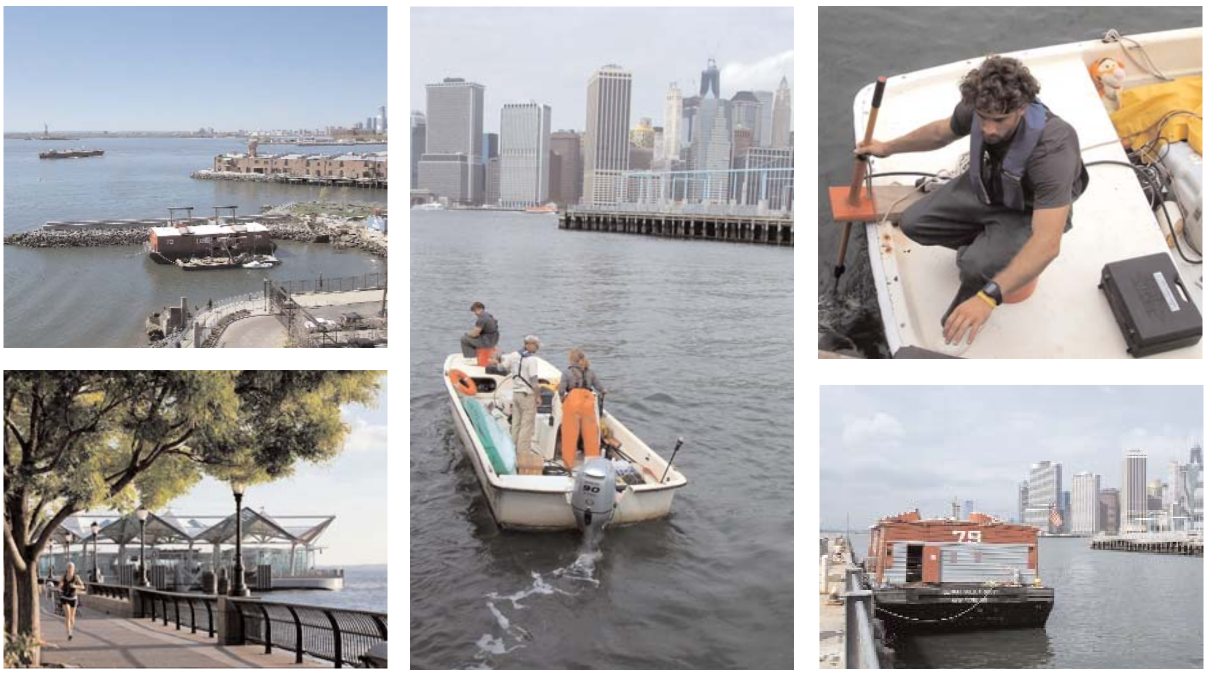
SOUTHWEST BROOKLYN WATERFRONT STUDY

THE PORT AUTHORITY
OF NY & NJ

FLOATING STRUCTURES PILOT PROJECT:
Fish Utilization & Responses and
Hydrodynamics & Sediment Transport

PROJECT SUMMARY REPORT
July 2015



Project Sponsor:
The Port Authority of New York and New Jersey
Project Funding:
Bi-State Dredging Fund, through The Port Authority of New York and New Jersey

Prime Consultant:
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Fish Utilization & Responses
Woods Hole Oceanographic Institution - Hydrodynamics & Sediment Transport

Photos (clockwise from top left): Waterfront Museum Barge in Red Hook, SW Brooklyn, NY; Data Collection, Piers 5-6, Brooklyn Bridge Park, NY; Data Collection with DIDSON, Piers 5-6, Brooklyn Bridge Park, NY; Waterfront Museum Barge, Piers 5-6, Brolyn Bridge Park, NY (Photos by Nautilus International, 2012); World Financial Center Floating Ferry Terminal, New York, NY (Photo by The Port Authority of New York & New Jersey, 2009).

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OF NY & NJ

PROJECT SUMMARY REPORT
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1 - INTRODUCTION

by Nautilus International Development Consulting, Inc.

PROJECT SUMMARY REPORT
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1 - INTRODUCTION

Floating structures are in increasing demand in New York Harbor for environmentally beneficial uses which serve important regional needs for revitalization of the waterfront and adjacent waterways, such as commuter ferry terminals. Expanded ferry networks not only have the potential to connect waterfront communities while reducing greenhouse gas emissions, but also played an important role in regional emergency responses after both 9/11 and Hurricane Sandy. Potential applications for floating structures range from ferry landings and other water-borne transportation to climate adaptation and public waterfront access.

The Port Authority of New York & New Jersey (PANYNJ) sponsored this Floating Structures Pilot Project from 2011 to 2014 to conduct scientific research about the environmental effects of nearshore floating structures on the aquatic habitat in New York & New Jersey's harbor. The pilot project focused on two research topics: 1) fish utilization and response to floating structures and 2) their effects on hydrodynamics and sediment transport. This Project Summary Report includes a summary of the research objectives and previous scientific studies, a description of new data collected, an analysis of data and results, an explanation of major findings, a discussion of potential implications of the study, and recommendations for next steps.

Background

While a number of studies have been conducted under large over-water platforms, very little scientific data has been collected on smaller, more mobile floating structures. The PANYNJ's pilot project was designed to make a contribution to the scientific understanding of nearshore floating structures in the New York Harbor estuary to help build a body of knowledge about how these structures affect their environments - both positively and negatively.

In New York State, current regulations restrict the use of in-water structures. Those regulations are based on studies done under large platforms. The PANYNJ's pilot project is intended to contribute to an evolving understanding of floating structures that will help inform decisions about design and placement of these structures in New York Harbor; provide information to public and private operators of water-dependent businesses; and assist regulators in assessing the impacts of proposed floating structures.

Sponsors, Funding & Informational Meetings

The pilot was sponsored by the PANYNJ and funded through the Bi-State Dredging Funds. As part of their sponsorship, the PANYNJ convened a series of informational meetings to communicate and discuss ongoing findings during the course of the research, which were attended by federal, New York State and New York City public agencies, the local community board, and interested organizations.

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SW Brooklyn Waterfront Study

Port cities around the world are facing the question of how to combine economic development with environmental sustainability, especially in light of urgent global economic and environmental challenges. Under the PANYNJ's leadership, this dynamic study of the SW Brooklyn waterfront was started in 2009 based on international best practices and has explored many facets of the challenge, from modernization of industry to realignment of the workforce and mitigation of climate change. The Floating Structures Pilot Project is one of a number of pilot projects that have been undertaken to support sustainable redevelopment of SW Brooklyn's industrial port areas. Part of its impetus came from this study's Brooklyn-Rotterdam Waterfront Exchange in 2010 when the New York delegation learned that the Dutch are making extensive use of floating structures, some as large as small neighborhoods, as part of their revitalization of former port areas and adaptation to sea level rise.

Research Topics

Fish Utilization and Response - This part of the research study focused on quantifying the association of juvenile and adult fish with floating structures to determine use, benefits, and impacts. Correlations were analyzed between structures and dock features (such as currents and depths) and temporal factors (such as the season and year) that could modify estuarine habitat function for fishes.

Hydrodynamics and Sediment Transport - Structures that alter the flow of mobile sediments result in complex variations of erosion and deposition. Such modifications of harbor beds can influence environmental quality by remobilizing contaminated sediments and altering benthic habitat. They may also hinder navigation. This research investigated how floating structures change flow conditions and turbulence; spatial patterns of sediment resuspension, erosion and trapping; and the stability of sediment transport.

Project Team

The PANYNJ's Department of Planning & Regional Development oversaw an interdepartmental team for this pilot as well as a multi-disciplinary team of consultants. The other PANYNJ departments involved were: Engineering/Architecture Design Division, Government & Community Relations, Office of Environmental & Energy Programs, and Port Commerce. The project consulting team was led by Nautilus International Development Consulting, Inc., who was prime consultant to the PANYNJ on the SW Brooklyn Waterfront Study as a whole. Nautilus International's subconsultant was the Hudson River Foundation (HRF), who oversaw scientific research and acted as technical advisor. HRF subcontracted with the Institute of Marine and Coastal Sciences at Rutgers University of New Jersey for research on fish responses and Woods Hole Oceanographic Institution for research on sediment transport processes.

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by Hudson River Foundation

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2 - RESEARCH OBJECTIVES, SUMMARY FINDINGS, POTENTIAL IMPLICATIONS, AND NEXT STEPS

Research Agenda and Objectives

The project was designed to examine the potential environmental effects of floating structures by conducting scientific field investigations in New York Harbor. The effects of man-made structures on the Harbor's ecosystem, particularly the fish community, have been of concern to resource managers for many years. Recently, with proposals to place a variety of floating structures for various purposes in the Harbor (e.g., floating docks, permanently moored vessels, etc.), the need for better understandings of the environmental consequences of these structures has been raised by the resource managers. In consultation with the PANYNJ, Nautilus International Development Consulting and the New York State Department of Environmental Conservation, the Hudson River Foundation (HRF) identified two areas of research aimed at understanding how fish might utilize the waters under and around floating structures and at evaluating how the structures may affect hydrodynamics and sediment transport.

Perhaps the most challenging part of the project was setting up a controlled experiment whereby the biological and physical measurements could be made at particular sites in the Harbor, with and without floating structures. To do this, HRF acquired the use of a barge that could be transferred to two separate sites relatively efficiently. The Waterfront Museum Barge, with a home port in Red Hook Brooklyn (Pier 44) was selected as the floating structure to study along with its berthing area in Red Hook. The barge was temporary moved to Brooklyn Bridge Park (Pier 6) for two summer sampling seasons to provide a second study site. The use of the barge in this manner allowed for before and after comparisons, and eliminated any size or shape difference that may have been present if more than one floating structure had been studied. In addition, the two sites comprise different pier and shoreline features (open pier and pier with adjacent rip-rap shoreline) as well as different environmental conditions.

An important aspect of the project was maintaining a collaborative dialogue among the researchers, the PANYNJ and the other interested stakeholders. The initial meetings provided valuable information to the researchers on policy interests and considerations and project design options and logistics. Subsequent meetings on the progress of the research studies and on the interim and final research findings kept the stakeholders engaged in the project and vested in the research findings.

The end result was a unique study - to our knowledge, the first of its kind in an estuary - that utilized both new technology and established tools to gather and analyze data in innovative ways and provide valuable insight into the potential effects of floating structures in New York Harbor.

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Research Agenda and Objectives (Continued)

Fish Utilization Study

This study evaluated the effects of floating structures relative to open water to determine if floating structures change the abundance, species composition, or overall size composition of fishes. Drs. Kenneth Able and Thomas Grothues from Rutgers University were the selected study team. Drs. Able and Grothues have worked extensively on fisheries issues in New York Harbor including the following HRF and Environmental Protection Agency (EPA) -funded research projects.

- *Determination of Habitat Quality for Estuarine Dependent Fishes - 1992*
- *Habitat Quality in the New York/New Jersey Harbor Estuary: An Evaluation of Pier Effects on Fishes - 1993*
- *Fish Habitat Quality in the New York/New Jersey Harbor Estuary: Pier Effects on Dynamics of Distribution and Growth - 1996*
- *The Effects of Pier Shading and Prey Availability on the Growth of Juvenile Fishes in the New York-New Jersey Harbor Estuary - 1998*
- *Association of Adult Fishes with Piers in the Lower Hudson River: Hydroacoustic Surveys for an Unsampled Resource - 2007*
- *Impacts of Shoreline Modifications on Fishes and Crabs in New York Harbor - 2011*

The past work of Drs. Able and Grothues put them in a unique position to conduct this part of the project. To conduct fish research in confined waters in urban areas, like New York Harbor, requires use of special techniques and equipment. Drs. Able and Grothues have successfully developed protocols for using "state-of-art" acoustical equipment to detect and quantify pelagic fish under and around structures. These were successfully utilized in this study. The details of this study are contained in Appendix 1. The study was conducted over a two-year period to evaluate seasonal differences in the fish community and to provide at least one replicate of those seasons.

Hydrodynamics and Sediment Transport Study

This study evaluated the influence of floating structures on sediment erosion, deposition, and transport. It is located in Appendix 2. A detailed observational study of currents and sediment (suspended and bottom) in the vicinity of the floating structure was used to examine how perturbations to the flow and associated turbulence impact nearby sediment transport process. Drs. Rockwell Geyer and David Ralston of Woods Hole Oceanographic Institution were selected to conduct this study because they have extensive experience studying sediment transport processes in New York Harbor and in other estuaries. The following is a list of their most relevant research projects.

- *Particle Trapping by Tidal and Estuarine Circulation in the Lower Hudson - 1992*
- *Particle and PCB Transport and Exchange in the Lower Hudson Estuary - 1994*

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Research Agenda - Hydrodynamics and Sediment (Continued)

- *Spatial and Temporal Variability of Sediment and Contaminant Trapping in the Hudson Estuary - A High-Resolution Numerical Modeling Study - 1996*
- *Sediment Transport and Mass Balance in the Hudson River Estuary: The Contribution of the Spring Freshet - 1998*
- *Mechanisms of Sediment Deposition, Erosion and Long-Term Accumulation in the Hudson Estuary - 2000*
- *Salt Flux, Salinity Intrusion and Residence Time in the Hudson Estuary - 2003*
- *Retrospective Analysis of the Hudson River Estuarine Transport Processes: 1958-2004 - 2005*
- *Linking Fine-Scale Processes to Estuary-Scale Variations of Sediment Trapping and Erosion - 2007*
- *Sediment Delivery, Trapping and Storage during Extreme Flow Events in the Hudson River - 2013*

Summary Findings

Small-scale floating structures docked in shallow nearshore waters in New York Harbor during the summer and fall resulted in relatively minimal effects on the number and behavior of fish.

Floating structures similar in size to the barge used in this study (9.1m x 25m x .9m draft or 30ft x 82ft x 3ft draft) and in similar environments are expected to only minimally influence fish utilization of New York Harbor's nearshore habitats in summer and fall in the absence of long-term physical changes like shoaling or scour associated with barge presence. Comparable floating structures are also unlikely to affect fish utilization in other seasons when many species have migrated away from the estuary.

Shading effects varied by type of fish and the presence of other shading sources.

Small schooling fish and large fish showed no measurable response to the floating structure at the study sites. However, at the site with less shaded water nearby, small solitary fish responded positively to the floating structure: more of them were encountered under it during the day than in open, unshaded water. By contrast, these fish didn't respond differently either during the day or at night at the site adjacent to a large pier. Similarly, effects from comparable floating structures are also less likely along shorelines that are already shaded by other manmade structures such as wharves. In addition, shading effects are improbable from barges shading deep water along steep armored shorelines because deep waters are already shaded by turbidity.

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Summary Findings (Continued)

Small-scale floating structures have minor influences on the hydrodynamics, suspended sediment, and bed sediment composition.

The presence of the floating structure caused slight changes to bed sediment composition during a two-week period when moored in the slip at Brooklyn Bridge Park. High resolution sidescan sonar measurements detected the outline of the barge as a region of stronger backscatter, consistent with scour of the surface fluff layer and a shift toward coarser-grained substrate. Grab samples also showed that the sediment bed under the barge was coarser than at locations in other parts of the slip. The draft of the barge (0.9m or 3ft.) was shallow relative the water depth (5-6m or 16-20ft) at that location, but in the short time that the barge was present, the sedimentary environment adjusted to the slightly altered physical regime. Over longer time scales, the bed is likely to adjust to perturbation and reach a new equilibrium, through changes in the bathymetry (getting deeper) or changes in bed composition (getting coarser).

Sediment movement in the slips varied with sediment supply from the river, tidal advection at density fronts, and resuspension by waves from ferry wakes.

The study provides additional information about how sediment movements take place in the New York Harbor and, particularly, along its perimeter into boat slips. Sediment supply in the Harbor increased after a Hudson River discharge event and during spring tides, increasing the availability of sediment for delivery to the slips. During the flood tide, which was dominant at the study location, a salinity front moved suspended sediments from the channel into the slip towards the end of the tide. Suspended sediment concentrations and velocities were weaker during the ebb, leading to net landward flux. Tidal velocities in the slip were too weak to significantly resuspend sediment. Instead, resuspension in the slip was primarily associated with wave orbital velocities, with the wave forcing primarily due to ferry traffic in the Harbor.

These findings apply only to single floating structures in the short term. Larger clusters, different hydrodynamic settings, and cumulative effects over the longer term need further study.

In general, the research studies indicate that, while the barge did have minimal measurable effects on both fish utilization and sediment transport processes, the response in both cases was very subtle. Although the results suggest that the influences of a single barge are expected to be minimal, if barges accumulate or cluster together to change from small parts of the habitat mosaic to a dominant habitat feature, the potential for effects may increase.This issue of cumulative effects and concurrent habitat fragmentation is recognized for urban estuarine development nationwide and for many kinds of shoreline and nearshore structures. The effects of the size and draft of floating structures on the hydrodynamics and sediment transport also merit further study, taking into account how variability in forcing due to tidal velocities, salinity gradients, and wave exposure affects different locations in the Harbor.

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Summary Findings (Continued)

Potential Implications and Next Steps

The Hudson-Raritan Estuary Comprehensive Restoration Plan (CRP), co-sponsored by the PANYNJ, provides the framework for advancing a shared vision for a restored NY Harbor Estuary. The information gained through these studies will help advance several restoration targets and objectives (TECs) including the Shorelines and Shallows TEC and the Habitat for Fish Crabs and Lobster TEC which focus on enhancing the connections between different habitat types and the spatial arrangements between specific habitats. These studies provide new information about sediment movement in shallow estuarine waters and the use of nearshore habitats by fish under floating structures and adjacent to piers and hard riprap shorelines, and allows for the evaluation of effects of similar floating structures in similar environments. Although the results suggest that the influences of a single barge (of this size) are expected to be minimal, more research is needed to define the factors controlling the potential for effects of larger floating structures, for clusters of floating structures, and for floating structures in different locations and in different environmental conditions.

In addition, one of the unintended consequences of the hydrodynamics study was the finding that the many high-speed vessels in the Harbor, particularly ferries, are generating waves that produce increased currents in nearshore areas, as shown at Brooklyn Bridge Park. The management of dredged material and the increased dredged material management costs for handling contaminated dredged materials are ongoing policy concerns for the PANY/NJ, the US Army Corps of Engineers and other entities charged with maintaining the navigation channels and berthing areas of NY Harbor. It may be of interest to the Port Authority or other facility owners and operators to consider conducting further investigations into the potential impacts of the waves generated by boat wakes, including the possible enhancement of sediment accretion in berthing areas and near-shore channels

Additional studies that include observations and detailed modeling of flow characteristics around barges (or clusters or barges) of variable length and draft relative to the slip, in alternate environmental conditions (currents, tides, waves, wakes) in alternate locations (estuarine zone, basin depth and shape) and for longer durations, would help to further define the factors controlling the potential for effects. We note that barges are modular and mobile in comparison to other shoreline features, and thus they present an opportunity to study the potential for effects in a relatively controlled and cost-effective way.

3 - ACKNOWLEDGMENTS

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The PANYNJ would like to acknowledge their inter-departmental team, who shaped and directed the Floating Structures Pilot Project. This project would not have been possible without the generous participation of The Waterfront Museum, the subject of the research, and the owners of the two study sites, The O'Connell Organization and Brooklyn Bridge Park. In addition, the PANYNJ is gratefully for the active and enthusiastic participation of many public agencies, elected officials, and community organizations in making this pilot project a success. The participants in the informational meetings made valuable contributions throughout the work. Finally, special thanks go to the consulting team on the SW Brooklyn Waterfront Study as well as the research consulting team on this four-year pilot.

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Acknowledgments (Continued)

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July 2015

APPENDIX 1

FISH RESPONSE TO FLOATING STRUCTURES IN NEW YORK HARBOR

by Institute of Marine and Coastal Sciences
Rutgers, The State University of New Jersey

Fish Response to Floating Structures in New York Harbor

Final Report to
The Hudson River Foundation

Kenneth W. Able and Thomas M. Grothues

Revision
May 27 2015

Executive Summary

We examined the response of pelagic (in the water column) fishes to the presence of a barge moored along two shorelines (Red Hook with rip rap shore line, and Pier 6 with a pier shoreline) in New York Harbor in order to evaluate the effect of this type of floating structure. The response was statistically tested as a change in the probability of occurrence for three types of fishes under or adjacent to the barge. These included 1) small (<250 mm) solitary, 2) small schooling, and 3) large (>250 mm) fishes. These three fish types were categorized as proxies for species based on measures of their size and behavior using Principle Components Analysis (PCA). The response metric was chosen for each type of fish based on tests (Kolmogorov-Smirnov) of the overall distribution of that fish type. The actual measures of fish response used in the tests were made with a Dual-Frequency Identification Sonar (DIDSON) sonar using a high-frequency (1.1 kHz) mode with 96 beams, which is capable of resolving individual fish and their body shape and size. The DIDSON was lowered into the water along-side the barge at the bow, stern and side and rotated to survey water under the barge for complete coverage as well as to survey open water adjacent to the barge. As a preliminary test, it was also used to survey open water at both sites in the absence of the barge to determine if any potential test differences performed at the barge could be due to site differences unrelated to the barge, e.g. use of that habitat by different types of fishes that might respond to the barge differently. Further, the surveys were performed during the night, crepuscular (dawn/dusk), and daytime hours with the recognition that the primary mechanism of a response, if any, was likely to be related to shading and that this relationship could change with ambient light. Surveys were repeated over several months in two years (2011, 2012) to account for a robust and independent data set. DIDSON sampling was accompanied by ground truth net and trap sampling, water quality (salinity, temperature, dissolved oxygen) sampling, current flow (via Acoustic Doppler Current Profiler, ADCP), and light flux measures.

Small (<250 mm) solitary fishes were the most often encountered type of fish. Since their distribution differed at the two sites in preliminary testing, each site was tested for barge effects independently. At Red Hook, this type of fish responded significantly and weakly positive to the overhead presence (cover) of the barge, with higher probability of encountering fish under the barge than around it. They were also strongly more likely to be encountered at night and during crepuscular periods, and the relationship of their response to the barge weakened at night suggesting that fish moved away from this cover into open water at night time when the difference in light became less strong. At Pier 6, where a pier provides abundant shading relative to the barge, there were much fewer encounters with this type of fish overall and there was no measurable response of the fish to the barge, with similar probability of occurrence under and adjacent to the barge and regardless of daylight cycle.

The second most common type, small schooling fishes, primarily Atlantic silversides but also bay anchovy and some herrings, were also abundant in schools of four to thousands of individuals. Their distribution at the two sites was similar, so site samples were pooled. The response of small schooling fish to the barge was weakly negative and not significant. There was no measurable relationship cover over the course of the daylight cycle, nor did the overall probability of occurrence of these fish change much over the daylight cycle. Small schooling fish were much more likely to be in the open water in front of the barge (the bow facing the

river), than at the side or stern suggesting a secondary (other than shading) effect of the barge's presence, such as emulation of shore or edge habitat.

Large fish, primarily striped bass and bluefish, were scarce and sparsely distributed and this may have affected the ability of tests to find differences even if there were some. There was no measurable difference in the probability of their occurrence relative to site, so sites were pooled for a bigger sample size. Large fish were slightly and significantly more likely to be encountered during the nighttime than during the day, but there was no measurable response as a probability of encounter under or adjacent to the barge regardless of the daylight cycle.

Our interpretation, based on this and other works, is that large predatory species with dark-adapted retinal pigments range over many habitats especially at night and will include the use of shaded edges as ambush sites from which to prey on small fishes during the day. Small schooling fishes avoid these same shaded areas in order to better feed based on visual recognition of food and perhaps to avoid predation. Additionally they are less able or less inclined to school at night or in the dark and so some of the decrease in abundance may be due to a dissolution of schools into single fishes. Aside from schooling-type fish that are not schooling, singletons are comprised of other species that may be dark-adapted (such as young striped bass and black sea bass) and other solitary species that use darkness rather than schooling as cover from predation.

Overall the response of pelagic fishes to the cover or even nearby presence of a small barge is weak, but more detectable when the barge is the only shade source than when it is tied to an already large shaded pier or at night, when the difference in light level between shaded and unshaded habitat is diminished.

Recommendations

Small barges and other floating structures are unlikely to influence utilization of New York Harbor near-shore habitats in summer and fall in the short term; i.e. in the absence of long term physical changes like shoaling or scour associated with barge presence. They are even less likely to have an effect in in other seasons when many species have migrated from the estuary. Effects are also less likely for barges shading deep water along steep armored shorelines than in shallow water because deep waters are already shaded by turbidity, and are also less likely along shorelines that are likewise already shaded by other artificial structures such as piers. However, if large structures are considered (e.g. Kitazawa et al. 2010, Wang and Wang 2015), then they are likely to have the same negative effects as piers.

Additional studies of larger floating structures (e.g. swimming pool barge) will help provide scale for future deliberations as well as comparisons relative to multiple piers of different sizes (Grothues et al. in review).

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1.0 Introduction

The value of estuaries to the persistence of healthy populations for many economically and ecologically important fish species has been well documented including for the Hudson River and portions of New York Harbor (Able and Fahay 1998, 2010, Beck et al. 2001, Waldman et al. 2006a, b). Despite their recognized importance, estuaries have been greatly altered through increasing development and urbanization (Airoldi et al. 2007, Glasby and Connell 1999). New York Harbor estuary is the epitome of these types of alteration and has high potential for restoration (Vision 2020). Alterations include floating structures such as barges (both existing and planned), but their impact on living natural resources, particularly fishes, still needs to be quantified and perhaps should be the focus of mitigation efforts (Ludwig and Iannuzzi 2006, Rosenzweig et al. 2011).

Other studies, especially our own, have extensively commented on the impacts of shading by 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. 1998, Able and Duffy-Anderson 2005). 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 availability (invertebrate counts) under piers. Presumably, this was a function of decreased ability to see prey in the dark under continuously shaded piers. These studies clearly identified a negative effect of the mechanism (shading) on shallow water habitat suitability and fish production. In recent studies, pelagic fishes such as bay anchovy, silversides, river herring, weakfish, bluefish, and larger striped bass were studied (Able et al. 2013, Grothues et al. in review).

This study sampled the abundance of fish as a response to the presence or absence of a barge tied to shoreline as a realistic condition of how barges are used along harbor shorelines. The design accounts for the response of fish in open water where the barge would be moored in its absence and compares it to the response of fish in similar open water during its presence, the response of fish in water under the barge when it is there (shaded condition) during all times of day and night and also accounts for the effect of a location, that is, the same experiment in a different location.

2.0 Materials and Methods

2.1 Sample Sites

The primary sampling was conducted at sites along the lower East River and its confluence with the Hudson River along Brooklyn, New York (Table 1, Figure 1). Sampling of fishes as a response to a barge presence took place along the Brooklyn Bridge Park (BBP) shoreline and south of the park at Red Hook. The experimental unit is the Waterfront Museum barge (25 x 10 m), a mobile showboat and museum currently tied to Pier 44 in Red Hook at 290 Conover Street, Brooklyn (Figure 2). The embayment in Red Hook where the barge is tied is surrounded by riprap. As an experimental treatment to disengage a potentially obfuscating location effect from the barge effect, the barge was moved to Pier 6 (foot of Atlantic Street, Brooklyn) just south of the BBP (Figure 3). This area is surrounded by pilings and shoreline bulkheading. The water under the barge and its adjacent open water at Red Hook was sampled and unoccupied water at Pier 6 mooring site (Figure 4) was sampled in the first sample rotation period (2 days and nights). After the barge was moved to Pier 6, the water under the barge and the surrounding adjacent open water was sampled again, as well as the area vacated by the barge in Red Hook (second annual sampling rotation, 2 days and nights). Potential mooring sites for the Pool Barge in BBP (Pier 1 or 2, vicinity of Cranberry St., Brooklyn) were also sampled. The sites were visited in two seasons (summer and fall) of two years (2011 and 2012) but it was not possible to completely balance the design with respect to both time and site. The barge was sampled at Red Hook and also after its deployment at Brooklyn Bridge Park. Another larger site near the Brooklyn Bridge Park (between Piers 1 and 6) was assessed to discern what fish assemblage that might be impacted if the Pool Barge were to be moved there, with the goal of determining where the least impact might be. These sites vary in that the Red Hook site is low energy while the Brooklyn Bridge Park site can have high current speeds. Repeated sampling of few sites provides a way to sample over a range of transient water quality conditions that could affect assemblage presence while controlling for the inherent variability of different locations.

Table 1. Sampling effort for floating structure sites in the lower East River, Brooklyn, NY in both 2011 and 2012. See Figure 1 for sampling locations.

		Barge Present			**Barge Absent**		
Location	Date	Day	Night	Crepuscular	Day	Night	Crepuscular
Pier 1	June 2011				15		
	Aug/Sept 2011				6	7	
	July 2012				5	4	
Pier 6	July 2011	3	2				
	Aug/Sept 2011				7	7	
	July 2012	8					
	Sept 2012	12	26	6	15	8	
Red Hook	Aug/Sept 2011	26	20	2			
	July 2012	38	19	9			
	Sept 2012	16	21		5	8	4

Figure 1. Study sites in Brooklyn, New York in New York Harbor for 2011 and 2012.

Figure 2. Lehigh Valley Museum barge located at mooring at Red Hook.

Figure 3. Lehigh Valley Museum barge located at Pier 6 with Rutgers University crew sampling with DIDSON along the side of the barge.

Figure 4. Sampling with DIDSON on a pole mount at Pier 6 with the barge absent.

2.2 Technical Approach

We used a DIDSON multibeam sonar to sample both large and small fishes. This involved sampling with minimal disturbance of fishes before and after barge movement to the mooring site. The DIDSON provides high-resolution images across numerous habitat types through the use of dual beam (1.8 MHz and 1.1 MHz) ensonification. At the likely range of 1-10 m (oblique through 0-5 m water depth) and a 1.25 x 5 m (across by downrange) window, the resolution varied between 2.5 mm and 10 mm per pixel. Sampling was at a moderate rate of 8-10 frames per second (depth dependent for processor reasons) to detect movement. Fish movement is diagnostic, helping to break fish outlines from their background (see movie clips at http://marine.rutgers.edu/rumfs/ or at www.soundmetrics.com, Able et al. 2013). 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). Objects in the water column can be individually counted and sized using available routines. A splash-proof laptop computer attached to the DIDSON within the support vessel (motor skiff 20' with outboard) allowed real-time viewing so that the scientists can adjust focus and direction for closer inspection of potential targets. Notes on the barge and other relevant features of the mooring site were dictated onto a voice recorder integral to the DIDSON software. These, as well as GPS tracks were 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. We have used similar methods to video-record fish on submersible dive surveys (Sullivan et al. 2000, Sullivan et al. 2003) and work using DIDSON in the Hudson River (Grothues and Able 2010). Visual census, or its video or acoustic counterpart is a well-developed technique appropriate to census of mobile fishes in complex environments (Seaman 2000).

Prior to testing the main effect of barge presence or absence that is the basis of this study, we evaluated the types of fish present at the study site and their general distribution. This was necessary in order to choose the appropriate data treatment for the main effects test, which can be sensitive to deviations from underlying assumptions. Large fish such as striped bass can be individually counted in DIDSON videos and identified by characteristics of the individual fish image while small fish must be classified and enumerated based on computed classification algorithms that utilize multivariate characteristics of the schools. We extracted measures of the number of fish in a school, minimum and maximum length of fish in a school, distance to randomly selected fish to their nearest neighbor and second nearest neighbor, height of fish, and organization (1 to 4 from random to highly organized) for all incidents of fish schools that numbered 4 fish or more and were measurable (515 events). These variables form a collective basis for distinguishing fish that are of the same type and size and are orienting to each other as a "school" versus different types co-occurring in an "aggregation" because of a common attractor, such as a food patch. Principle components analysis (PCA) was used to differentiate types of fish on the basis of these variables. PCA is an iterative regression algorithm that plots samples in 2-dimesnional space relative to their similarity based on multiple input variables describing the samples. PCA and complementary cluster analysis (for consensus) was performed in MATLAB using scripts native to the Statistics toolbox therein (i.e. pdist.m, linkage.m, dendrogram.m, princomp.m, and biplot.m). Each set of measures was centered and standardized to unit variance prior to classification analysis because they are represented on different scales. This prevents one factor from driving the classification simply because it has higher numbers. Classification was assisted by some groundtruthing (wire mesh traps, cast nets, and gill nets) of fish for identification.

2.3 Environmental Sampling

Each barge visit was accompanied by physical-chemical sampling (temperature, salinity, dissolved oxygen, secchi disk, tidal stage) using a YSI 80 (Yellow Springs Instruments, Yellow Springs OH). A single physical-chemical measure was representative of all points for that particular barge visit because the water flow and mixing is extensive. Light measurements during a barge visit occurred underneath the illuminated and shaded edges of the barge as well as in open water. During one day, the light meter was rigged on a "clothesline" to pull it underneath the barge to measure a gradient across the middle. The line was kept tight to keep the sensor at the same depth relative to the barge as much as possible. This was repeated several times over the course of the day/tide. Flow in three dimensions in each habitat was characterized using an acoustic Doppler current profiler (ADCP) during one visit of each site in each year. The ADCP was deployed on a boom mount from the boat that places it just below the waterline. This sampling was episodic and not representative of all tides but was only intended to supplement a complimentary and rigorous ADCP study by Rocky Geyer (Woods Hole Oceanographic Institute).

DIDSON sampling measured both fish abundance and the frequency of occurrence of "events" (e.g. fish schools or singletons both from a single independent event) in each point count direction. Fish counts were standardized to survey time in post-processing. Features of the fish acoustic targets (position in water column, length of individuals, spacing, school dimensions, etc.) provided probability scoring of sonogram features to fish species (Able et al. 2014).

2.4 Sample Design

Directed sampling in each year took place in the summer and fall, when numerous resident and migrant fish species gather in the lower estuary and young-of-the-year fish, especially of prey species such as Atlantic silversides and bay anchovies, have attained a large enough size to be detected (> 30 mm) with the DIDSON. Juvenile fishes sufficiently large to distinguish by ensonification (> 30 mm), and adults of small species such as bay anchovy and Atlantic silversides are common beginning in June and larger individuals, such as subadult or older predatory fishes (e.g. striped bass, white perch, and bluefish) utilize New York Harbor most in early summer and migrate in fall (Able and Fahay 2010 and unpublished data). Sampling continued through dusk and into nighttime to examine diurnal shifts in habitat use, an important consideration in regard to shading effects. Groundtruthing occurred to provide voucher specimens for correct classification of DIDSON images in earlier studies in the same general study area (Able et al. 2013, 2014).

Based on our recently completed DIDSON sampling efforts for both New York City Parks and Recreation and the Hudson River Foundation (Able et al. 2013, 2014, Grothues et al. in review), we used point counts for the proposed study. We have found that the majority of fishes by number and frequency of occurrence are small, schooling forage species (Grothues and Able 2010), and that these are patchy and act in concert as a single, slow-moving organism that DIDSON is capable of imaging (Able et al. 2014). The point-count sample design used to map fish distributions among habitats or barge features was based on the current design used for mapping bird distribution in complex habitat because this study, like that of birds, relies on visual techniques. The point count method (USDA Forest Service 1995) has been found to maximize precision and accuracy of population estimates relative to data collection economy. A potential problem of the point count method is how to account for differences in the distance of detectability that may result among different habitats; this problem is largely eliminated by use of the DIDSON because the focal depth is self-limiting into a fixed-radius point count, in effect standardizing surveys to area. The fixed-radius point count method increases the resolution of habitat choice. Further, the small size of the surveyed area from any one point mitigates another potential problem of the method, which is a decay of ability to distinguish individuals from conspecifics over increasing distances (Petit et al. 1995). Thus, DIDSON provides the ability to visualize much of the water column underneath and away from the barge from a few points.

A sampling rotation included the point count method, which established a grid of three sample points at the Waterfront Museum Barge and its adjacent open water habitat (Figure 5). One point was at the center of each exposed side of the barge. The side against the pier was not sampled. From each sample point, the detection radius by DIDSON was visualized for a set period of five minutes in each of the four principle directions relative to the barge axes before proceeding to the next point. Thus, each point occupation created four samples (two along the barge edge for and aft, one underneath the barge, and one away into open water or, in the case of stem and stern into the water adjacent to the pier) for a total of twelve samples, and these differed as a function of the shoreward (quiescent and shallower), or offshore (wave-exposed and deeper) side of the barge. Bow or stern point samples also potentially differed in the flow of a wake eddy field due to exposure of tidal or wind driven surface flow. The total 16 samples accumulated 80 minutes of DIDSON imagery per site visit covering combinations of shaded/lit, bow wave/stern eddy, and barge edge or center. In 2011 we had 3 sampling rotations in the summer and 5 in the fall, whereas in 2012 there were 6 sampling rotations in the summer and 10 in the fall including both site locations with the barge present and absent (Table 1). Unfortunately when the barge was moved in 2011 we were unable to sample Red Hook with the barge absent due to electrical problems with the DIDSON unit.

DIDSON point occupations were made from a shallow-draft skiff tied to the barge. The five-minute period allows for the count of transient fish while minimizing the boundary effect that happens when individuals from adjacent fields move in and are counted while fishes moving out of the survey field are not subtracted (Wolf et al. 1995). Visits were repeated during the day, night, and crepuscular (dawn/or dusk) periods over four days each in summer and fall in each of two years. Barge visits included several open water samplings of unoccupied sites for before-and-after site comparisons; these include at least four points with four samples (principle Cartesian ordinates) each along the un-occupied Pier 1 and 2 sites.

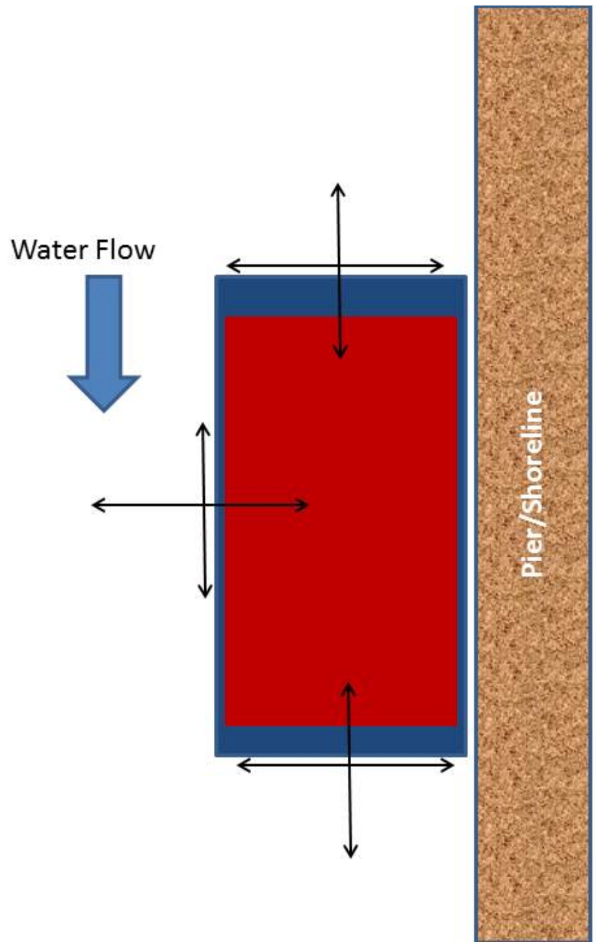

Figure 5. Sampling protocol

2.5 Statistical Analysis of Main Effects

Based on results from the PCA (see Results section) the response of fish to barges was evaluated separately for 1) large fish (singletons), 2) small pelagic singletons, and 3) small pelagic schooling fish.

It is typical in fish sampling to encounter samples (in this case DIDSON files) in which no fish are observed. This is not necessarily a result of fish avoiding a treatment or habitat, but simply a result of the ratio of total fish to total habitat, so that there is a chance of seeing no fish even in samples of good habitat. This type of distribution, called zero-inflated data, presents potential difficulties to analysis if unrecognized because it can weaken the ability to describe meaningful relationships (Tu 2006). Therefore, we first tested the distribution of observations in fish abundance and accordingly adjusted the significance testing by using probabilities drawn from appropriate distributions (e.g. Normal, Poisson, Binomial, see below). We checked for heteroscedacity of distributions using the Kolmogorov-Smirnov goodness-of-fit test of the estimated distribution against the normal distribution (kstest.m in MATLAB).

Based on these tests (reported in Results below) the distribution of fish in all categories were zero-inflated. The probability that fish of each category occurred in a treatment was thus modeled using the probit function; that is returning a likelihood that fish of that category would be present rather than trying to predict abundance as a response, and were tested for significance against the Poisson distribution:

$$f(x) = (\lambda^{x} * e^{-\lambda})/x!$$

with $x = 0$ to $< \lambda$, where λ is the expected value of x (the mean abundance or occurrence) and e is the base of the natural logarithm. The dispersion of the actual distribution was estimated in order to calculate the standard error.

Data for schools of small pelagic fish were log(CPUE+1) transformed, which recognizes that some of the variation in abundance is inherent as the social action of schooling species while allowing that schools may be more or less likely to recruit and keep schoolmates in one or another environment (barge treatment, in this case). They were linked using the Log distribution.

Prior to multivariate analysis, sites (Red Hook, Pier 6) were compared for the "No Barge Present" treatment to see if they could be pooled. This tested whether they had different fish abundances to begin with, so that any differences in testing when the barge was at a site would not be conflated with a barge effect. Each category of fish was tested separately. For this we applied a Kruskal Wallis test (KW, ANOVA model using median instead of means because of heteroscedacity, kruskallwallis.m, MATLAB) with all dates and times pooled.

Thereafter, only the samples during which a barge was present at the site were used, including samples taken at or away from the barge, and with samples at the barge including those looking into open water away from the barge, along the barge, or under the barge. The relationship of fish abundance (with pooling treated based on KW test results) to fixed treatment factors Cover (C: exposed, under), diurnal period (P: day, night, crepuscular), the interaction between diurnal and cover (P*D), and random effects of repeated measure were quantified using the generalized linear model (GLM) (McCullagh and Nelder 1989, Hastie and Tibshirani 1990) with all categorical fixed treatment effects and random replicate effects. Because treatments are categorical, interactions had to be treated as separate element-wise functions. Thus, Transformed Abundance (A) modeled as a function of being under or not under *j*-th Cover treatment and in the *k*-th Period treatment is:

$$A_{jk} \sim f(\beta_0 + C_j + P_k + (C*P)_{jk} + \varepsilon_{jkl})$$

Where
β_0 = intercept; $j = 1, 2$; $k = 1, 2, 3$; $l = 1, 2, \ldots, n$; and n is the number of replicates; * indicates elementwise multiplication between all categories of C and P respectively, f is the previously described link function specific to the category of fish being tested; and ε is error (or residual).

Errors are assumed to be mutually independent and approximately normally distributed. The hypothesis test for the main fixed effect is H1: $Cover_{open} = Cover_{under}$ given that a barge is present.

We also tested Exposure (E: side, stern, bow) to evaluate if fish using open water near the barge were differentially distributed. Significant differences in this 3-treatment test were examined in pairwise tests using the Tukey-Kramer Honest Significant Difference (HSD) test (pairwise.m, MATLAB).The barge was moored with the stern to the north in Red Hook and to the east in Brooklyn Bridge Park, but in both cases parallel to the shoreline structure with the bow facing fetch while the stern was sheltered, forming a cove with the right angel of the main shoreline behind it. This could be expected to cause a sheltering effect if any, while ordinal direction may effect shading.

3.0 Results

3.1 Environmental Conditions

Environmental conditions were very similar between years and locations in most cases. Salinities, however, averaged between 6-7 ppt in 2011 and then went up to around 24-25 ppt in 2012 (Table 2). The lower salinity in 2011 was likely due to Hurricane Irene, which made its ninth landfall in Brooklyn with heavy rain on August 29, 2011, several days before sampling. The lowest average temperature was at Pier 6 in 2012 at 20.9°C (Table 2). Dissolved oxygen was lower in 2012 (average 5.09- 5.86 mg/L) than in 2011 (average 6.12- 9.96 mg/L) but remained well above stress levels (generally 3 mg/L for fish) during sampling (Table 2).

Table 2. Average environmental conditions at each sampling location in both 2011 and 2012.

		Barge Present			**Barge Absent**		
Location	Date	Temperature (°C)	Salinity (ppt)	DO (mg/L)	Temperature (°C)	Salinity (ppt)	DO (mg/L)
Pier 1	2011	-	-	-	23.42	7.21	8.19
	2012	-	-	-	23.68	25.20	5.10
Pier 6	2011	23.4	22.94	8.14	23.5	6.71	9.96
	2012	20.9	24.67	5.35	20.95	24.39	5.13
Red Hook	2011	23.44	7.44	6.12	-	-	-
	2012	22.62	25.55	5.23	20.38	24.74	5.86

3.1.1 Light Intensity

At Red Hook the lowest light levels were found at the stern of the barge (2.6 – 30.1) and the highest levels were seen in open water (49.9 – 645.8 µmol m^{-2}) (Figure 6). At Pier 6 the lowest daytime light levels under the barge edges were found at the bow of the barge (3.35 – 54.8 µmol m^{-2}), whereas the highest levels were found at the stern of the barge (26.8 – 3427.0 µmol m^{-2}) (Figure 7). At a distance of 1 m under the barge, the light levels are less than they are deeper in the water. This indicates that the bargeshadow is angled (like for any terrestrial object) so that a light meter directly under the barge (at 1 m depth this is near the hull) is in the shadow line, while at 2 and 3 meters depth it is at the edge or completely out of the shadow line even though it is horizontally in the same place.

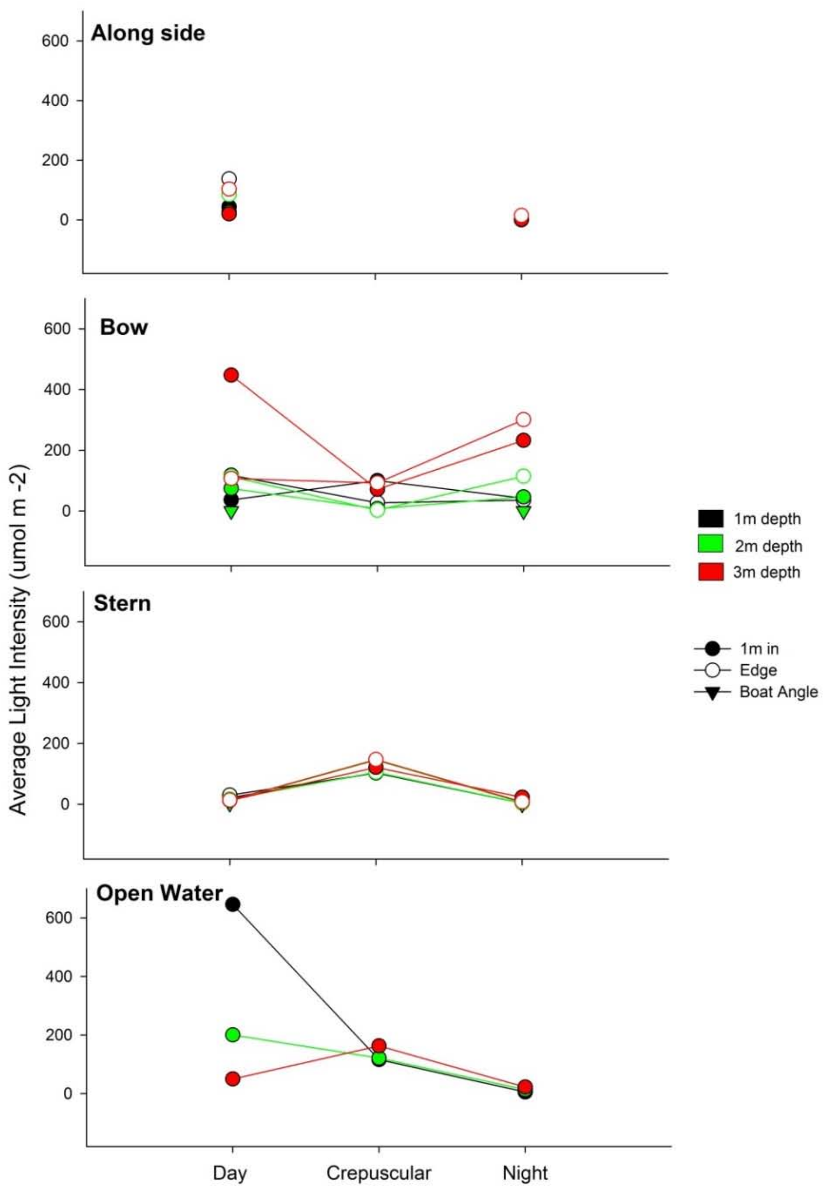

Figure 6. Light intensity at Red Hook, by location and depth

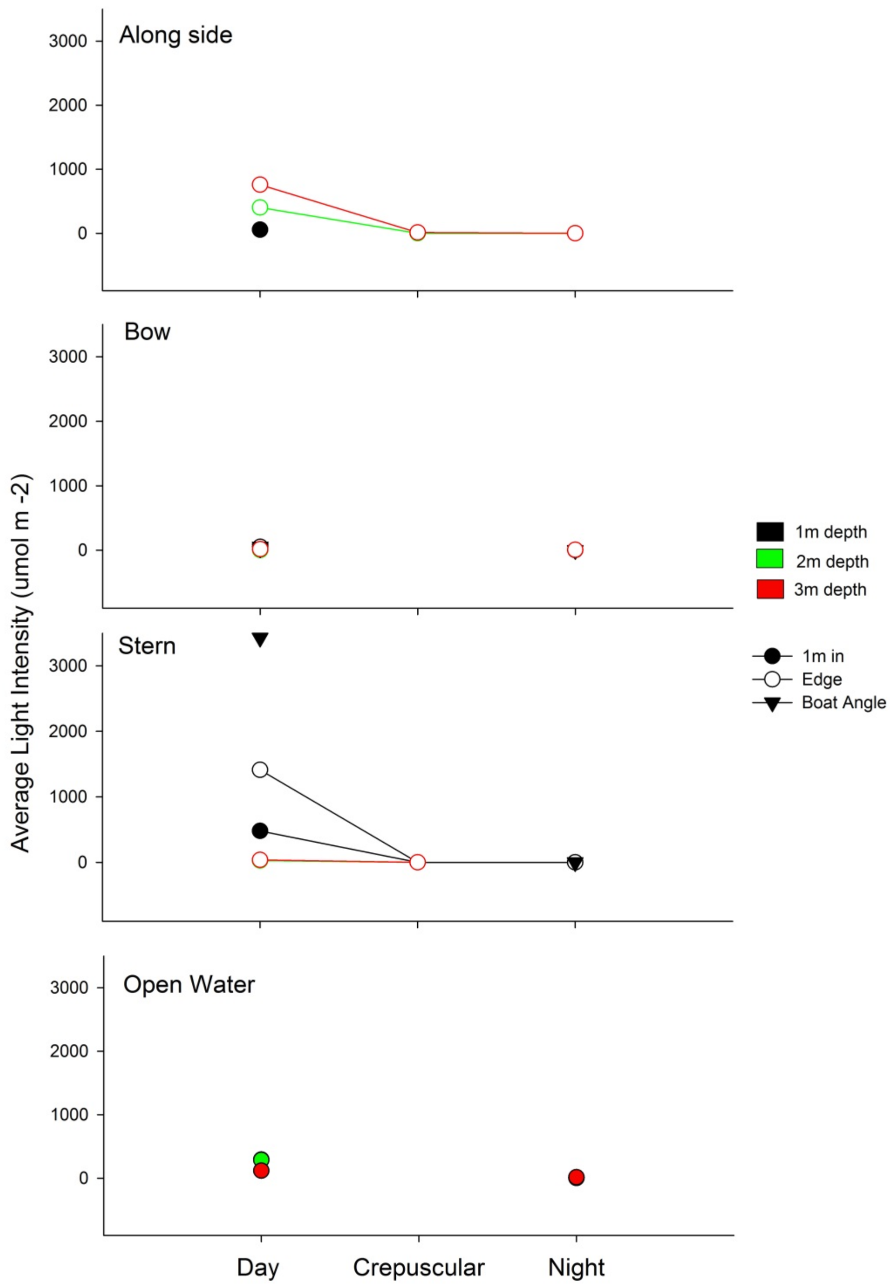

Figure 7. Light intensity at Pier 6 by location and depth

3.1.2 Flow

Transect along side, behind, and in front of the barge with an ADCP did not reveal flow structures created by the barge at the scale of these ensembles that would be important refuges or opportunistic feeding areas for pelagic fishes; i.e., eddy fields or bow wake “pillows” that allowed fishes to minimize effort while being near higher flow areas that bring food. However, it should be noted that the barge was always in low current areas (<0.25 m/s average flow). This is similar to some current and planned applications but is very different from others, such as ferry landing platforms currently near Wall Street. ADCP transect made in high flow areas for the sake of comparison, such as alongside the Pier 1 bulkhead, revealed areas of strong shear at the corners of structure where flow separated from the mainstream and thus create these kinds of refuges. A barge would be expected to have a similar effect. Flow as measured by ADCP is presented as vector diagrams in the appendix.

3.2 General Fish Characterization

Encountered fish ranged from the approximate limit of DIDSON resolution (~ 30 mm) to greater than 700 mm, but was greatly skewed towards smaller fish with a mode in the class of fish 50-100 mm long (Figure 7), which is representative of the numerous Atlantic silverside that appeared to dominate the schools of small pelagic fish. These were much more abundant during sampling in 2012 than 2011 and the smallest size class (30-50 mm) was also more abundant in 2012. In 2011, larger fish (3 size classes representing fish of 100 -250 mm) were much more abundant. Many factors outside of the study area effect fish presence and the size/frequency and total abundance distributions may reflect different timing in sampling and even the simple progression of growth and mortality of similar starting numbers of the same species (see Figure 8 for comparison across other years). This is presented here not as an effect of barges but rather in recognition of the fact that different life stages or species of fish were sampled that could potentially respond differently to barges as a growth-related habitat shift.

Abundance almost solely (93%) explained the latent variance in school structure among encounter events. Since it was a continuum rather than clustered (shown both by PCA biplot , Figure 9, and cluster analysis as a cascading dendrogram, Figure 10), it was not considered relevant as a discriminating factor for the classification of schools. Therefore, analysis was repeated without this factor. Inter-event similarity in the ensuing analysis was best discriminated based on distance to nearest neighbor and distance to second nearest neighbor and greatly skewed towards small distances (indicating tight schools) with only a few occurrences having large neighbor distances (indicating aggregations) (Figure 9), in good general agreement with the more subjective scoring categories used here (Table 3, 4) and in previous work (Able et al. 2014). However, these were the end of a continuous spectrum, rather than strongly structured clusters (Figures 9). Thus, these schools are likely to have been composed of the same species, with individuals growing throughout the sample year. Therefore, we felt confident that the simple classification used represented fish schools of similar species constitution but different ages/sizes. This differentiated them from classes of “large singleton” and “small singleton”, and co-occurring but un-associated “small group of small singletons” (e.g. small fish, that simultaneously but < 4 at a time, crossed the vision field but not oriented to each other). For the purpose of evaluating fish response to barges, the subcategories assigned in the original scoring were of small schooling fish or aggregating pelagic fish were thus combined as “small schooling pelagic fish” (Table 3, 4) to yield 3 types of fish for which response was measured: small pelagic singletons, small schooling pelagic fish, and large pelagic fish.

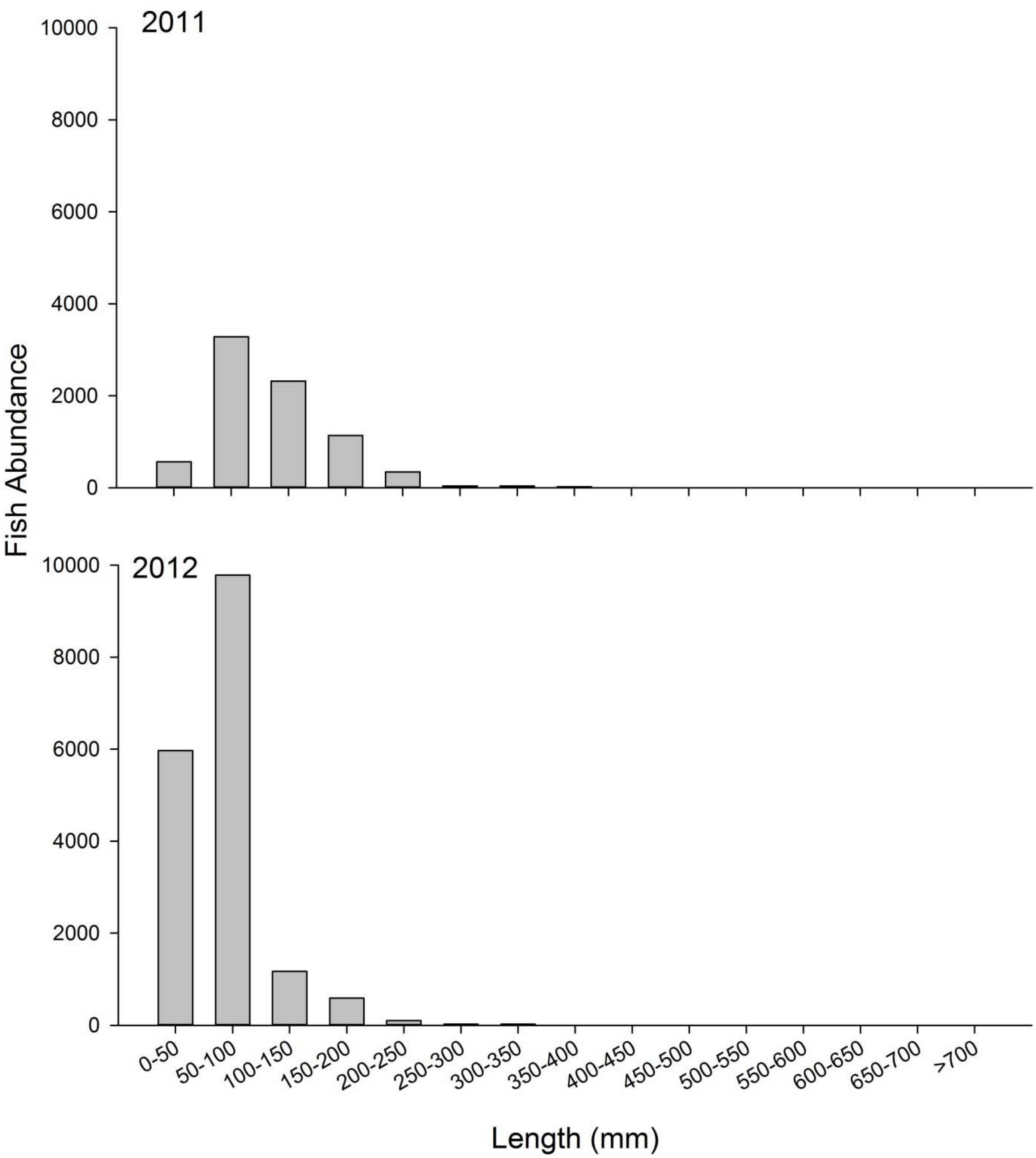

Figure 7. Fish abundance by length frequency distribution with DIDSON at all floating structure study sites in both 2011 and 2012.

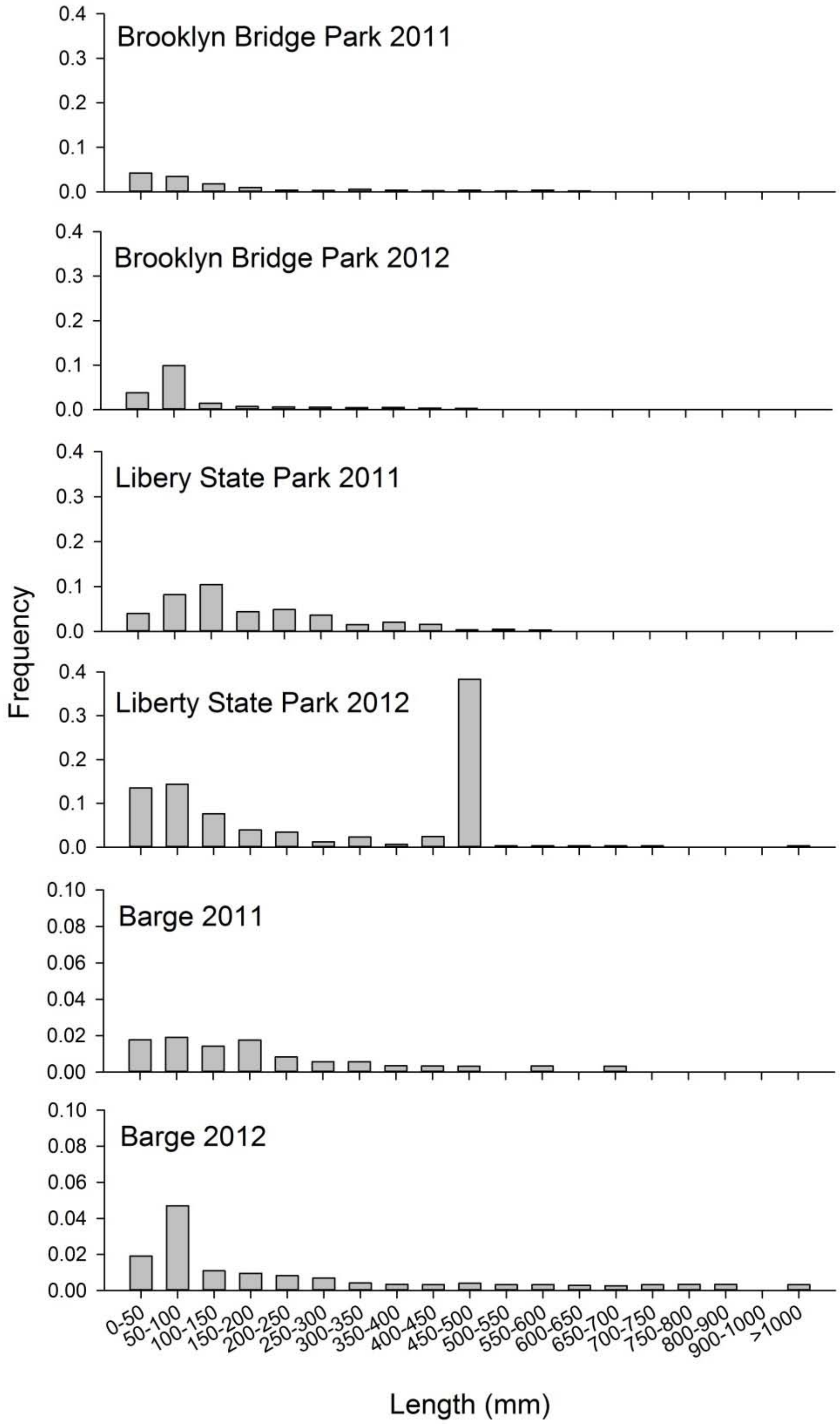

Figure 8. Comparison of length frequency for multiple locations sampled by DIDSON in 2011 and 2012. Barge categories include both barge present and absent.

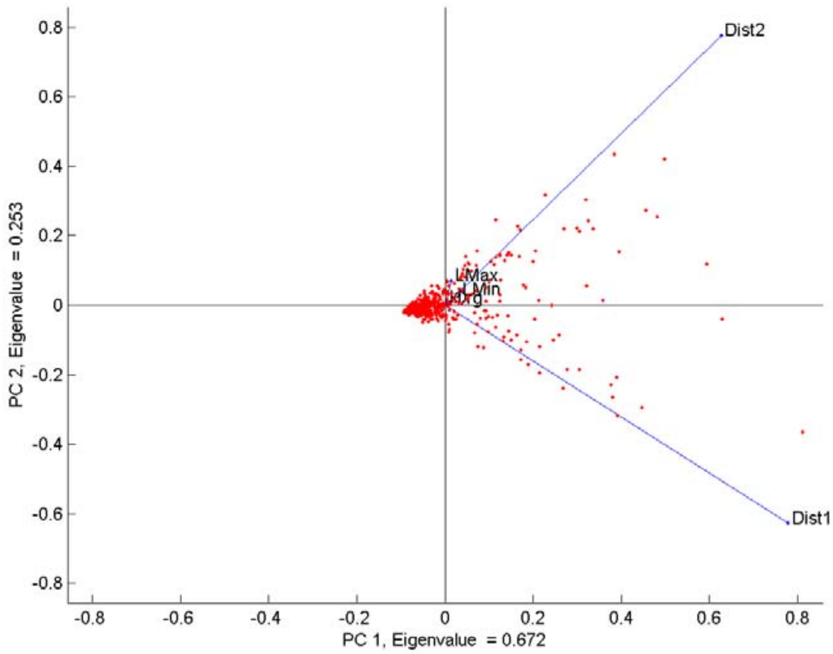

Figure 9. PCA biplot of fish events sampled by DIDSON. Red dots represent samples, with more similar samples plotting closer together. Blue vectors point in the direction of increase for the variables. Most are too short to see in this plot, illustrating the importance of inter-neighbor distance in resolving the gradient compared to the other variables.

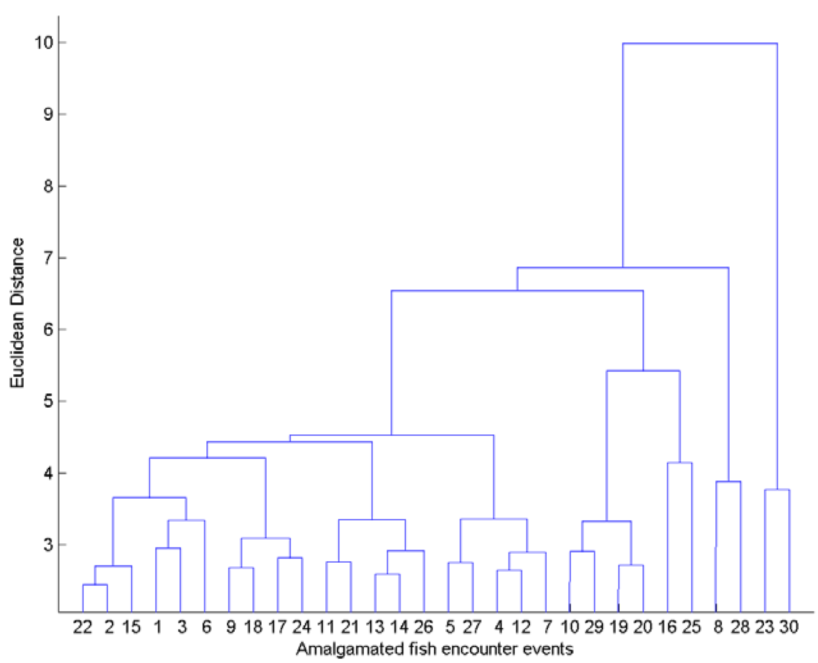

Figure 10. Results of cluster analysis of fish events sampled DIDSON as a Euclidean distance function of fish size, orientation, and spacing variables for consensus with PCA.

Table 3. Total fish abundance in each fish category by sampling location in 2011 and 2012. Categories based on criteria in Able et al. (2013) for continuity with other work. Categories marked by asterisk were combined for analysis as “schooling small pelagic fish” based on PCA analysis of the current data set only.

Category	**Pier 1**	**Pier 6**		**Red Hook**		**Total**
	Barge Absent	Barge Present	Barge Absent	Barge Present	Barge Absent	
large aggregation of small pelagic fish*	0	0	0	1079	0	1079
large pelagic singleton	23	12	6	81	4	126
large school of small pelagic fish*	5347	0	768	5125	0	11240
small aggregation of small pelagic fish*	133	81	41	205	0	460
small pelagic singleton	370	175	335	1706	22	2608
small school of large pelagic fish*	0	0	0	8	0	8
small school of small pelagic fish*	2111	289	1264	1372	92	5128

Table 4. Fish category events by sampling location in 2011 and 2012. Categories are based on criteria in Able et al. (2013) for continuity with other work. Categories marked by asterisk were combined for analysis as “schooling small pelagic fish” based on PCA analysis of the current data set only.

Category	**Pier 1**	**Pier 6**		**Red Hook**		**Total**
	Barge Absent	Barge Present	Barge Absent	Barge Present	Barge Absent	
large aggregation of small pelagic fish*	0	0	0	4	0	4
large pelagic singleton	16	11	6	70	3	106
large school of small pelagic fish*	47	0	7	17	0	71
small aggregation of small pelagic fish*	8	4	1	25	0	38
small pelagic singleton	269	154	279	1375	19	2096
small school of large pelagic fish	0	0	0	2	0	2
small school of small pelagic fish*	134	24	73	130	8	369

Of the 301 DIDSON samples recorded during both years, 37 contained no fish. A total of 2282 occurrences of single fish (unassociated with other fish) were counted in the remaining sample files. Relatively few of these (106, totaling 126 individuals) were large fish such as striped bass or single Atlantic menhaden (Table 3, 4). There were 8 large fish (Atlantic menhaden) in two large fish school occurrences (Table 3, 4). Additionally, there were 517 occurrences of fish schools among the various categories. The number of individuals in a given school ranged from as few as four (by definition) to many as 2322 (estimated), but were greatly negatively (left) skewed in the distribution of abundance with a median of 12 fish per school but a mean of 36.

The distributions of all three of these categories, as well as the $\log_{10}$ transform of the small schooling fish category, were found to differ significantly from the normal distribution using the KS test (two sided test for unequequal size, K = 0.5, p = 2.6178e-056), thus justifying use of the probit link function and the Poisson distribution comparison in the GLM.

3.3 Groundtruth Sampling

No fish were collected in the traps during groundtruthing. A single Atlantic menhaden was captured in a gill net set alongside the barge in Red Hook. Sonar showed a number of targets that appeared to be Atlantic menhaden at the site at that time and these were captured by the gillnet during the same sampling trip in different sites (Hudson River Foundation funded work on shoreline structures) and those were also imaged on DIDSON, sometimes while in the net. Likewise, several Atlantic silverside, the dominant small schooling fish in the nearshore environment (Grothues and Able 2010), were captured during consecutive cast net sampling while also being imaged on DIDSON sonar. However, a number of silversides and Atlantic menhaden were captured during groundtruth sampling at nearby sites during this same period during synergistic DIDSON sampling of shorelines and open water controls for a Hudson River Foundation funded project on fish response to shoreline structures. The species composition observed in these efforts reflect those observed previously in the same area (Able et al 2013, 2014).

3.4 Fish Response to Shading by a Barge

Fish response to the overhead presence (cover) of the barge differed based on the type of the fish for which it was measured (small pelagic singletons, small schooling pelagic fish, and large pelagic fish).

3.4.1 Large Pelagic Fishes

There was no among-site difference in the abundance of large fish when the barge was not present (KW test, mean ranks: 24.5882, 23.6667, p = 0.7353, Table 5).

Table 5. Results of Kruskal-Wallis test for distribution of large fish at Red Hook and Pier 6.

Source	**SS**	**Df**	**MS**	**Chi-sq**	**Prob>Chi-sq**
Site	9.2157	1	9.2157	0.1143	0.7353

Error	3.6988e+003	45	82.1952	
Total	3708	46		

Therefore we combined samples from both sites in testing for the difference in treatments of cover (under or exposed) and relative to period when examining the response of large pelagic fish to the presence of the barge. (Instead of the word “shade” or “shaded”, we use “under” to mean samples covered by the overhead presence of the barge, or in other cases a pier, and “exposed” to indicate not covered in order to explicitly differentiate this from a condition of being shaded by the cast shadow of the barge or an adjacent structure that does not cover the site overhead, such as a sample taken alongside the barge, pier, or rip-rap, see Able et al 2014.) The intercept of the GLM was significant. We found that the probability of encountering large fish in samples increased significantly at night relative to daytime or crepuscular periods but the magnitude increase of this probability was small. There was no significant difference in the probability of encounters with large fish as a function of whether the sample was under the barge or exposed, or as an interaction of cover and period of day (Table 6).

Table 6. Results of GLM for the probability of occurrence of large fish under various conditions associated with a barge at Red Hook and Pier 6. Degrees of Freedom = 192, S_fit = 0.0937

Effect	Coefficient	P	t	Interpretation
Intercept	-3.0918	0.0000	-31.1501	Significant intercept
Night	0.3022	0.0149	2.4561	Increased probability of fish at night
Crepuscular	-0.2138	0.5270	-0.6338	
Covered	0.0218	0.9180	0.1031	
Night*Covered	-0.1834	0.5308	-0.6279	
Crep.*Covered	0.4060	0.4551	0.7485	

For large fish that were not under the barge, there was no significant difference in the use of habitat at the side, bow, or stern of the barge (Table 7).

Table 7. Results of Kruskal-Wallis test for difference in the abundance of large fish in exposed samples relative to exposure of the barge.

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Groups	172.1	2	86.038	0.52	0.7692

Error	24742.4	74	334.357
Total	24914.5	76	

3.4.2 Small pelagic singletons

For small singletons, there was a significant difference (KW Test, p = 0.0014) in the abundance of small pelagic singletons among sites, with almost twice as many relative to unit effort at Red Hook (mean ranks: 15.5882, 28.7667, Table 8).

Table 8. Results of Kruskal-Wallis test for difference in the abundance of small pelagic singletons at Red Hook or Pier 6.

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Site	1.8845e+003	1	1.8845e+003	10.1974	0.0014
Error	6.6165e+003	45	147.0330		
Total	8501	46			

Therefore, we did not pool these, but tested them separately. At Red Hook, the intercept of the GLM (representing the condition of a daytime sample not under cover of barge) was significant. There was a significant and strong increase in the probability of encountering small single fish in night time samples relative to daytime, and also a significant and strong increase in the probability of encountering single fish in crepuscular samples relative to daytime samples. There was a significant but only moderate increase in the probability of encountering small single fish underneath the barge relative to samples away from the barge. This, however, decreased at night as an interaction between night and barge cover. There was low confidence that a decrease in the probability of similar magnitude resulting from the interaction of crepuscular and cover was real, i.e. the condition was not significant at the alpha = 0.05 level given the low sample size with this particular combination (Table 9).

Table 9. Results of GLM for the probability of occurrence of small singletons under various conditions associated with a barge at Red Hook. Degrees of Freedom = 138, S_fit = 0.1894.

Effect	Coefficient	P	t	Interpretation
Intercept	-2.2465	0.0000	-26.9018	Significant intercept
Night	0.6842	0.0000	6.6404	Increased probability of fish at night
Crepuscular	0.7889	0.0000	5.4907	Increased probability of fish at dusk
Covered	0.4076	0.0038	2.9479	Increased probability of fish under barge
Night*Covered	-0.5245	0.0086	-2.6641	Decreased probability of fish at night under barge

Crep.*Covered	-0.6994	0.1432	-1.4723

At Pier 6, the intercept of the GLM (representing the condition of a daytime sample not under cover of barge) was also significant. However, none of the trends represented by change in the slope coefficient was significant (Table 10).

Table 10. Results of GLM for the probability of occurrence of small pelagic singletons under various conditions associated with a barge at Pier 6. Degrees of Freedom = 48, S_fit = 0.1613

Effect	Coefficient	P	t	Interpretation
Intercept	-2.0428	0.0000	-18.0381	Significant intercept
Night	0.0207	0.8884	0.1410	
Crepuscular	-0.5973	0.1805	-1.3590	
Covered	-0.2800	0.4482	-0.7646	
Night*Covered	0.2381	0.5964	0.5332	
Crep.*Covered	0.1909	0.8276	0.2190	

For small pelagic singletons that were not under the barge, there was no significant difference in the use of habitat at the side, bow, or stern of the barge (Table 11).

Table 11. Results of Kruskal-Wallis test for difference in the abundance of small pelagic singletons in open water relative to exposure of the barge.

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Groups	403.4	2	201.688	0.81	0.6673
Error	37485.1	74	506.556		
Total	37888.5	76			

3.4.3 Small Schooling Pelagic Fish

There was no among-site difference in the abundance of small schooling pelagic fish when the barge was not present (KW test, mean ranks: 20.3824, 26.0500, p = 0.1196, Table 12).

Table 12. Results of Kruskal-Wallis test for difference in the abundance of small schooling pelagic fish at Red Hook or Pier 6.

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Sites	348.5603	1	348.5603	2.4229	0.1196
Error	6.2689e+003	45	139.3098		
Total	6.6175e+003	46			

Therefore, we combined samples from both sites for the GLM. The intercept of the GLM (representing the condition of a daytime sample not under cover of barge) was significant. There was a significant and strong decrease in the probability of encountering fish schools at night. There was a weak decrease in the probability of encountering fish schools under the barge during the day, but this was not significant and did not change significantly during the night or crepuscular periods (Table 13).

Table 13. Results of GLM for the probability of occurrence of small pelagic singletons under various conditions associated with a barge at Red Hook and Pier 6. Degrees of Freedom = 192, S_fit = 0.0578

Effect	Coefficient	P	t	Interpretation
Intercept	-2.7866	0.0000	-68.1851	Significant intercept
Night	-0.2637	0.0006	-3.5026	Decreased probability of fish at night
Crepuscular	-0.0415	0.7064	-0.3772	
Covered	-0.1581	0.1352	-1.5001	Decreased probability of fish under barge
Night*Covered	0.0031	0.9880	0.0150	
Crep.*Covered	-13.3082	1.0000	-0.0000	

There was a significant difference in position of fish that were not under the barge relative to the Exposure of the barge (Table 14.) Therefore, we proceeded with a pairwise test and found that Abundance at the side and bow were similar to each other but different as a group from the stern, with a greatly decreased probability of finding fish at the stern (Table 15).

Table 14. Results of Kruskal-Wallis test for difference in the abundance of small schooling pelagic fish in open water relative to exposure of the barge.

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Groups	5264.2	2	2632.08	12.93	0.0016
Error	25678.3	74	347		
Total	30942.5	76			

Table 15. Result of Tukey-Kramer Honest Significant Difference pairwise test of differences among treatments.

	Treatment 2	Lower Bound	Estimated difference in means	Upper Bound
Side	Bow	-8.5680	4.6785	17.9250
Side	Stern	-27.8757	-14.6292	-1.3827
Bow	Stern	-32.4237	-19.3077	-6.1917

4.0 Discussion

4.1 Summary of Fish Response to Barge Presence

The pelagic fish that were sampled with DIDSON were typical of New York Harbor area in size and type (Grothues et al in review, Able at al 2013, 2014). The length of fishes in this study overlapped broadly with previous values from DIDSON sampling at Brooklyn Bridge Park and Liberty State Park during the same year.

An alternative explanation for the presence of several solitary fishes is that these individuals separate from schools in response to shading during the day or reduced light at night. This could have occurred for the individuals of several schooling species common to the area including Atlantic silverside, Atlantic menhaden, and bay anchovy.

Small solitary fishes were the most often encountered type of fish. Their distribution differed at two sites in preliminary testing so each site was tested for barge effects independently. At Red Hook, this type of fish responded significantly and moderately positively to the presence of the barge, with more under the under the barge than around it. They were also strongly more abundant at night and during crepuscular periods, and the relationship of their response to the barge weakened at night suggesting that fish moved away from this cover into open water at night time when the shading became less of a difference. At Pier 6, where a pier provides abundant shading relative to the barge, there were much fewer encounters with this type of fish overall and there was no measurable response of the fish to the barge, with similar occurrence under and adjacent to the barge and regardless of daylight cycle.

Small schooling fishes, primarily Atlantic silversides but also bay anchovy and some herrings, were also abundant in schools of three to thousands of individuals. Their distribution at the two sites was similar. This type of fish, which represents the largest number of fish encountered, did not respond measurably to the presence of the barge at both sites. This relationship did not differ measurably over the course of the daylight cycle, nor did the overall abundance of these fish change much over the daylight cycle. Small schooling fish were more likely to be in the open water in front of the barge (the bow facing the river) exposed to waves, than at the side or stern suggesting a positive secondary effect of the barge's presence. This could be either an attraction to the structure of the barge or simply an accumulation whereby fish arriving from the open site will not proceed further.

Large fish, primarily striped bass and bluefish, were scarce and sparsely distributed and this may have affected the ability of tests to find differences even if there were some. There was no measurable difference in the probability of their occurrence relative to site, so sites were pooled for a bigger sample size. Large fish were slightly and significantly more likely to be encountered during the nighttime than during the day, but there was no measurable response as a probability of encounter under or adjacent to the barge regardless of the daylight cycle.

The patterns for all three types of fishes is inconsistent with that discovered relative to piers, which also shade the water but additionally have vertical structure and are much larger. For example, the relative size of the largest and smallest piers are much larger than some floating structures and much larger than the barge used in this study (Figure 11). There was no measurable response of fishes to shading by the smallest pier studied separately (Grothues et al. in review) which is 268 times as large as the barge. This is additional evidence that structures as small as the barge are not likely to have negative effects on pelagic fishes.

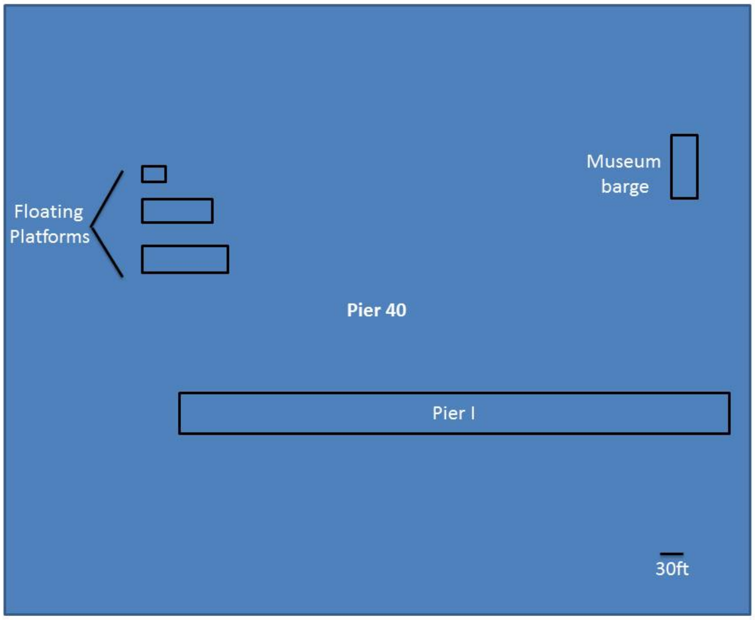

Fig 10. Scale of various structures in the New York Harbor that provide shade. The largest (periphery) blue square represents the area of Pier 40.

In summary, our interpretation, based on this and other works, is that large predatory species with dark-adapted retinal pigments use shaded edges as ambush sites from which to prey on small fishes. Small solitary species or schooling species not in schools may concentrate under the shaded area of a barge in the absence of larger shaded structures fishes. A downward trend of schooling fishes under the barge was moderate despite being not significant and may have been measurable with a larger sample size, but in any case does not appear to be as strong as avoidance of the underside of large deeply shaded piers.

4.2 Outreach/Communication

Outreach included hands-on introductions to field science in fish ecology and technology through mentorship of students from New York Harbor School and St. Francis College (Brooklyn, NY) who accompanied us in the field. Presentations included those to the NY/NJ Port Authority and broader audiences at the Hudson River Foundation seminar series.

4.3 Recommendations

Small barges and other floating structures are unlikely to influence utilization of New York Harbor near-shore habitats in summer and fall in the short term; i.e. in the absence of long term physical changes like shoaling or scour associated with barge presence. They are even less likely to have an effect in in other seasons when many species have migrated from the estuary. Effects are also less likely for barges shading deep water along steep armored shorelines than in shallow water because deep waters are already shaded by turbidity, and are also less likely along shorelines that are likewise already shaded by other artificial structures such as piers. However, if large structures are considered (e.g. Kitazawa et al. 2010, Wang and Wang 2015), then they are likely to have the same negative effects as piers.

Additional studies of larger floating structures (e.g. swimming pool barge) will help provide scale for future deliberations as well as comparisons relative to multiple piers of different sizes (Grothues et al. in review).

5.0 Acknowledgements

Numerous individuals contributed to sampling and file review including Jenna Rackovan, Tom Malatesta, Roland Hagan, Christine Denisevich, Jen Smith, Evan Reed, Stacy Belgiovene, and Andrew Hassall. Thanks to Captain Timothy LaFontaine of the Army Corps of Engineers and ACoE dispatchers and personnel for greatly facilitating staging out of the ACE Caven Point Facility. Robert Chant provided instruction for the ADCP use and processing. Thoughtful comments on earlier presentations of these results provided food for thought. Bonnie Harken, Dennis Suzkowski, and Jim Lodge assisted withy hepful comments throughout this program. Funding for this project came from the Port Authority of New York & New Jersey through the Hudson River Foundation.

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SOUTHWEST BROOKLYN WATERFRONT STUDY

THE PORT AUTHORITY OF NY & NJ

PROJECT SUMMARY REPORT
Floating Structures Pilot Project
July 2015

APPENDIX 2

THE INFLUENCE OF FLOATING STRUCTURES ON SEDIMENT TRANSPORT PROCESSES

by Woods Hole Oceanographic Institution

Revised Final Report

The Influence of Floating Structures on Sediment Transport Processes

Hudson River Foundation

Grant #008/12R

David K. Ralston and W. Rockwell Geyer

Woods Hole Oceanographic Institution

April 17, 2014

Executive Summary

A field experiment was performed in New York Harbor to determine the influence of floating structures on sediment transport processes. A 75 foot long barge was placed at two different locations along the Brooklyn waterfront, one at Brooklyn Bridge Park and the other at Red Hook, for roughly two weeks. Measurements of currents, water properties, suspended sediment, and bottom sediment properties were conducted to determine whether the presence of the barge altered the sediment transport processes and whether the presence of the barge altered the sedimentary environment. In addition to the investigation of the influence of the barge, the study also addressed the mechanisms of sediment transport in New York Harbor as they influence the distribution of suspended sediment and the trapping of sediment in slips.

The study clearly identified the importance of fluvial and tidal processes in delivering sediment to the slips. Discharge events deliver sediment from the lower Hudson estuary to the Harbor, leading to greater ambient sediment concentrations following discharge events. Tidal processes remobilize bottom sediments, which preferentially accumulate in bottom salinity fronts. This sediment is transported into the slips as bottom-water intrusions laterally from the main channel.

Once sediment gets into the slips, the ambient currents are too weak to remobilize it, and the resuspension within the slips occurs only as a result of wave motion. The source of the wave motion is not from natural phenomena such as wind or offshore swells, but rather from the wakes of vessels traveling along the East River. The waves show a strong daily periodicity that is correlated with the level of ferry activity, with peaks during the rush-hours of weekdays and a broader distribution during weekends.

The presence of the barge did alter the bed sediment composition during the two weeks it was moored in the slip at Brooklyn Bridge Park. Sidescan sonar recorded the distinct outline of the barge as a region of stronger backscatter, consistent with scour of the surface fluff layer and a shift toward coarser grained, more acoustically reflective substrate. Grab samples also showed that the bed under the barge was coarser than at locations in other parts of the slip, where the bed was almost entirely fine sediment.

The mechanism responsible for the increased erosion at the barge is related to the interaction between the floating structure and the wave orbital velocities under the barge, increasing bottom stress and leading to enhanced scour of fine sediment. The theoretical mechanism for the interaction between the waves and floating structure still needs to be refined and quantified in detail.

The impact of the barge on the sedimentary regime was subtle, and could only be detected with careful measurements of sediment texture. In the short time that the barge was present, the sedimentary environment was adjusting to the slightly altered physical regime. Over longer time scales, the bed is likely to adjust to the perturbation and reach a new equilibrium, through changes in the bathymetry (getting deeper) or changes in bed composition (getting coarser).

1. RESEARCH OBJECTIVES

The goal of this study is to determine the influence of floating structures on the scour and trapping of sediment in New York Harbor, with a particular focus on how floating structures may modify sediment transport conditions in slips at the edges of the harbor. Specific objectives are 1) to determine how floating structures influence the flow conditions; 2) to determine the patterns of sediment resuspension, trapping and erosion in the vicinity of these structures; 3) to predict the long-term consequences of the presence of structures in the sedimentary environment under and around floating structures.

A broader scientific goal of this study is to develop methodologies for the investigation of fine-scale variability of hydrodynamic and sediment-transport processes in estuaries, particularly as influenced by variations in bathymetry and structures at scales of meters to 100's of meters. These scales have received scant investigation in the past, due mainly to our inability to resolve these scales. Yet recent field and modeling studies of estuaries have revealed that processes at scales of meters to 100's of meters often critically influences the transport and distributions of key variables (such as salinity, suspended sediment and momentum) at the scale of the estuary as a whole [*Lerczak and Geyer*, 2004; *Scully et al.*, 2009; *Ralston et al.*, 2010]. The measurement techniques and analyses incorporated in this study have helped refine our ability to study sediment transport processes in estuaries at these scales.

2. BACKGROUND

Floating structures are common features of the New York Harbor waterfront, most notably commuter ferry terminals but also including the floating swimming pools managed by the New York Parks and Recreation department as well as innumerable vessels of various sizes, semi-permanently or permanently moored along the waterfront. The shoaling around the USS Intrepid that impeded its renovation several years ago provides an illustration of the challenges and cost associated with siltation around floating structures in New York Harbor. The slips along the perimeter of the harbor have been known to have significant siltation for many years [*Panuzio*, 1965]; this siltation occurs with or without floating structures due to the reduced velocity of the water within the slips and the asymmetry of sediment transport between incoming water (high in suspended sediment) and outgoing water (low in suspended sediment). Trapping of suspended sediment by bottom salinity gradients in the vicinity of the slips also may reinforce the flood dominance of sediment transport and enhance the rates of deposition. Floating structures located in the slips may in some cased enhance siltation and in others to mitigate it, depending on the dominant hydrodynamic processes.

Historically, the most important consideration with respect to siltation of the waterfront was the maintenance of adequate depth for the berthing of vessels. However as the priorities have shifted toward enhancement of environmental quality and alternative means of utilizing the waterfront, the question is not simply to maximize berthing capacity with a minimum of dredging costs. Rather we are interested in determining whether a sustainable morphology can be established along the waterfront that supports a healthy benthic community as well as the various commercial and recreational uses, and to what extent floating structures may influence the mechanisms of erosion and deposition.

Previous studies starting with Panuzio (1965) and others more recently [*Geyer et al.*, 2001; *Woodruff et al.*, 2001; *Ralston et al.*, 2012] have documented mechanisms by which sediment is trapped within the Hudson estuary. High concentrations of suspended sediment in the main channel of the estuary and harbor provide the source material for shoaling along the perimeter of the harbor [*Panuzio*, 1965]. The mechanisms responsible for shoaling in these lower energy environments are simple in concept, but the details of the dominant mechanisms depend sensitively on the site geometry and associated spatial gradients in velocity that determine sediment delivery, remobilization, and trapping. The presence of a floating structure will change the velocity structure, mainly due to the displacement of a volume that the ambient fluid must go around or under. Potential factors affecting sediment transport that can be affected by the presence of a floating structure include the barotropic tidal currents, the baroclinic velocity structure, and the orbital motions of waves. To characterize and account for this complexity, the most sensible approach is empirical and site-specific.

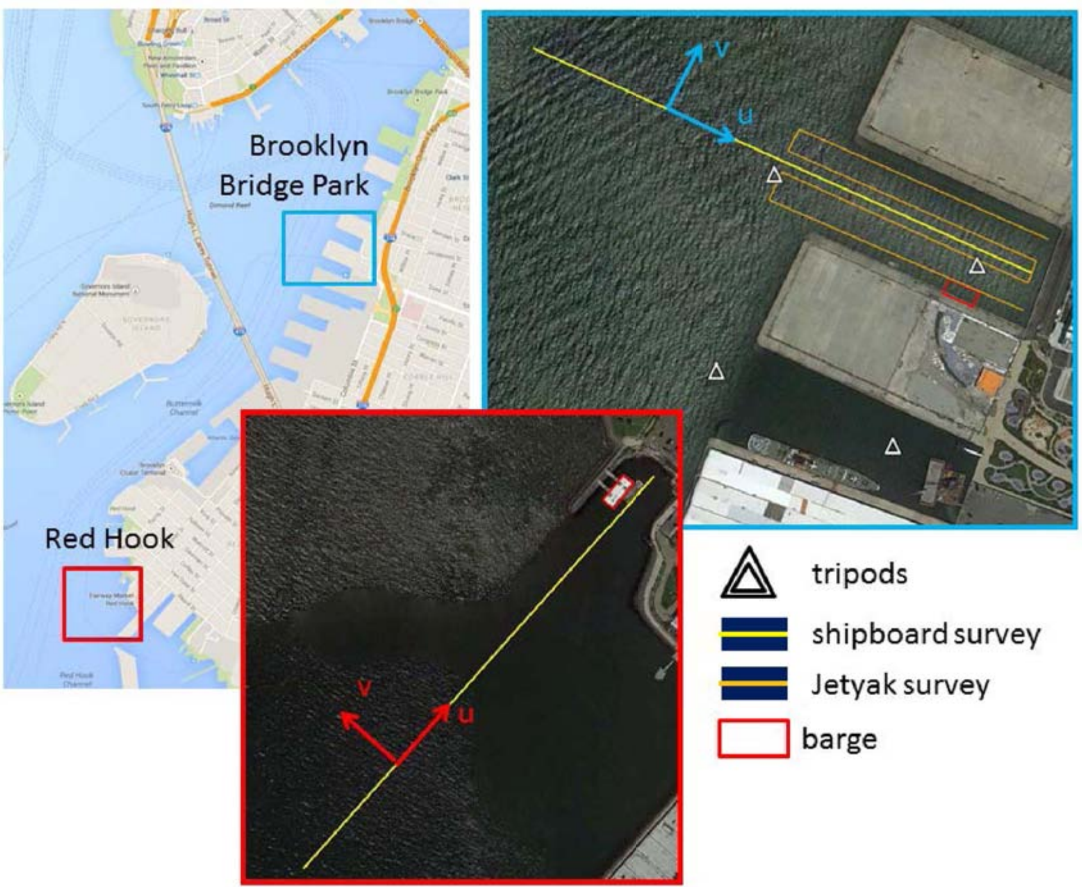

Figure 2.1. Map of study sites at Brooklyn Bridge Park (upper right) and Red Hook (lower). Survey lines and tripod locations are shown, as are the rotated velocity coordinate systems.

3. APPROACH

The experimental approach was to observe the effects of a small floating structure at two locations along the Brooklyn waterfront using a variety of field observational techniques. The floating structure was the Lehigh Valley Railroad Barge No. 79, home of the Waterfront Museum. The barge is 75 ft long with a draft of 3 ft, and is typically moored in Red Hook, Brooklyn at Pier 44. For this study, the barge was moved to Brooklyn Bridge Park (BBP) at Pier 6 for 2 weeks in late June and early July 2013, and subsequently the barge returned to Red Hook (Fig. 2.1). Observations of currents and water properties including salinity and suspended sediment concentration were made at both locations using shipboard surveys and moored time series measurements. Bed sediment characteristics were evaluated using bottom grab samples and sidescan sonar mapping.

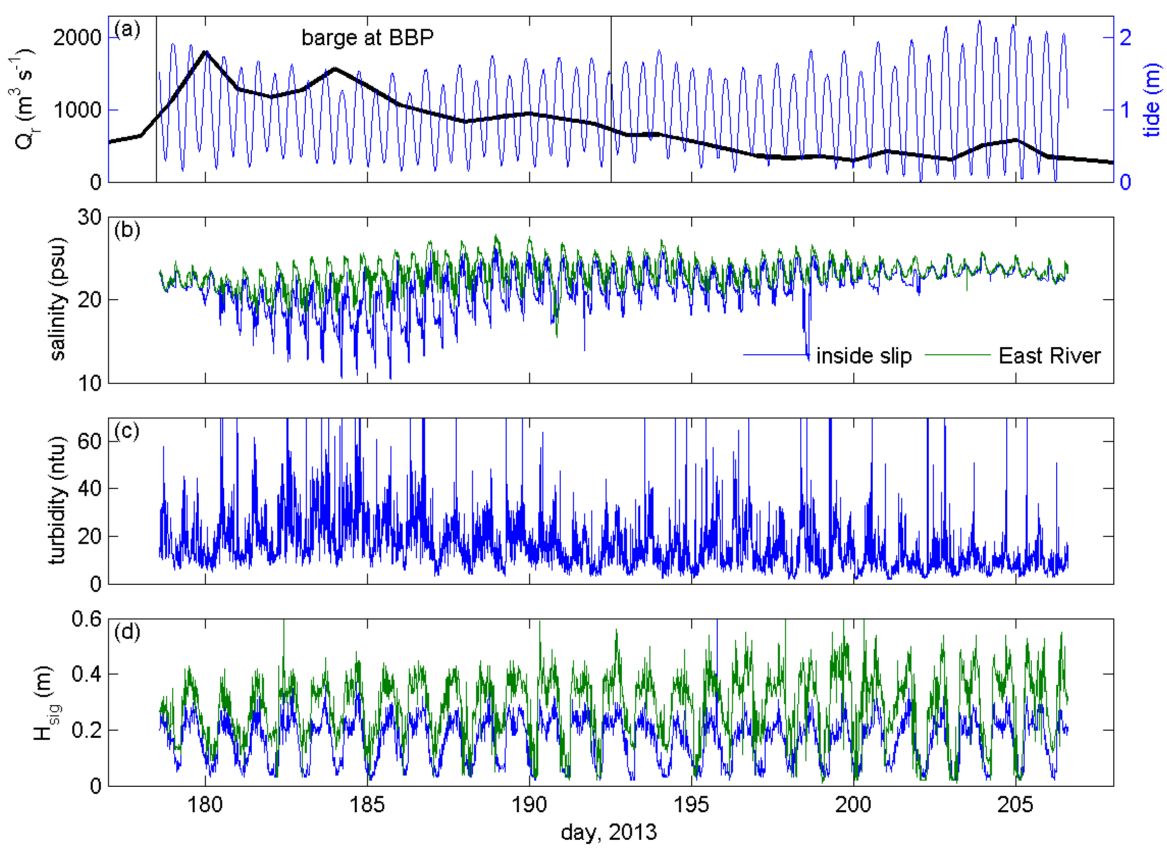

Figure 3.1. Time series from moorings at Brooklyn Bridge Park (BBP); (a) Hudson River discharge at Green Island and water level at the moorings, also noting the period the barge was moored at BBP; (b) near-bottom salinity inside and outside the slip; (c) near-bottom turbidity inside the slip; (d) significant wave height inside and outside the slip.

Observations were conducted at both study locations, but a majority of the effort was focused on the Brooklyn Bridge Park site. The Brooklyn Bridge Park location represented a clear example of the near-term effects of a floating structure moored for a known period of time in a new environment. In contrast, conditions at the Red Hook site represent the cumulative effects of processes over the years the Waterfront Museum has been at that location, and thus the impact of the perturbation associated with moving the barge was relatively modest over a 2 week period. The surrounding bathymetry and infrastructure at Red Hook, including a complex set of submerged breakwaters and derelict pier pilings, made shipboard operations more challenging and the hydrodynamic processes highly site-specific. The slip at Brooklyn Bridge Park was more tractable as a study site and the bathymetry there was representative of the series of slips nearby along the Brooklyn waterfront. Therefore the focus of this report is on the Brooklyn Bridge Park site.

The observations spanned approximately 1 month, and variations in forcing conditions over this period affected conditions at the study sites (Fig. 3.2). A discharge event in the Hudson River increased flow at Green Island to about 1800 $m^3 s^{-1}$ shortly after deployment, so the supply of freshwater and suspended sediment to the Harbor was greater than typical of summer, low discharge conditions. Hudson River discharge decreased through the study period such that the latter half of the study it was 300-500 $m^3 s^{-1}$. Tidal forcing varied with spring-neap cycle, with deployment and recovery occurring around spring tides.

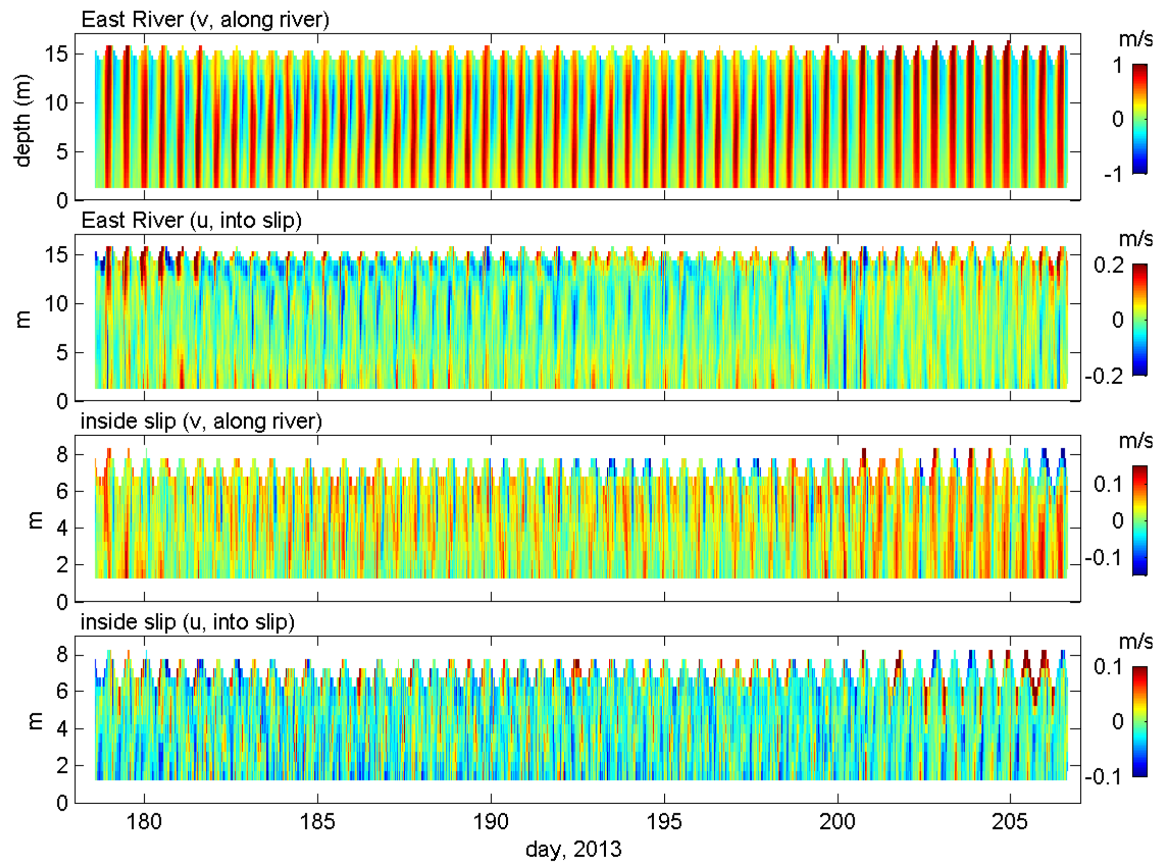

Figure 3.2. Velocity time series from the East River (top panels) and inside the slip (bottom panels) at Brooklyn Bridge Park. Velocities have been rotate by 25˚ from north to align with the slip.

3.1 Moored time series

Two tripods were deployed at the Brooklyn Bridge Park location for the duration of the study (June 25-July 25, 2013). The tripods were positioned with one located inside the slip, parallel with the location of the moored barge, and the other just outside the slip in the East River (Fig. 2.1). Average depths at the two locations were 7.4 m and 14.9 m, respectively. Each tripod had an acoustic Doppler current profiler (ADCP) to measure both tidal currents and wave properties. Both tripods had a near-bottom conductivity-temperature-depth (CTD) sensor to measure salinity and water level, and the tripod inside the slip had an optical backscatter sensor (OBS) to measure turbidity. Turbidity data were converted to sediment concentrations based on regressions to suspended sediment concentrations measured in water samples during previous observational studies in the Hudson estuary.

The moorings recorded near bottom-salinity and turbidity (Fig. 3.1) and water column profiles of velocity (Fig. 3.2) during the period the barge was moored at Brooklyn Bridge Park and for 2 weeks after its return to Red Hook. The velocity have been rotated by 25° east of north so that the axes are aligned with the slip – positive *u* velocities are into the slip, and positive *v* correspond with the flood tide in the East River. Along-river velocities in the East River reached speeds greater than 1 m/s, and were strongly flood dominant. Tidal velocities in the slip were much weaker, with along-river velocities typically less than 15 cm/s. Tidal velocities were greater in both the river and the slip during the spring tides at the beginning and end of the record. Hudson River discharge affected the salinity signal, as minimum salinities in the slip occurred several days after the discharge event (Fig. 3.1). Salinities in the slip were less than in the river, reflecting both lateral gradients and vertical stratification due to the differences in bottom sensor depths.

The tripod moorings were located in the slip between Piers 5 and 6, where the barge was moored, for the period from June 27 to July 25. Prior to barge arrival (June 25-27), the moorings were deployed in the adjacent slip between Piers 6 and 7 (Fig. 2.1). The two sets of mooring positions had similar locations relative to the piers, although the bathymetry between Piers 6 and 7 was slightly deeper. Data recorded during the 2 days at the initial deployment location are used to illustrate transport processes that appear to be important for piers located along this section of the East River, and perhaps more generally for low-energy environments adjacent to an estuarine channel.

3.2 Shipboard surveys

Shipboard surveys were conducted at both of the study sites, both with and without the barge present. Surveys were conducted aboard the *R/V Mytilus* using an ADCP to measure velocity and acoustic backscatter continuously and taking water column profiles at discrete stations along the axis of the slip with a CTD and OBS (Fig. 2.1). The bathymetry of each slip was mapped using an echo sounder.

In addition to the shipboard CTD surveys, higher resolution surveys of the velocity and acoustic backscatter in the slip at Brooklyn Bridge Park were made using an autonomous surface vehicle, the jetyak (Fig. 3.3). The jetyak surveyed 4 parallel lines along the slip, repeating the survey lines approximately every 10 minutes over the tidal cycle. The jetyak deployment in this study was the first of its kind for an autonomous surveying in an estuarine environment. The autonomous vehicle collected data at a spatial and temporal resolution that would not have been feasible with standard shipboard surveying, and freed up personnel to simultaneously collect additional survey data and samples from the research vessel.

Figure 3.3. The autonomous surface vessel jetyak surveying in front of the barge at the Brooklyn Bridge Park slip.

The ADCP records acoustic backscatter in addition to water velocity, and the backscatter can be used as a proxy for suspended sediment concentration. For each of the survey periods, ADCP backscatter profiles were compared with the turbidity recorded by the OBS during CTD casts (Fig. 3.4). Acoustic backscatter profiles were corrected for beam spreading and attenuation due to absorption by the water as described in the RDI Manual. The non-linear relationship between acoustic backscatter and optical turbidity was then applied to create higher resolution cross-sections of suspended sediment than was possible with the discrete CTD casts alone. The ADCP backscatter data from the moored tripods were also compared with the co-located OBS measurements. Over the 1 month deployment, the relationship between the acoustic and optical backscatter varied more than in the short survey periods, perhaps due to changes in grain size associated with the river discharge (delivery of finer particle) and spring-neap tidal amplitude (larger particles suspended during spring tides). Acoustic backscatter scales with scattering volume, so it is sensitive to large particles, while optical backscatter scales with scattering cross-section and is more sensitive to fine particles.

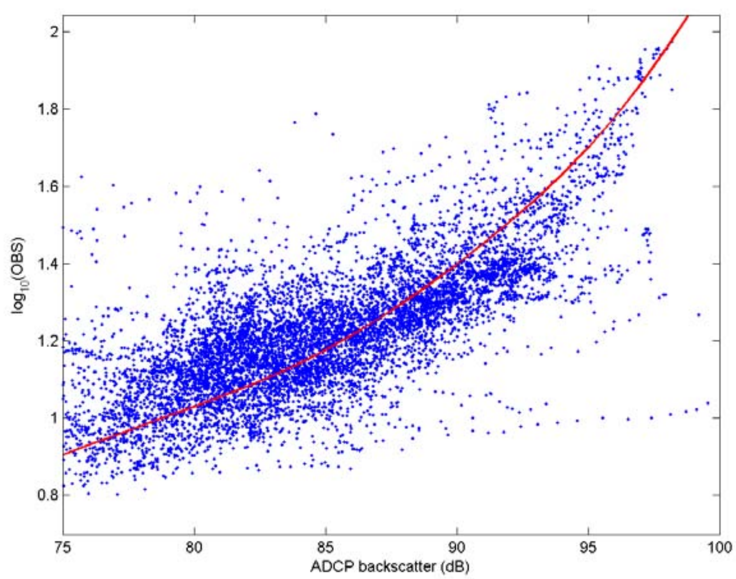

Figure 3.4. Acoustic backscatter from the ADCP vs. optical backscatter from CTD profiles during the surveys at Brooklyn Bridge Park June 26-28. Red line is fit used to convert ADCP backscatter to turbidity.

Representative cross-sections from the shipboard surveys are shown for the Brooklyn Bridge Park site (Figs. 3.5). Survey velocities have been rotated by 25° east of north so that the axes are aligned with the slip, with positive *u* velocities into the slip, and positive *v* for the flood tide in the East River. During the flood, velocities in the East River were northward at greater 1 m/s, but velocities in the slip were much weaker, typically less than 15 cm/s. Lateral salinity gradients were observed, both at a surface front in the East River (prominent at tidal hour 2.8 hr and 3.7 hr) and between the East River and the slip. The lateral salinity gradients relaxed toward the end of the flood as velocities slacked and isopycnals flattened. Suspended sediment concentrations were greatest near the bed during maximum currents, but the region of high sediment concentration extended into the slip with the lateral relaxation toward the end of the flood.

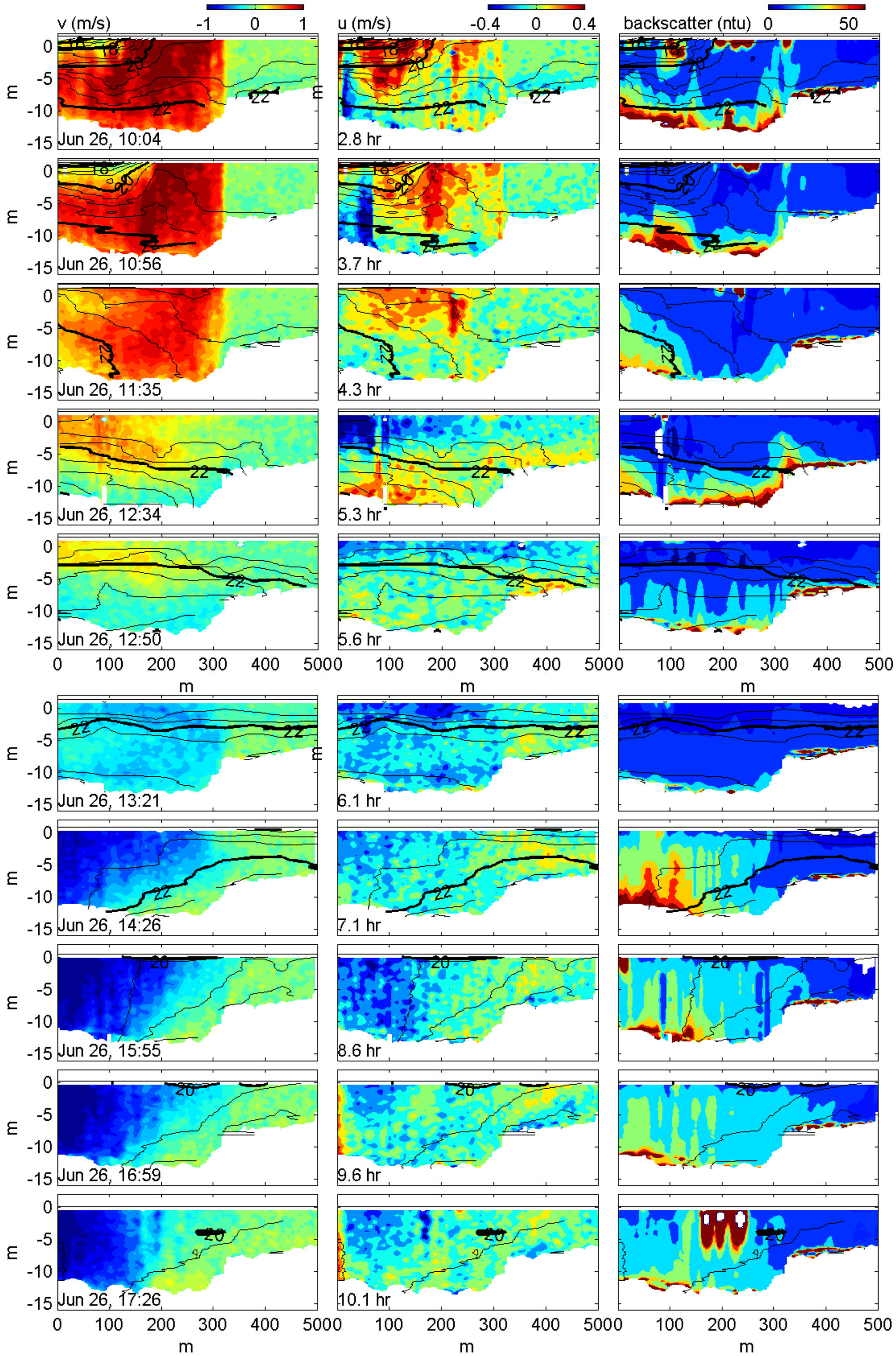

Figure 3.5. Survey from Brooklyn Bridge Park: velocity along-channel (left), into the slip (middle), and acoustic backscatter (right) with salinity contours. Date and tidal hour (0 = start of flood) are noted. High backscatter near the surface in the lower panel is an artifact due to bubbles from prop wash.

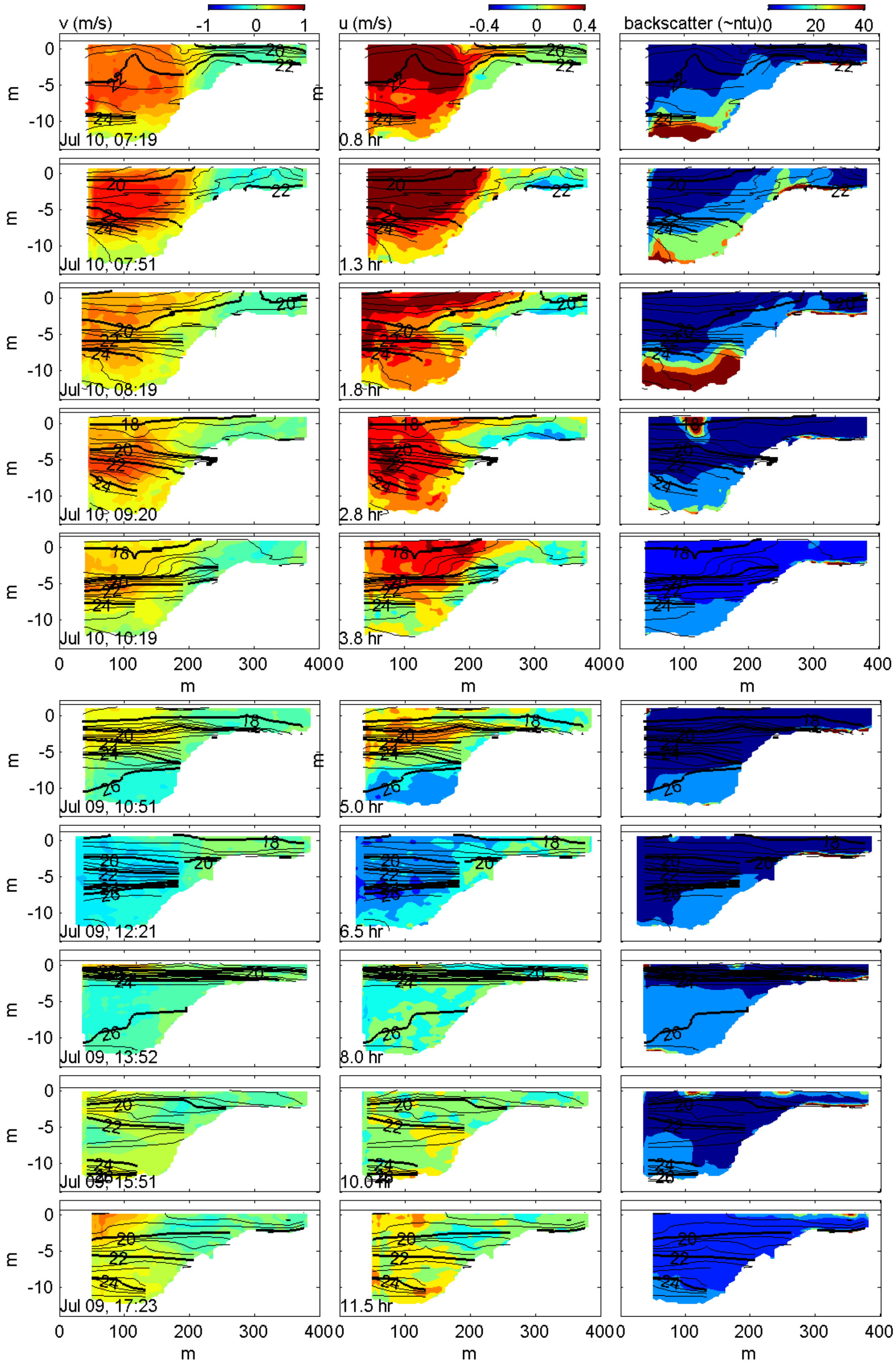

Figure 3.6. Survey data from Red Hook: velocity along-channel (left), into the slip (middle), and acoustic backscatter (right) with salinity contours. Date and tidal hour (0 = start of flood) are noted. High backscatter near the surface (rows 4 and 9) is an artifact due to bubbles from prop wash.

During the ebb, again there was strong lateral shear between the channel and the slip. Differential advection made the channel fresher than the slip creating a lateral salinity gradient. This survey was during spring tides, so in the channel the currents were sufficiently strong to mix the stratification away early in the ebb and resuspended bed sediment, while in the slip the currents were weaker, stratification remained, and sediment concnetrations were much lower. The lateral circulation in the slip was weak but late in the ebb it was consistent with an density-driven exchange, with flow out of the slip near the bed and into the slip at the surface.

Shipboard surveys are shown for the Red Hook site (Fig. 3.6). For Red Hook, velocities have been rotated 40° west of north so that postive *u* is into the slip and positive *v* for the flood tide in the Harbor. As at Brooklyn Bridge Park, velocities in the slip were much lower than just outside the slip in the Harbor. Early in the flood (tidal hours 0.8-1.8) high concentrations were observed outside the slip from the acoustic backscatter. Based on the upwelling of isohalines, there appeared to be a lateral intrusion of high sediment concentrations into the slip during this period. This region of greater suspended sediment passed by the Red Hook site at the beginning of the flood, and it is possible that it is the result of the same frontal trapping and propagation that is seen toward the end of the ebb at the Brooklyn Bridge Park site. Overall, the velocities in the Harbor outside the Red Hook slip were strongly flood dominant, with only a brief period of weak ebb currents (Fig. 3.9). Suspended sediment concentrations outside the slip increased during the ebb but were much less than during the flood, and there was little sediment resuspension in the slip.

3.3 Sidescan Surveys

Side-scan sonar surveys were performed during the surveys on June 26-28, July 9-11, and July 25, using an Humminbird 800 Khz sidescan sonar. The sidescan data provide bottom texture data that were used to determine the general characteristics of the bottom (Fig. 3.7) and to detect possible changes associated with the floating structure. During the June survey the sidescan was deployed on the jetyak, and during the July surveys it was deployed on the R/V Mytilus. The sidescan data from the jetyak was found to be too noisy for accurate bottom characterization, so only the July sidescan data are included in this analysis. The sidescan evidence of erosion due to the floating structure is presented in section 4.

3.4 Sediment Sampling

Grab samples of surficial sediment were obtained at the two field sites on July 10, 2013. The samples were obtained using a Ponar grab sampler (Fig. 3.8). A total of 18 grab samples were obtained, 8 at Red Hook and 10 at Brooklyn Bridge Park. The grab samples were obtained along the axis of each of the slips and at the barge location. The sediment was found to be mostly fine-grained within the slips, transitioning to coarse-grained in the more energetic environment outside the slips (Fig 3.9). The influence of the floating structure on grain size variability is presented in section 4.

Figure 3.7. Sidescan sonar image of the slip at Brooklyn Bridge Park on July 29, 2013. Fine-grained sediment appears dark, and coarse-grained sediment and other bottom features appear lighter. Grazing angle with distance from the survey vessel also matters, with brighter return along the centerline of the vessel track.

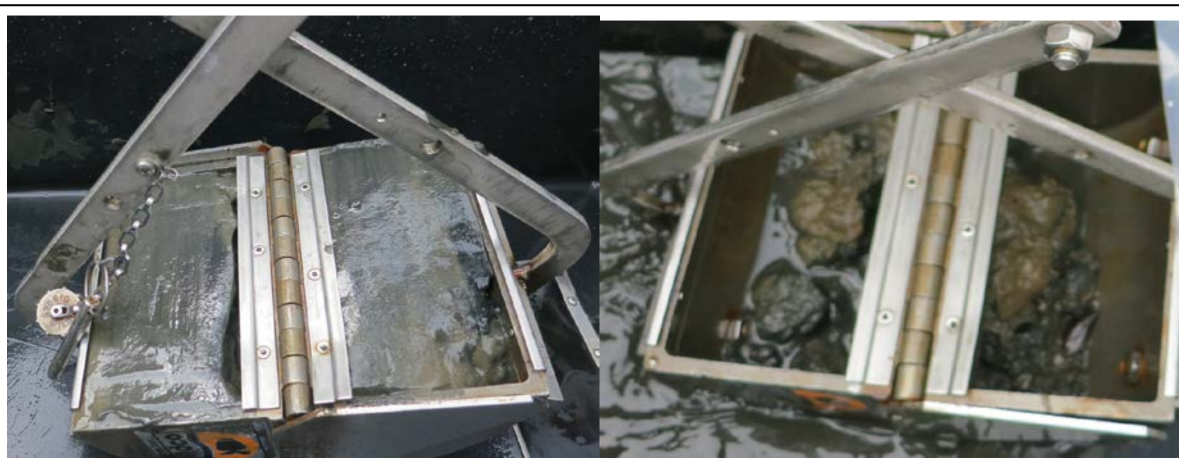

Figure 3.8. The Ponar grab sampler, showing samples from the Brooklyn Bridge Park site. The left image is fine sediment obtained at the location of the barge near the inner end of the slip, and the right image shows a sample of coarse sediment obtained just outside the slip in the East River.

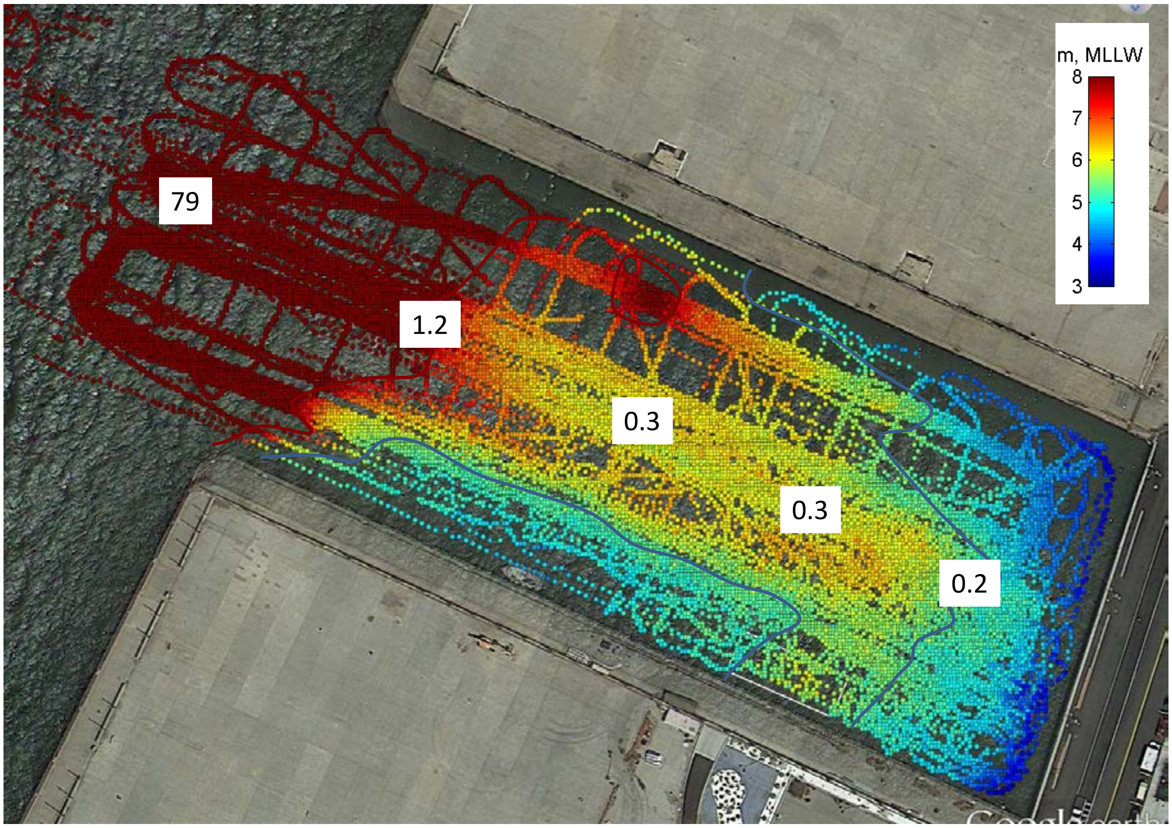

Figure 3.9. Percent coarse sediment at selected grab-sample locations at Brooklyn Bridge Park, overlaid on bathymetry obtained by the jetyak surveys. The fraction of coarse material increases gradually within the slip, and it becomes much coarser in the East River.

4. ANALYSIS

4.1 Mechanisms affecting sediment delivery to the slips

Lateral intrusions of sediment-laden bottom water into the slips

To understand potential effects of floating structures on sediment dynamics in slips we must first identify the dominant physical processes controlling the supply and resuspension of sediment in the slips. A connection between the along-estuary trapping and advection of suspended sediment in the East River and a lateral, density-driven transport of sediment into the slips appears to be important at each of the study sites. Both the moored and shipboard data indicated that distinct events occurred near the end of the flooding tide that resulted in net transport of sediment into the slips. The mechanism was observed during all of the surveys that included the end of the flooding tide (shown in Fig. 3.5 for the June 26 survey), but the survey on July 11, 2013 will be used to describe the transport process in greater detail. During the late flood (Fig. 4.1), high salinity (24 psu) bottom water moved from west to east from the East River into the slip, with eastward near-bottom currents of 0.25 m/s. Near-bottom suspended sediment concentrations were high in the East River at this time (bottom panel). Near the end of flood tide (Fig. 4.2), high salinity water entered the slip laterally from the East River, and suspended sediment concentrations were elevated throughout the slip.

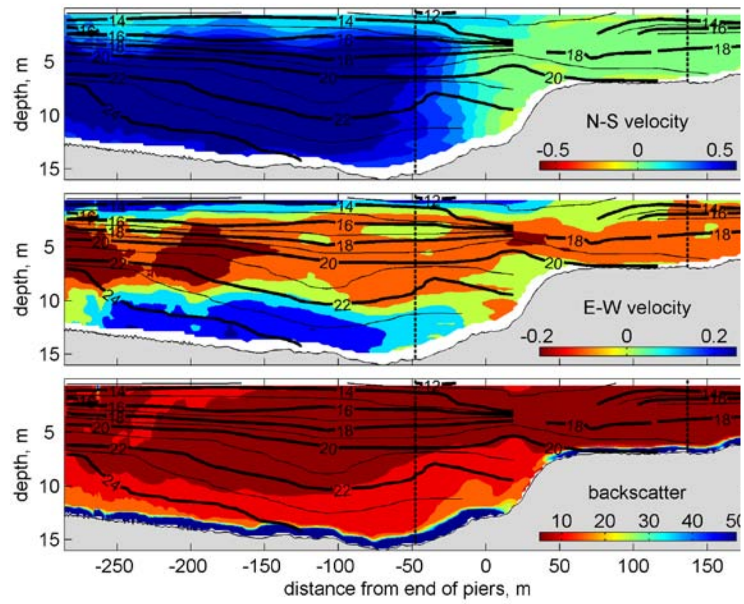

Figure 4.1. Flood tide on July 11, tidal hour 4.6 (late flood) along-channel velocity (top), velocity into the slip (middle), and acoustic backscatter calibrated to turbidity (bottom) with salinity contours. Vertical lines indicate tripod locations.

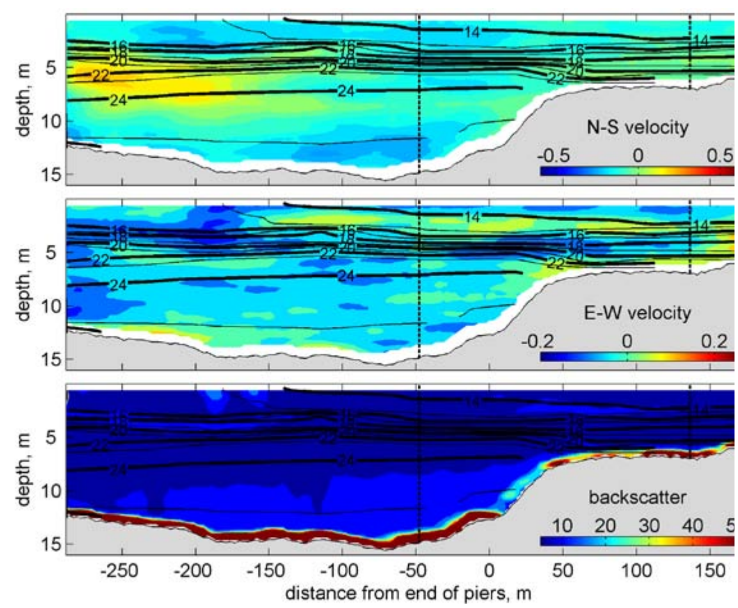

Figure 4.2. Flood tide on July 11, tidal hour 6 (end of flood).

The jetyak surveys provide more detailed spatial resolution of the inflow events and clearer evidence of the inflow within the slip (Fig. 4.3). Near the end of flood tide on June 27, the jetyak surveys indicated bottom inflow greater than 0.2 m/s at the northern side of the slip and occupying more than half the water column, decreasing to 0.1 m/s at the southern side. Ten minutes later, the velocities were more uniform from north to south, with currents of 0.15 m/s along all four of the transects. The rapid changes in velocity structure over such short time intervals are explained by the short spatial scales—the lateral velocity anomaly can traverse the 100 m length of the slip in less than 10 minutes at the observed speeds.

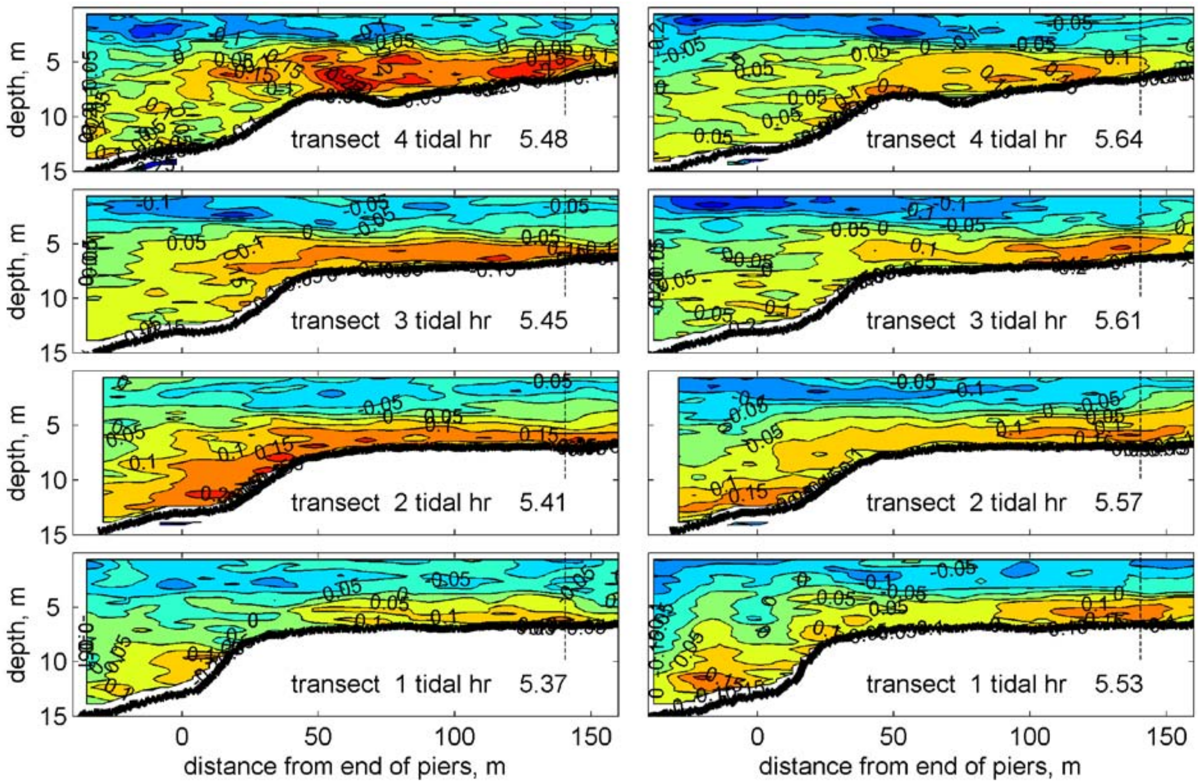

Figure 4.3. Velocity in along-slip direction based on jetyak surveys at the end of flood tide from Brooklyn Bridge Park on July 11, tidal hour 5.37-5.54. The four transects are along the slip and spaced by 25 m, with transect 4 along the north side of the slip and transect 1 at the south side. Bottom inflow is evident at all transects, but its intensity varies on short time and space scales.

Pulses of near-bottom water flowing into the slip around the end of the flood tide with magnitudes of 0.15-0.2 m/s were also apparent in the moored data (Fig.4.4). These velocity pulses were coincident with a sharp rise in salinity and with a short pulse of increased turbidity (Fig. 4.4, 3rd panel). The coincidence of stronger near-bottom currents and increased suspended sediment produced net inflow of sediment into the slips during these events. A net accumulation of sediment associated with these inflow events was estimated by integrating the sediment flux at the tripod location and assuming the accumulated sediment was uniformly distributed between the tripod and the end of the slip (Fig. 4.5). Assuming a sediment bulk

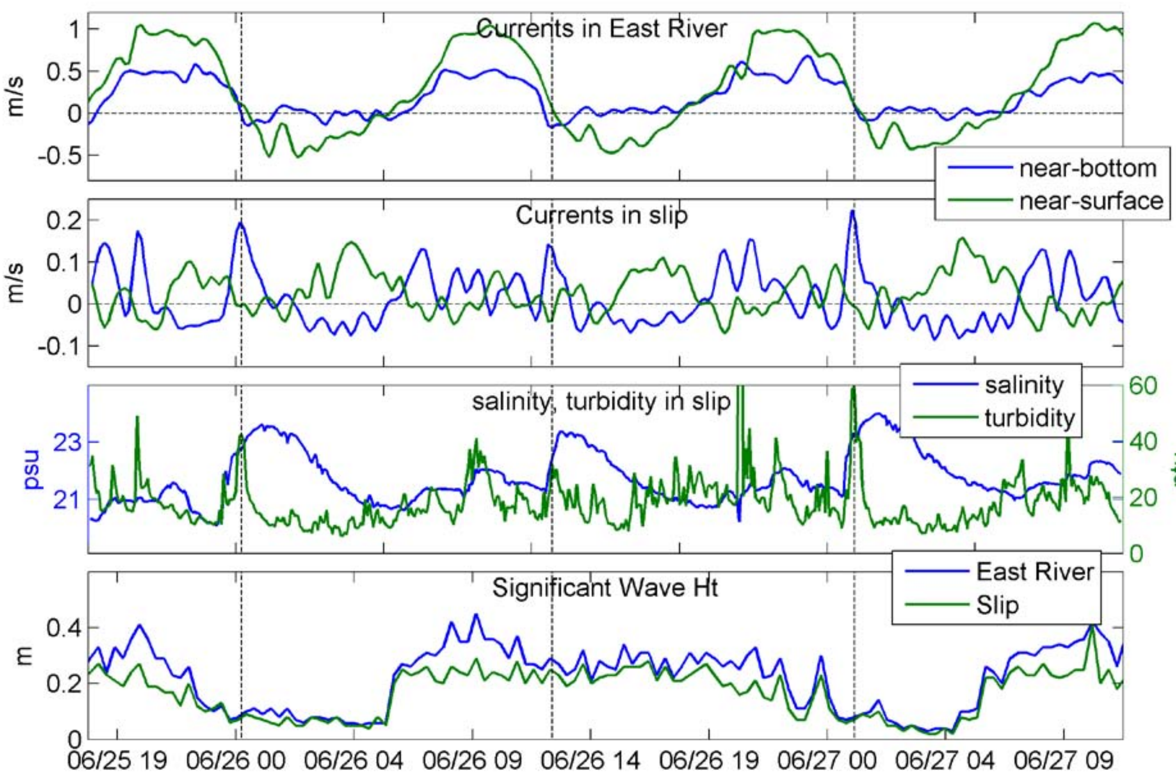

Figure 4.4. Along-channel currents in East River (top panel), currents in the slip (2nd panel), salinity and turbidity in the slip (3rd panel), and significant wave height in the East River and the slip. Events of inflow in the slip are shown with vertical dashed lines. These correspond with elevated turbidity, but they are not correlated with wave amplitude.

density of 500 kg/m^3, the sediment flux over a 2-day interval was approximately 3 mm. The inner tripod was moved to a different location on June 27, and after it was moved the data no longer recorded sediment inflow events, although the velocity signal of the inflow events was still observed. This change in the moored observations is probably due in part to the change in location of the mooring to a more southerly position with weaker inflow.

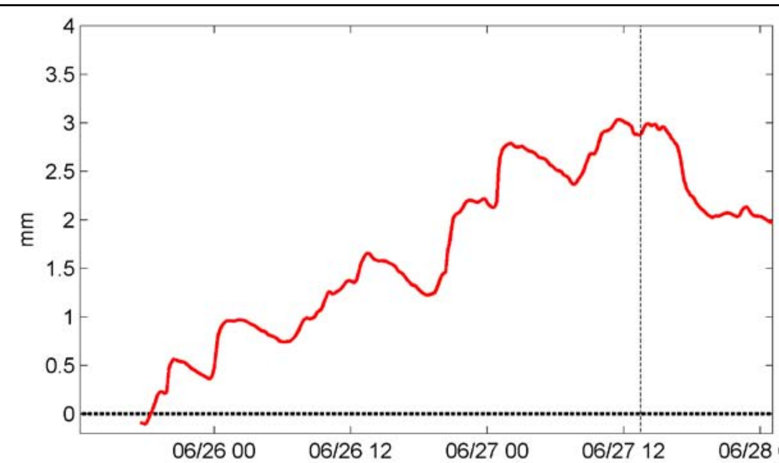

Figure 4.5. Net accumulation of sediment for the first 3 days of the deployment estimated from sediment transport in slip, assuming a horizontal convergence scale of 100 m and a bulk density of 500 kg/m^3. The vertical line indicates the time at which the tripod was relocated. This estimate provides the approximate magnitude of redistribution of sediment based on the water column data.

Variability of suspended sediment in the slip

The concentration of suspended sediment in the slip showed significant variability at short and long timescales. To determine the long-timescale variability, the data were filtered to remove tidal and other short-term fluctuations, as shown in the red curve in Fig. 4.6. The concentration peaked in early July, and it declined through the rest of the deployment. The river discharge showed a similar peak in early July and a decrease over the rest of the deployment period. A statistical analysis revealed that the variations of concentration were found to be highly correlated with the discharge at a lag of 2 days (r^2=0.64).

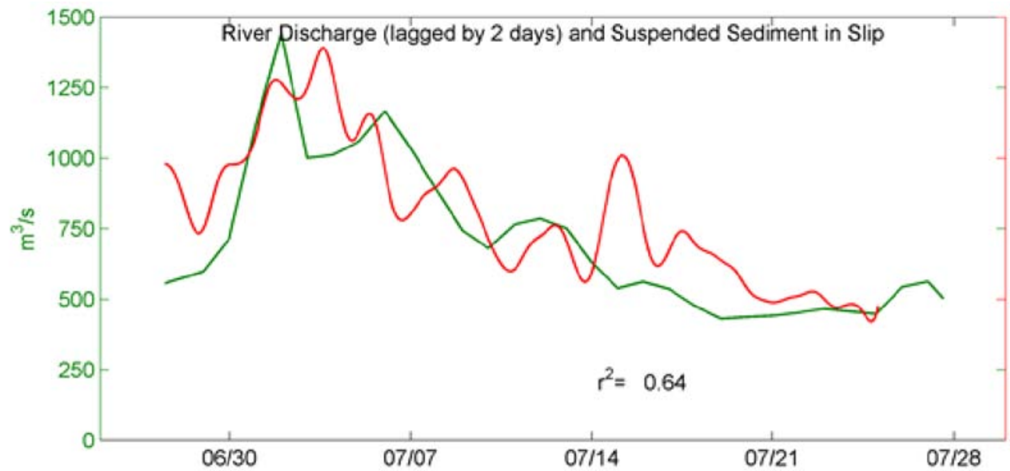

Figure 4.6. Hudson River discharge at Green Island (green) and suspended sediment in the slip (low-pass filtered to remove short term variability (red) for the period of the deployment. The regression coefficient of 0.64 is highly significant, indicating that river flow strongly influences the low-frequency variability of suspended sediment in the slip.

The correlation between discharge and suspended sediment is expected, based on observations in the river and model results [*Wall et al.*, 2008; *Ralston et al.*, 2013]. The Ralston et al. model indicates that sediment is remobilized from the trapping zones in the estuary when discharge increases, and this sediment is advected into the Harbor during the period of high flow. The advective distance between the estuarine trapping zones and the Harbor is on the order of 30 km, so a 2-day lag is consistent with a propagation of 15 km/day or an average advective speed of 0.18 m/s. This advective speed is consistent with the tidally averaged velocity associated with a significant flow event, based on model results and observations [*Geyer et al.*, 2001; *Ralston et al.*, 2013], indicating that the peak sediment concentrations observed in the slip in early July likely originated in the estuarine turbidity maximum zone of the Hudson River.

Variations of suspended sediment in the East River

Although the East River tripod did not have an optical backscatter sensor, the variability of suspended sediment was estimated based on the variations of acoustic backscatter of the ADCP. Suspended sediment in the East River was found to be highly correlated with tidal range, as shown in Fig. 4.7. Spring tides occurred at the beginning of the deployment (tidal range 2 m), and suspended sediment concentrations were greatest. As tidal range dropped, suspended sediment concentrations dropped, although they still had significant tidal variability. Concentrations increased again at the end of the deployment during the strong spring tides. Interestingly, concentrations in the river did not have a large response to the high flow conditions, in contrast to the concentration data in the slip. This may reflect changes in grain size, with larger grain sizes being resuspended during spring tides dominating the acoustic backscatter signal over the finer grain sizes that arrived with the discharge event.

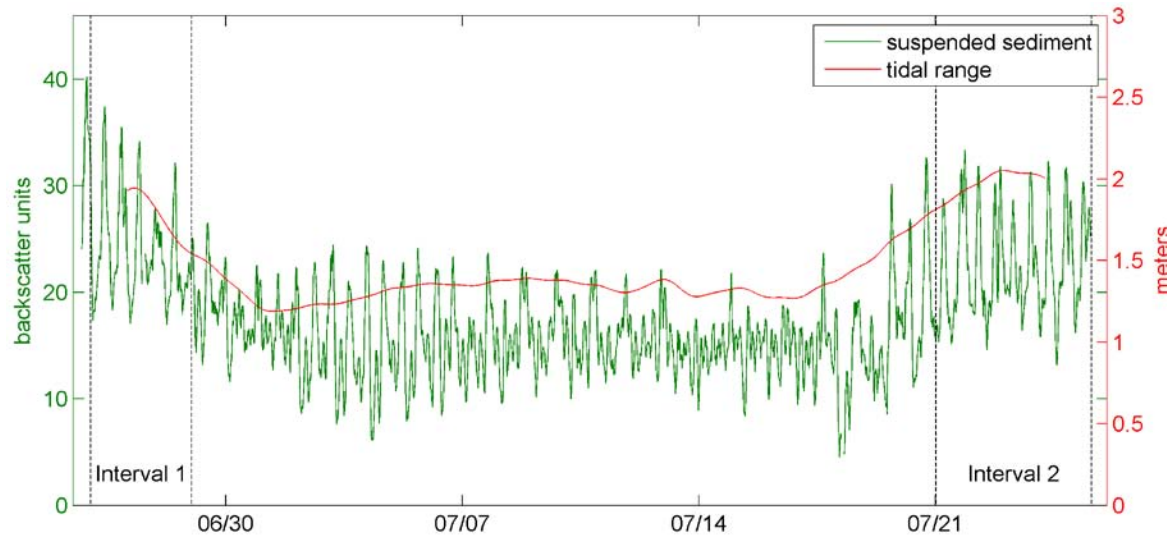

Figure 4.7. Suspended sediment variation at the bottom tripod in the East River (as represented by acoustic backscatter) in green, compared with tidal range in red to show the spring-neap dependence of the suspended sediment in the East River. .

The tidal variations of suspended sediment in the East River show variations that appear to be related to the propagation of a bottom salinity front. Salinity and suspended sediment during the two spring tide Intervals 1 and 2 (Figs. 4.7 and 4.8) show a peak in concentration around hour 3, corresponding to peak flooding tide, and another peak around hour 5, at the end of the flood tide. The peak at the end of the flood corresponds to a sharp increase in bottom salinity, which is indicative of the passage of a salinity front. This increase in salinity corresponds to the observed changes during the surveys shown in Figs. 4.1 and 4.2. Thus these data demonstrate that during spring tide conditions, the passage of the front past the East River tripod at the end of the flood corresponds with a marked increase in near-bottom turbidity.

Returning to the question of how sediment is delivered to the slip, there appear to be two factors involved, 1) an increase in concentrations during high river-flow events (lagged by two days), and 2) frontal advection during spring tides, which originates in the East River and propagates into the slip at the end of the flood tide. Both of these processes appear to be important, but the study did not have adequate temporal resolution to determine the relative importance of the river flow and spring-tide delivery in terms of the long-term sediment budget of the slips.

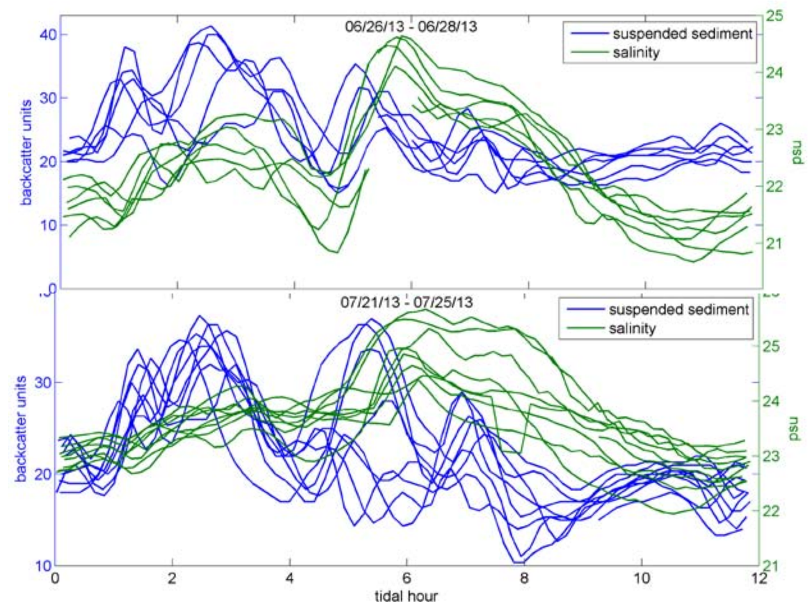

Figure 4.8. Tidal variation of suspended sediment and salinity at the bottom tripod in the East River during Interval 1 (upper panel) and Interval 2 (lower panel). Peaks in suspended sediment occur close to tidal hour 5 (end of flood), when the salinity is increasing steeply in association with the salinity front.

4.2 Sediment resuspension in the slips

From the mooring data, we can evaluate the forcing factors that are associated with sediment resuspension. Sediment resuspension is assumed to depend on the bottom shear stress above some threshold for resuspension, which is close to 0.1 Pa for the fine sediments observed in the slips. The bottom shear stress results from both currents and waves, and the measurements at the tripod in the slip provided both wave and current information with which to determine their relative contributions to stress.

The calculation of bottom stress due to currents was based on a quadratic formula: $\tau_c = C_d u^2$, where u is the velocity 1-m above the bed and the drag coefficient is estimated at C_d =0.003 during weak wave conditions, and it is augmented as waves get bigger based on the wave-current interaction [*Grant and Madsen*, 1986]. For wave-generated stress, the estimate is based on $\tau_w = 0.5 f_w u_w^2$, where f_w is a wave friction factor that depends on wave and bed conditions [*Madsen*, 1994], and u_w is the orbital velocity of the waves, calculated from the wave amplitude, period, and water depth as measured by the velocity profiler at the tripod.

The results of these stress estimates in the slip for the mooring deployment are shown in Fig. 4.9 (upper panel). The bottom stresses due to the currents were always small—less than 0.05 Pa even when considering the augmented drag coefficient due to wave-current interactions. In contrast, the bottom stresses due to the wave orbital motions in the slip were about an order of magnitude greater than stresses due to the mean current. Based on a nominal threshold of resuspension of 0.1 Pa, the measured waves would be expected to produce resuspension of sediment in the slips. The observed fluctuations in suspended sediment appear to have a similar periodicity to the wave-induced stress. This motivated a statistical analysis to determine if these fluctuations in turbidity were caused by waves.

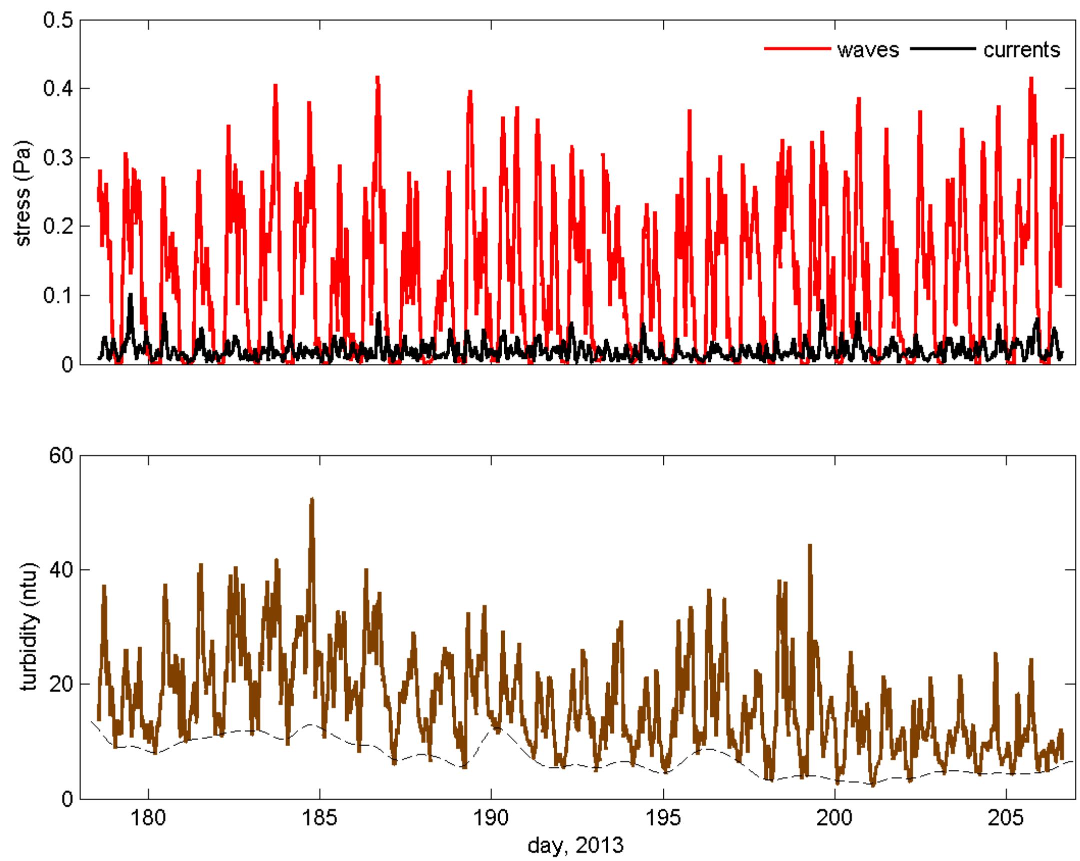

Figure 4.9. Time series at the mooring in the slip of bed stress calculated from the waves and tidal currents (top panel) and turbidity from the OBS (bottom).

To directly correlate the calculated wave stresses with the near-bottom turbidity, we divide the record into several day periods to remove some of the trends in sediment supply at longer time scale (Fig. 4.10). Based on this analysis, the correlation between wave-induced stress and resuspension is almost always significant (r^2 between 0.35 and 0.51).

Early in the record, the background levels of suspended sediment increased due to the input from the discharge event. In the period after the discharge event (e.g., days 3-6 and 6-9), the correlations between suspended sediment and wave stresses were greatest ($r^2 > 0.5$). The correlations generally decreased through the record, likely because the sediment introduced by the discharge event gradually was redistributed to lower stress environments and thus no longer available for resuspension, and tidal resuspension in the East River may have been played a greater role (cf. Fig. 4.7). The increased correlation in the middle of the record (days 15-18) came after spring tides that may have remobilized some deposits and briefly increased the supply of sediment in the slip. During the spring tides at the end of the record, the correlations were low (r^2 ~0.2) even though the wave-induced stresses were similar to the previous periods. Sediment concentrations were lower during this period than early in the record, consistent with a reduction in the local supply. Throughout the record however, it is clear that the stresses from the mean current were not correlated with the local sediment concentrations.

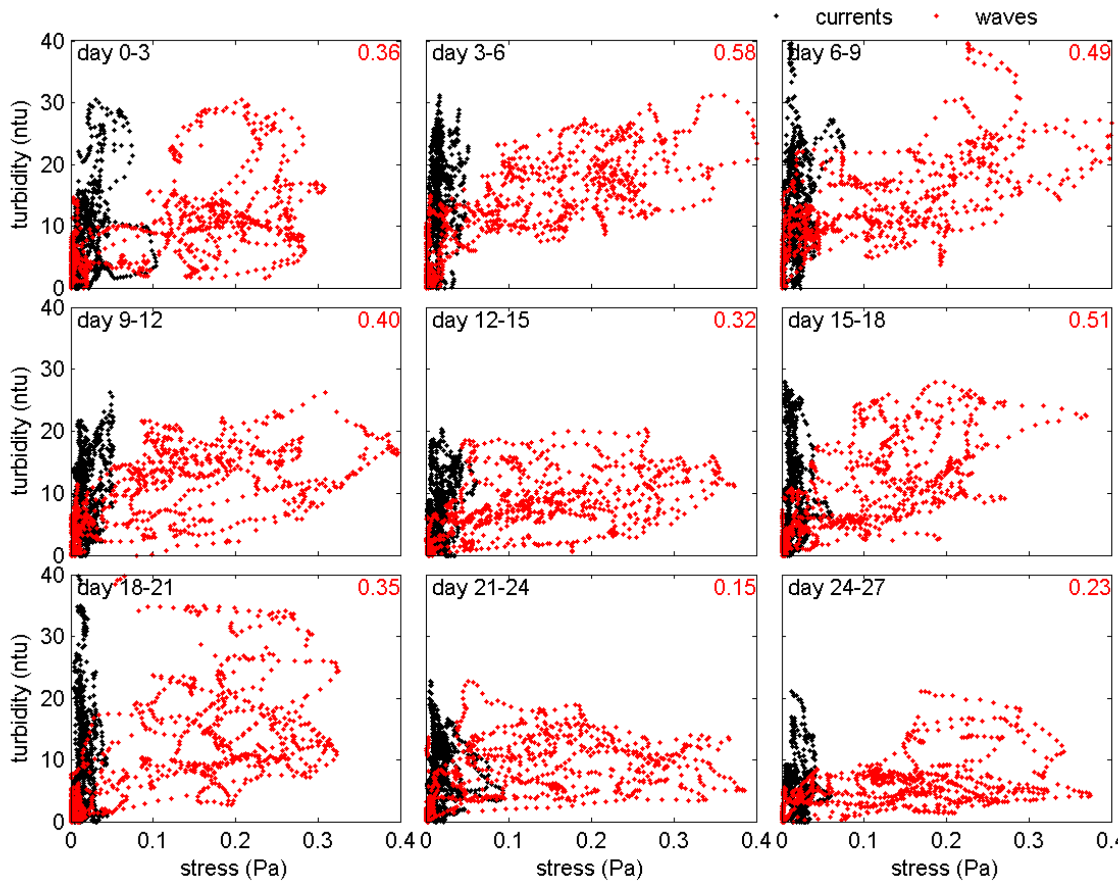

Figure 4.10. Correlation at the mooring in the slip between sediment resuspenion and bed stress due to currents and waves. Data are divided into 3 day groups to account for changes in sediment supply. Correlation coefficients (r^2) for the wave stress are shown in the upper right of each panel.

A question then arises as to the source of the wave energy in the river and the slip. One possibility is that they are locally generated wind waves, but neither wave amplitude nor direction were correlated with the local winds. Instead, it appears that wakes from vessel traffic in the Harbor is the primary source of wave energy, and in particular wakes from passenger ferries. Numerous ferries dock in lower Manhattan across from the Brooklyn Bridge Park site, and many ferry routes travel along the East River. During summer months, ferries also dock just south of the study site between slips 6 and 7. The daily cycle in wave amplitude at the moorings varies with the day of the week (Fig. 4.11). On weekdays, the maximum wave energy occurs in the morning and early evening with the rush hour commutes. On weekends, the tourist traffic begins later in the morning and is more evenly spread through the day. In both cases, wave energy is greatly reduced at night. The wakes generated by the ferries are relatively long period (~4 s) compared with locally generated wind waves, so the wave orbital velocities extend to the bottom despite the 7 m water depth at the mooring in the slip.

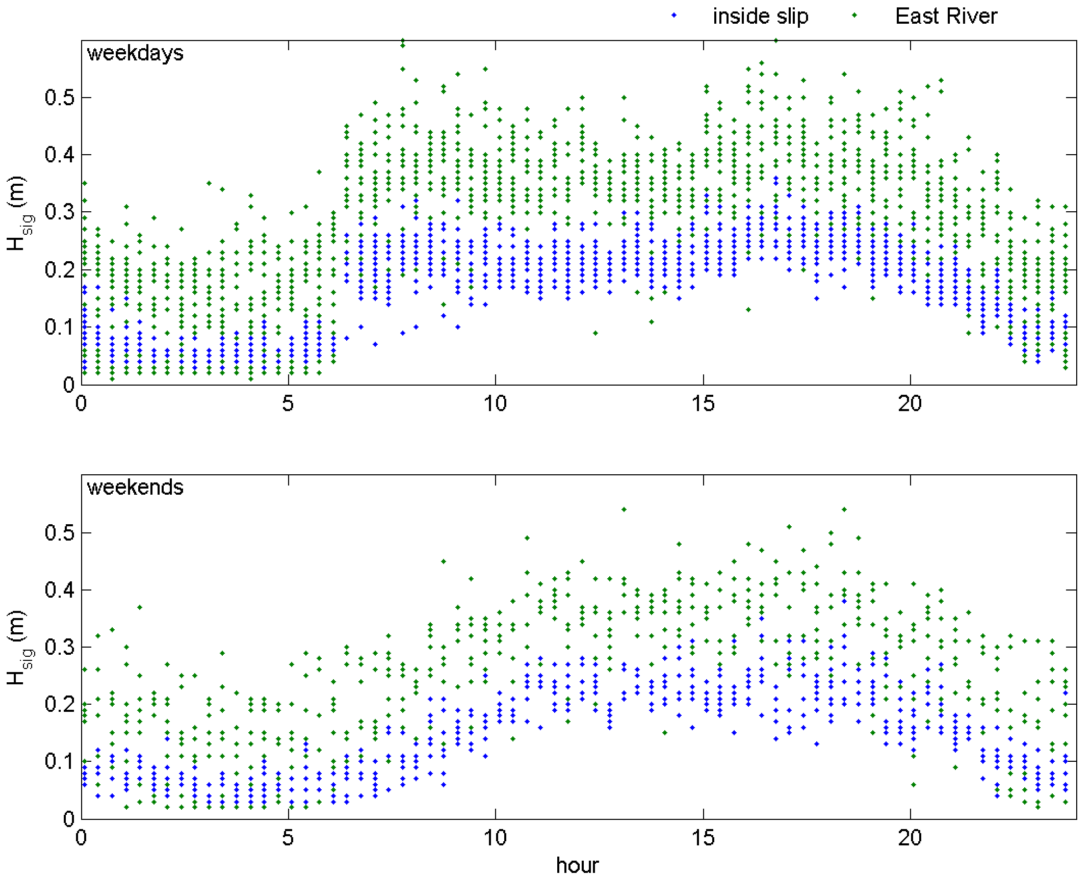

Figure 4.11. Significant wave height vs. time of day at moorings in the slip and in the East River for weekdays (top panel) and weekends (bottom).

4.3 Changes in bottom composition associated with the barge

A set of sidescan sonar surveys were conducted on July 11, 2013, just after the barge departed from the Brooklyn Bridge Park slip, having been moored there for the previous 2 weeks. The surveys indicated a change in acoustic reflection in a rectangular area exactly corresponding to the location of the barge (Fig. 4.12). The lighter color of the sidescan image indicates more acoustic reflection, which is likely associated with coarser sediment. The survey conducted on July 29, 2 weeks after departure of the barge, still showed some difference in texture at the location the barge had been, but the signal was much fainter (Fig. 4.13).

Figure 4.12. Side-scan images of the bottom sediment texture on July 11, 2013, showing a change in sediment texture at the location the barge was docked for the previous 2 weeks. The lighter color indicates rougher sediment texture, suggesting that some fraction of the fine sediment was winnowed away under the barge.

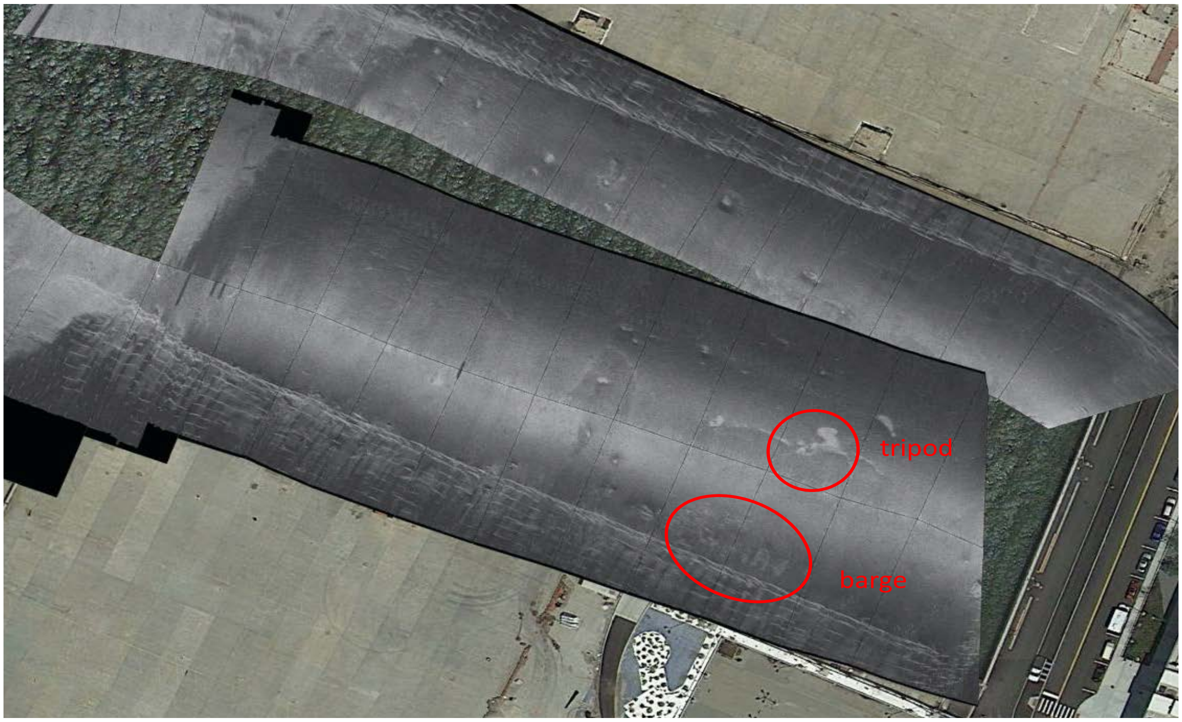

Figure 4.13. Sidescan survey on 7/29/2013, two weeks after barge departure.

Grab samples obtained on July 11, just after the barge departed, were analyzed for their coarse fraction, to determine if the grain size was any different from the ambient sediments in the slip. The analysis indicated that the sediment at the barge location was still dominated by the fine fraction, but the coarse fraction was significantly higher (twice to more than six times as high) as the ambient surficial sediments within the slip (Fig. 4.14). This increased coarse fraction provides ground truth for the side-scan observation of increased roughness at the barge location.

Both the side-scan and sediment grab samples suggest that fine sediment was winnowed from the sediment surface during the presence of the barge, implying enhanced erosion at that location. The amount of sediment that was actually removed from under the barge could not be well quantified. The change in coarse fraction would suggest an erosion of up to 3 cm, but the observed concentrations of suspended sediment in the slip suggest that changes over the two-week timeframe should be more on the order of several mm to 1 cm. In any case the erosion was not large enough to have a measurable influence on the bathymetry, and the change in surficial sediment conditions was fairly subtle.

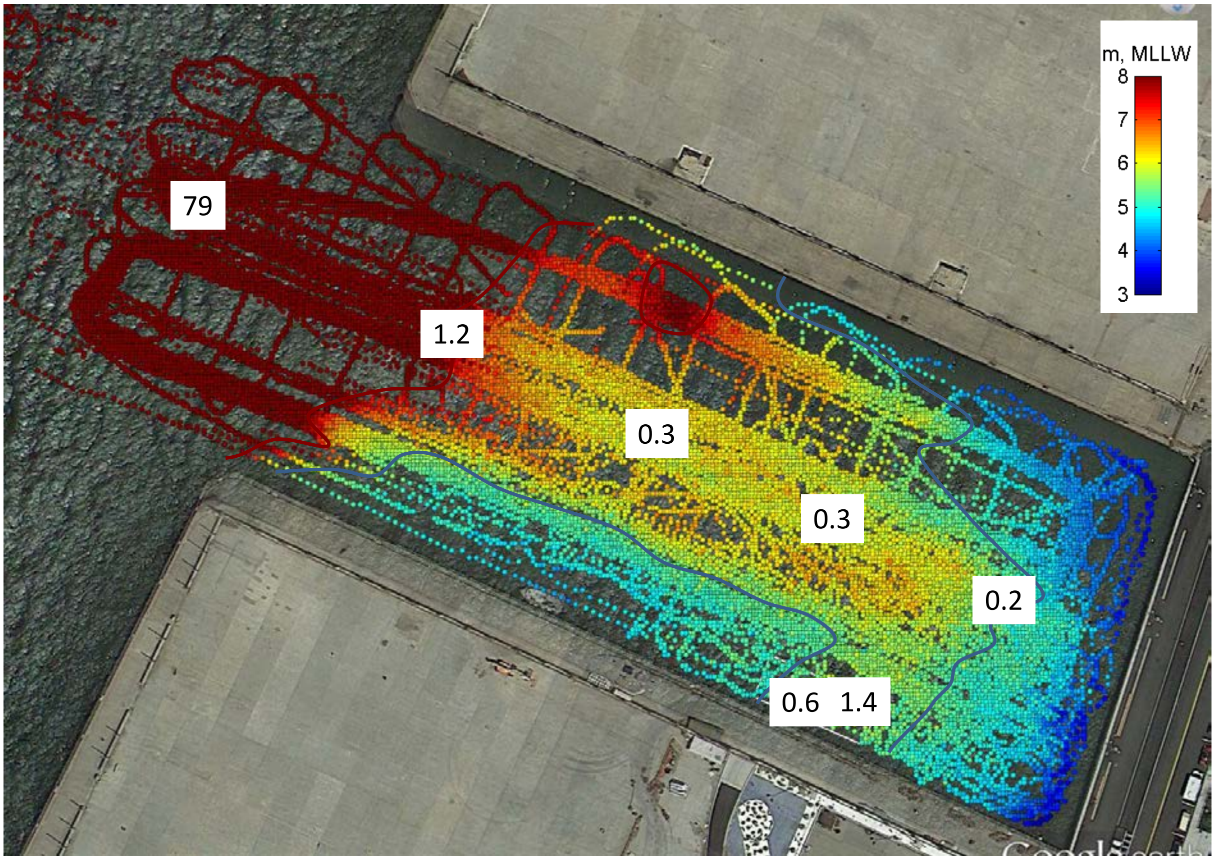

Figure 4.14. Percent coarse sediment along the axis of the slip at Brooklyn Bridge Park and also at the location the barge was moored just prior to the sampling. The coarse fraction is slightly higher at the barge location than the adjacent locations in the slip.

5. SUMMARY

5.1 Key findings

The major results of this study relate both to dominant sediment transport processes in the slips and to the effects floating structures can have on modifying the bed sediment composition.

1. The suspended sediment supply in NY Harbor depends on the river discharge and the spring-neap cycle. Discharge events deliver sediment from the lower Hudson estuary, while greater resuspension of bed sediment during spring tides leads to higher concentrations than during neaps. The ambient suspended sediment concentration affects the rate of sediment trapping at bottom salinity fronts in the Harbor, and these fronts provide the initial step in the delivery of sediment to the slips, as detailed in the next finding. The scope of these observations was too limited to identify the location of frontal trapping in the Harbor, but previous model results show a front that is generated south of Governors Island and propagates up Buttermilk Channel and the East River, which is consistent with the observations from this study.

2. Suspended sediment enters the slips as a tidally forced gravity current. Strong velocities in the East River move higher salinity and higher suspended sediment concentrations in the channel past

the slip during the flood tide. Late in the flood, the lateral density gradient generated by this differential advection relaxes and higher salinity, higher suspended sediment water propagates into the slip as a gravity current. The salinity front is a regular, tidal feature, but the sediment concentration, and consequently net transport into the slip, is modulated by the sediment supply in the Harbor, as described above.

3. Wave orbital velocities provide the dominant source of bed stress for resuspension of sediment in the slips. Tidal currents in the slip are extremely weak and associated bed stresses are less than the threshold for sediment resuspenion. Waves enhance the bottom roughness felt by the mean currents, but mean current bottom stresses remain small even with the enhanced wave roughness. In contrast, bottom stresses due to the waves are often greater than 0.2-0.3 Pa. Although the slip was relatively deep at the measurement location (>7 m), the waves were long period (4-5 s) with significant wave heights of 0.2-0.5 m, and thus had significant orbital velocities at the bed.
4. The waves that dominate sediment resuspenion in the slip are produced predominantly by vessel traffic in the Harbor, and in particular by passenger ferries. The wave energy in the East River and in the slip has a distinct daily pattern, with maximum wave energy during weekday rush hours and a more uniform wave climate that starts later in the day on weekends. The waves are uncorrelated with local wind forcing, and the relatively long wave periods (4-5 s) are consistent with 12-15 knot speeds of vessel traffic.
5. The bed sediment composition changed under the barge during the two weeks it was moored in the slip at Brooklyn Bridge Park. Sidescan sonar recorded the distinct outline of the barge as a region of stronger backscatter, consistent with scour of the surface fluff layer and a shift toward coarser grained, more acoustically reflective substrate. Grab samples also showed that the bed under the barge was coarser than at locations in other parts of the slip where the bed was almost entirely fine sediment.

5.2 Implications

Based on these observations from the Brooklyn Bridge Park and Red Hook sites, we can consider more generally the sediment dynamics of slips in the Harbor and potential effects of floating structures on hydrodynamics and sediment transport.

1. Interaction between the floating structure and waves from ferry wakes is the most likely explanation for the enhanced resuspension and removal of fine sediment from under the barge. The mean currents in the slip were extremely weak, and even with acceleration under the barge due to blockage of the near-surface region, the bottom stresses due to the mean currents were too weak to substantially alter the bottom composition. The wave stresses were an order of magnitude greater than the mean current stresses, and an enhancement of the wave orbital velocities under the barge could increase bottom stress and scour fine sediment. The theoretical mechanism for the interaction between the waves and floating structure still needs to be refined and quantified in detail.
2. Bed composition in the slips is likely near equilibrium with the forcing conditions, so slight changes in the hydrodynamics, such as introducing a barge with 1 m draft in 7 m of water depth, can induce immediate changes in the bottom composition. Over longer time scales, the bed is

likely to adjust to the perturbation and reach a new equilibrium, for example through changes in the bathymetry (getting deeper) or changes in bed composition (getting coarser). The time scale of adjustment is likely seasonal and is modulated by the sediment supply – during higher discharge periods, ambient sediment concentrations are greater and the system would adjust more quickly than during late summer, low discharge periods when sediment supply and potential remobilization is more limited. The adjustment time inferred from the sidescan surveys at Brooklyn Bridge Park was greater than 2 weeks, but the Red Hook site appeared to have reached equilibrium and had a relatively uniform bottom composition despite the permanent barge mooring site.

5.3 Future Directions

This study was limited in scope and duration, but it suggests additional lines of inquiry to build on these results.

1. The detailed interaction between floating structures and surface gravity waves depend on properties of the structure (length, draft, shape, orientation), waves (amplitude, period), and basin (depth, shape, shoreline slope). For floating ferry terminals, vessel characteristics and the docking location also may be important. Bringing in expertise in wave theory and naval architecture could provide a more complete understanding of the wave processes, perhaps by using an idealized model of a floating structure and mapping its response to wave forcing over parameter space. The results of a focused modeling exercise would then need to be placed in the environmental context of observed forcing conditions and potential effects on sediment dynamics.

2. In the slip at Brooklyn Bridge Park, sediment delivery was primarily due to lateral advection of a salinity front and sediment resuspension was driven by waves. An open question is the extent to which these processes apply at other locations in the Harbor. Previous work has shown that fronts are ubiquitous in the Hudson estuary [*Ralston et al.*, 2012], but the location of slips with respect to the frontal formation and propagation might affect the rates of sediment delivery. Ferry traffic around lower Manhattan provides ample wave energy at the Brooklyn Bridge Park site, but slips adjacent to channels with less vessel traffic may have less wave-driven resuspension and consequently greater shoaling. The relevant scales to address this problem, from fronts and slips (10s of m) to trapping in the Harbor (~10 km), are becoming tractable to resolve with realistic circulation and transport models. Realistic models in conjunction with targeted observations could provide the tools to evaluate more generally the processes governing sediment dynamics in the Harbor.

3. The barge used in the observations for this study was modest in size, with a draft and length that were small fractions of the water depth and basin length. The observations suggest the immediate effect of a new mooring location was to induce scour of fine sediment under barge. Alternatively, the *U.S.S. Intrepid* at Pier 86 on the Hudson River provides an example of a floating structure that led to enhanced deposition of fine sediment in the slip. These different responses may be due to the sizes of the floating structures relative to their slips, but also may depend on differences in sediment delivery and removal processes between the two sites. The parallel approaches identified in the previous two bullets could help resolve the discrepancy and provide more general basis for predicting the response of sediment transport processes to floating structures.

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THE PORT AUTHORITY
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PROJECT SUMMARY REPORT
Floating Structures Pilot Project
July 2015

APPENDIX 3

RESPONSE TO COMMENTS & GLOSSARY

PROJECT SUMMARY REPORT
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APPENDIX 3 -
RESPONSE TO COMMENTS & GLOSSARY

Response to Comments on Pilot Project

Larger Context and Harbor Restoration

Comment: Woods Hole Oceanographic Institution's introduction mentions that the study of sediments in New York (NY) Harbor was previously concerned primarily with maintaining berthing for ships and reducing dredging costs, but now we are thinking more about a healthy ecosystem and what form that will take. Please provide some context for this based on the Port Authority of New York & New Jersey's (PANYNJ) Hudson-Raritan Estuary Comprehensive Restoration Plan (*CRP) and how its target ecosystems (TECs) tie in with this study.*

Response: The management of dredged material and the increased dredged material management costs for handling contaminated dredged materials are ongoing policy concerns for the PANYNJ, the US Army Corps of Engineers and other entities charged with maintaining the navigation channels and berthing areas of NY Harbor. The Hudson-Raritan Estuary CRP includes several restoration targets and objectives (TECs) tied to addressing related ecosystem level problems including bathymetric alterations, shoreline modifications and sediment quality problems. The CRP provides the framework for advancing a shared vision for a restored NY/NJ Harbor Estuary and the establishment of a mosaic of new and restored habitats.

Overlap/Synthesis of Studies

Comment: The two research studies seem to overlap in the sense that the hydrodynamics and sediments affect the habitat for fish. Is there a way to communicate the overlap, maybe around the TEC for shorelines and shallows in terms of encouraging intertidal zones with stable slopes and illuminated shallow water?

Response: The research studies conducted here provide new information about sediment movement in shallow estuarine waters and the use of nearshore habitats by fish under floating structures and adjacent to piers and hard riprap shorelines. The studies provide new insights into the significance of the transition zones and their importance in terms of cover and refuge. This information will help advance the Shorelines and Shallows TEC and the Habitat for Fish Crabs and Lobster TEC which focus on enhancing the connections between different habitat types and the spatial arrangements between specific habitats.

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Response to Comments (Continued)

Response to Comments on Fish Utilization Study

Context

Comment: More context about existing research on shoreline modifications and especially shallow, nearshore habitats would be helpful. Please make the connections between the importance of healthy fish populations in the estuary as a whole and why this study was done nearshore. At what times of year is shallow water a "nursery" and did that coincide with the study?

Response: The fact that shorelines serve as important habitat has been empirically determined. The reasons are most likely multivariate and the mechanisms are not yet clear, which is one of the reasons that this study was necessary. However, several important ideas are being validated through continued research. These are the concepts of 1) shoreside subsidies to the marine environment, 2) refuge from predation, and 3) high productivity due to light penetration. Shoreside subsidy is the provisioning of important components through connection with a different habitat. For example, plant wrack that accumulates on beaches is an important breeding site for insects, the larvae of which are food for small juvenile fishes. Creeks that penetrate an unarmored shoreline lead to marsh pool habitat that is well oxygenated and for some shore fishes provides intermittent drying that prevents fungal infection and a refuge from predatory fish, likewise, small fish may take refuge from larger fish in water that is too shallow for the larger fish. This may work only on gently sloping shorelines, and shorelines that have submerged or emergent aquatic vegetation with stems that provide structural refuge. Light penetration is important for two reasons. It fuels primary production (photosynthesis) which is the base of the food web and is especially important for smaller fish closer to the food web base, and it allows many species of fish to forage because that is how they locate their food. While estuaries are highly productive because of a large nutrient load that comes with the sediment they transport from upriver, that same sediment or algal blooms caused by it may block light penetration and cause nutrients to remain unused until they are out to sea. Thus, the shallow parts of estuaries are unique because that is where light penetration and nutrients coincide for enhanced productivity.

Fish of different species spawn all year and have thus divided the estuarine nursery as a time share. However, little growth happens in winter because of the physiological limitation of temperature on life's chemistry. Thus, those larvae that overwinter in the estuary still have their growing season in spring and summer and even into early fall. This is the time of highest potential growth or mortality and the highest abundance of fish in the size category that comprises this important class. We did sample during this period.

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Response to Comments on Fish Utilization Study (Continued)

Pelagic Fish

Comment: Why did earlier research focus on juvenile benthic fish while this study only collected data on large and small pelagic fish? Are some of the smaller solitary fish actually juvenile versions of large ones? Do you anticipate any effects of floating structures on benthic fish, such as increased oxidation under them?

Response: Earlier studies focused on juvenile benthic fish because the technology to study juvenile pelagic fish did not yet exist. That technology was developed principally out of response to needs for underwater surveillance after the 9/11 terror attacks.

By species, many of the smaller fish are in fact juvenile stages of larger fishes. However, they do not last long as small individuals because they suffer extremely high mortality and because they quickly grow out of the small size range. Further, the two dominant species of pelagic fishes, bay anchovy and Atlantic silverside, remain small and are mostly annual, reaching sexual maturity in their first year. It is also important to note that the small stage is this stage at which mortality or survival determines recruitment and the size most dependent on shallow water habitat, and therefore it is the size class that warrants particular attention.

We do anticipate that floating structures will have important effects on juvenile benthic fishes, but these should be similar effects shown for piers, for which our past studies demonstrated an inability to feed and grow in shade. There is no anticipated difference in oxidation above the sediment under a floating structure. We suspect that this is a misunderstanding related to the reported signature of newly deposited vs scoured sediments in the accompanying report. Oxygen is consumed by microbes and chemical processes in mud and newly disturbed mud is thus identified.

Study Sites

Comment: Add more information about the draft and orientation of the barge, water depths at the barge mooring sites, and why these sites were chosen. How do they compare to NY Harbor in general? Also, relate the study locations to typical ferry docking locations. For example, would deeper water with higher velocity of currents mean less fish but more eddy fields?

Response: Our study was focused on the Lehigh barge because of its availability. We cannot comment definitively on the distribution of other barges as typical or atypical, except to note that we have seen barges deployed in similar settings but also in very different, highly turbulent and deeper water settings (e.g. Wall Street Ferry Terminal) and also in very calm, very shallow settings (e.g. Liberty Golf Course) where they may even rest on the bottom during low tide.

Pelagic fish are known to use eddy fields to maintain position while feeding on food

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swept downstream, but we cannot comment on whether that is the case here. The use of such fields may be governed by such other factors as the proximity to other resources or refuges or to the level of turbulence.

Edge Effect

Comment: Describe the difference between the findings here versus at Pier 40. Could the size of the floating structure involved make it viewed as all "edge?" Does the ratio of shaded edges to deeply shaded water make a difference?

Response: It is very likely that the ratio of shaded to deeply shaded water makes a difference in its importance as a resource or something to be avoided. For single fish, light availability under narrow structures may be such that the whole structure approximates edge. We also have evidence from earlier studies at different piers that the determination of what is "edge" may be scaled to school size for schooling fishes. Schooling pelagic fish may place priority on the proximity of schoolmates, and when shaded area is small relative to the size of a school, there is less avoidance. This is an idea arising from observation and has not yet been tested.

Shading Sources

Comment: Along with manmade piers which shade water, what is the effect of tall waterfront buildings casting shadows that shade the water? The reason this is important is that passenger ferries are often sited to support new waterfront developments, such as the highrises in Williamsburg, Brooklyn.

Response: At Pier 40 we sampled pelagic fishes in open water on the north (shaded) and south (unshaded) edges and found no significant difference. However, there are also water flow differences between the north and south sides, which we decoupled to the extent possible by sampling on flowing and ebbing tides. However, this divides the variance among smaller subsamples and lowers the potential for the test to reveal significant differences. If a difference does exist, it is likely to be weak. Note that shading may be cumulative - weak shade may not be sufficient to hinder fish use of very shallow habitat, but it effectively deepens shallow water where this is defined on the basis of light penetration to the bottom.

Recommendations for Further Study

Comment: This section seems somewhat minimal given discussion at the seminars and interest in this research. Would you also recommend adding another year's data? How about sampling between the barge and adjacent pier, or testing different distances of the barge from the shoreline to see if that allows more sheltered habitat? Do you think research on growth-related habitats would help in making decisions about where and when to allow floating structures in shallow, nearshore environments?

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Response: Additional sampling is recommended especially where access is allowed so that balanced designs can apply rigorous statistical tools. This would especially include barges of different sizes in the same or similar mooring settings, as well as barges of the same size in different mooring settings. These include high traffic settings and entail preparation and collaboration with users to ensure safe and statistically robust sampling.

Response to Comments on Hydrodynamics and Sediment Transport Study

Ferry Waves

Comment: Isn't a major finding here that ferry waves resuspend sediments in slips adjacent to their routes, depending on wave orbits and water depths, with or without the involvement of floating structures? If we are trying to make informed decisions about where to position ferry routes and docks, we need to understand whether or not suspending near-shore sediments is helpful or harmful.

Response: Yes, the role of ferry wakes for sediment resuspension is one of the main results of this study, and an important consideration moving forward. A question remains as to how important the wakes are in regions that are less heavily trafficked than this busy part of the East River.

Dredging

Comment: Add some background about how the study sites are positioned relative to any dredged channels. When discharged sediment moves into the Harbor in its "main channels," how do those correlate with dredged shipping channels? Does spring dredging combine with Hudson discharges to increase suspended sediment?

Response: Nearby channels in the Harbor are dredged, but the basic processes of trapping of sediment at density fronts followed by tidal movement of the fronts and suspended sediment up the channels and into the slips also occurs in natural estuarine channels. Fronts form in the deeper channels and thus sediment is trapped there. The seasonal variation in sediment supply depends more on the increase in river discharge during the spring with snowmelt and precipitation than the dredging schedule.

Bathymetry of Slip

Comment: Is the difference in depths between the channel and slip due entirely to accumulation of sediments or has there been a "shelf" here historically? Isn't there scouring near the Buttermilk Channel due to previous landfills which narrowed the distance between Brooklyn and Governors Island for circulation?

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Response to Comments on Hydrodynamics Study (Continued)

Response: We did not investigate the historical bathymetry of the region, but it is quite likely that it has been substantially altered by the infilling and dredging over the past 150 years or more.

Tides from Long Island Sound

Comment: Do the indirect tidal movements from the Long Island Sound, which are offset from those in the Harbor, affect this part of the Upper Bay, which is at the base of the East River?

Response: The tidal phasing between western Long Island Sound and NY Harbor drive the strong tidal currents in the East River, which is the channel at the edge of the slip.

Upper/Lower Estuary

Comment: The Executive Summary talks about a discharge event from lower Hudson estuary, but later text mentions Green Island, which is north of Albany in the upper estuary.

Response: Green Island is at the tidal limit of the Hudson River, and as such is the location of the USGS gauge measuring the flow in the Hudson. Suspended sediment supply from the river that then moves down into the Harbor increases with river discharge, making the flow at Green Island an important factor to understand the variability in suspended sediment in the Harbor. The suspended sediment that enters the Harbor comes most recently from the lower Hudson estuary, as there is a time lag between the input at the tidal limit (Green Island) and the delivery to the Harbor that may be months or years.

Pollution

Comment: Given that finer-grained sediments are concentrating in the slips and contaminants tend to adhere to those sediments, do any of these findings have implications for water quality?

Response: The fine grained sediments are more likely to associate with contaminants, but it is likely that subsurface contaminant concentrations, representative of sediment that was deposited decades ago, is more contaminated than surficial sediment. Certainly any major perturbation to the bed that erodes down into more contaminated sediments would need to be assessed for potential contaminant remobilization.

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Response to Comments on Hydrodynamics Study (Continued)

Salt vs. Sediment

Comment: It's not clear how the density of salt water coming in on the tides compares with the freshwater carrying sediments coming down the Hudson. Does the fresh water always flow at the surface over the salt water, or are there times in the year when the sediments it is carrying are heavier and coarser enough to outweigh the tides? When does the sediment start sinking to the bottom? Also, the overall "salt front," which happens usually north of New York City, should be distinguished from the local salinity fronts mentioned in the study.

Response: The sediment concentrations in the Hudson and in the Harbor are generally too low to significantly alter the density of the suspension. Instead, salinity is the dominant source of density differences, both vertically as stratification and horizontally as fronts. Salinity fronts can form at intermediate salinity differences (e.g., between water masses with salinities of 25 and 30 psu) in addition to the interface between fresh and salt at the landward limit of the salinity intrusion in the Hudson. In either case, the horizontal density gradients drive a two layer circulation, with the saltier water moving landward near the bed and the fresher water moving seaward near the surface. Suspended sediment is remobilized from the bed and mixed vertically by turbulence, but this vertical mixing is countered by settling of the sediment grains (heavier than water) back toward the bed. Vertical mixing of sediment is reduced when the water column is salinity stratified, as turbulent energy is lost through the mixing of heavier and lighter water, so the vertical distribution of sediment depends on the salinity profile.

GLOSSARY

Advection - transport by water velocities (e.g., of sediment, salt, momentum)

Backscatter - acoustic or optical signal reflected back to the instrument, used as a measure of suspended sediment concentration

Gravity current - exchange flow due to a horizontal density gradient with heavier (saltier) water moving underneath lighter (fresher)

Discharge event - increased river discharge associated with precipitation or snowmelt

Flood/Ebb - tidal phases, with flood for landward flow and ebb for seaward

Isopycnals - contours of constant water density

Neap - phase of the fortnightly variation in tidal amplitude with weaker tides (in contrast w/ spring tides)

Salinity front - sharp horizontal gradient in salinity

Sediment - sand, silt and clay

Scour - erosion

Shoaling - deposition

Tidal forcing/wind forcing - external forcing that drives coastal and estuarine flows

Tidal range - difference in elevation between high and low tidal water levels

Turbidity - measure of water clarity, which can be measured with optical backscatter and correlated with suspended sediment concentration

Wave orbit - velocities associated with waves (as opposed to lower frequency currents due to tides)