2020 POST-CONSTRUCTION OYSTER MONITORING FINAL REPORT

The Governor Mario M. Cuomo/New NY Bridge Project at Tappan Zee
Oyster Substrate and Water Quality Monitoring

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TABLE OF CONTENTS

INTRODUCTION

The mitigation requirement (New York State Department of Environmental Conservation (DEC) Permit ID 3-9903-00043/00012) to establish shell/hard bottom oyster habitat in the Hudson River was implemented during the summer of 2018. Eight hundred and eighty one reef balls and 422 gabions were deployed over an area of approximately six acres at three locations in the vicinity of the Governor Mario M. Cuomo Bridge. As part of the substrate placement phase of the project, water quality monitoring was conducted between June and November 2018 to characterize environmental conditions during the first oyster spat settlement event. A post-construction monitoring effort was also developed to help determine the effectiveness of the oyster habitat restoration program and consisted of two major components, namely: monitoring oyster settling, survival, and growth on artificial substrates at the three locations, and monitoring water quality at those locations. The oyster habitat restoration post-construction monitoring plan which outlined the methodology to be employed for the two year post-construction monitoring program (2019 and 2020) was prepared on June 19, 2017, amended on March 25, 2019, and was approved by DEC. The substrate and water quality monitoring program represents the final elements of the oyster habitat restoration effort that falls under the responsibility of the New York State Thruway Authority (The Authority).

This consolidated report discusses both the substrate and water quality elements of the post-construction monitoring program. It begins with a summary of the project history providing context for understanding the mitigation approach and its execution. It is followed by:

- **Attachment A**, the substrate monitoring report, which focused on obtaining density and size distribution data from oysters collected in fall 2019 and 2020 from the gabions and reef balls, and represents three years of spat settling (2018, 2019 and 2020). Attachment A was prepared through a collaboration of the Hudson River Foundation, the Billion Oyster Project, and the University of New Hampshire.
- **Attachment B**, the water quality monitoring report, which presents water quality data collected from April-November, 2020, and was prepared by AKRF, Inc.
- **Appendices A-C**, figures depicting salinity, dissolved oxygen, and temperature measurements from collections made by AKRF, Inc. in 2020.
- **Appendix D**, the final report for the Tier 3 oyster restoration pilot study (2015-2017). Appendix D was prepared by the Hudson River Foundation in partnership with the University of New Hampshire and the New York Harbor Foundation.
- **Appendix E**, the amended March 25, 2019 post-construction monitoring plan prepared by AKRF, Inc.

PROJECT HISTORY

Due to the location of the Tappan Zee Bridge near the northern limit of oysters in the Hudson River, successful oyster restoration in this area depended on the careful selection of restoration sites and substrates, and the consideration of habitat parameters that can affect oyster settlement, survival, and growth. To maximize the likelihood of creating successful, self-sustaining oyster habitat as mitigation for project impacts, an Oyster Work Group (OWG) was formed in 2013, consisting of: researchers conducting oyster studies in the Hudson River and New York metropolitan area; scientists and regulators from the New York State Department of Environmental Conservation (NYSDEC), National Marine Fisheries Service (NMFS), New York State Thruway Authority (the Authority), and their consultants; and stakeholders such as Scenic Hudson and Riverkeeper. The OWG agreed to conduct a series of studies on oyster settlement, water quality, and substrate effectiveness that would help guide the restoration effort that was required by NYSDEC Permit # 3-9903-00043/00012, Mitigation Conditions Ai-iv. The intent of this approach was to allow the Authority and NYSDEC to make more informed, science-based decisions on the most promising prescriptions and locations for oyster restoration in this region of the Hudson River. A four-tiered study plan was eventually developed by the OWG. The paragraphs below summarize the initial efforts to relocate oysters from the project's dredge zone and other steps leading up to the four-tiered study plan, and then presents highlights of the research and restoration efforts that were implemented.

RECONNAISSANCE GRAB-SAMPLING AND OYSTER RELOCATION

The dredge footprint for the project spanned eight acres of river bottom that contained live oysters in two discrete areas just north of the existing bridge, and east of the navigation channel along the Westchester shore. The dredging that was required for the construction of the new bridge could have resulted in the loss of these live oysters.

The Authority, in collaboration with the NYSDEC and the OWG developed an oyster relocation study, prior to the initiation of dredging in August 2013. The objective of the study was to identify a relocation area that would likely support survival and growth of live oysters transferred from the dredge footprint. The Authority, with consensus from the OWG, engaged the services of a contractor who collected 30 oyster and sediment samples from the potential oyster relocation area in late June 2013. Results indicated that while the sediment quality was generally good for supporting oysters, oyster densities in the proposed placement area were extremely low at about 6 oysters m^{-2}. A second study was then conducted in mid-July, 2013 that focused on an alternative placement area located about 3,000 feet south of the Tappan Zee Bridge just east of the channel ("the Glove", later designated as Site 0). Thirty samples were also taken at this this site and results indicated an average density of about 29 oysters m^{-2}, over the entire site, with densities exceeding 50 oysters m^{-2}. at the deeper western portion of the Glove.

Between July 23 and 29, 2013, Tappan Zee Constructors (TZC) harvested the two areas within the dredge footprint that contained live oysters and relocated them to the western portion of "the Glove" site. Sixty six tows were made with a shellfish dredge over the sampling period. TZC estimated that approximately 13,000-16,000 oysters, of which 3,000-4,000 were living, were relocated as part of this effort.

LITERATURE REVIEW

A white paper was prepared on the relative effectiveness of natural shell versus alternative materials (e.g., concrete reef balls) for eastern oyster restoration, including costs and logistical benefits or constraints associated with these various restoration substrates. The white paper, also synthesized studies of other abiotic characteristics besides substrate type that influence oyster restoration success, and then summarized the methods and outcomes of several oyster restoration projects that had been undertaken in recent years throughout New York Harbor and the Hudson River. It was concluded that there are many uncertainties about what restoration methods would be most appropriate for and likely to succeed in the Tappan Zee region of the Hudson River, where habitat suitability for oysters is already marginal due to low salinity levels and predicted increases in the frequency and magnitude of freshets as a result of global climate change. The OWG recommended that the restoration effort to mitigate effects of the project begin with a series of studies that would help determine the most appropriate locations and substrate types for the restoration effort.

GENETIC DISTINCTIVENESS AND SALINITY TOLERANCE OF TAPPAN ZEE OYSTERS

To address questions about the larval connectivity and gene flow between Tappan Zee populations of oyster and other possible Hudson and East River stocks, Cornell University (Matt Hare Lab) was contracted to analyze population structure based on genomic analyses of DNA variants that provide tracers of demographic history. Samples were collected from Philipse Manor and "the Glove" site. These oysters were compared with oysters from Prall's Island off of Staten Island and from multiple sites in the East River. All Hudson River oysters between Philipse Manor and Staten Island were genetically homogeneous, but showed subtle genetic differentiation relative to East River oysters. Given that the data demonstrated regular recruitment (settlement of wild oysters) in the Tappan Zee area, it was concluded that hatchery-reared oysters should not be used to "seed" the substrates used in the restoration effort. Instead, emphasis should be on improving or adding to habitat so that more of the natural larval production has an opportunity to settle, grow and reproduce, thereby increasing the population that appears to be well adapted to this low salinity environment.

FOUR-TIERED RESTORATION STUDY PLAN

Following the recommendation of the literature review and discussions with the OWG and NYSDEC, it was decided that a series of studies of oyster settlement, water quality, and substrate effectiveness would be conducted prior to restoring any acreage of hard bottom habitat. A four-tiered study plan was developed with considerable input from the OWG, and initiated in the spring of 2015.

The plan included the following tiers:

Tier 1: Selection of Candidate Sites

Tier 2: Benthic Sampling to Characterize Oyster Density and Size, and Refinement of Candidate Sites

Tier 3: Substrate Effectiveness, Spat Collectors, and Water Quality

Tier 4: Hard Bottom Restoration and Monitoring

TIER 1: SELECTION OF CANDIDATE SITES

The Tier 1 site selection process involved the mapping of existing oyster reef habitat and the characterization of environmental conditions relevant to oyster persistence in the Tappan Zee area. GIS analysis of side-scan imagery of the river bottom taken in 2000 and 2014 was used to identify sites where oyster reefs appear to have grown or remained stable over this 14-year time period. Growth or stability in size was taken to indicate that: (1) the environmental conditions in these sites (e.g., salinity, dissolved oxygen, current velocity, wave energy, food availability) are suitable for oysters, (2) the addition of suitable hard substrate may facilitate the expansion of existing reefs more quickly than they would otherwise, and (3) a source population is present that may provide oyster larvae to help sustain the restored sites.

After reviewing the side-scan imagery, and also taking into consideration salinity, depth, sediment type, sediment environment, and the locations and results of previous benthic grab sampling in recent years, the OWG agreed to nine candidate sites in which to collect grab samples in the spring of 2015. Seven of these nine areas were south of the bridge while the two other sites were north of the bridge, to the east of the navigation channel.

TIER 2: BENTHIC SAMPLING TO CHARACTERIZE OYSTER DENSITY AND SIZE, AND REFINEMENT OF SITE SELECTION

Grab samples were collected during the spring of 2015 at the nine sites selected in Tier 1. The survey involved a first-round of sampling in which 10 grab samples were collected from randomly selected points within each of the nine sites. The sites were then ranked according to oyster density, and the five sites with the highest densities were selected for a second round of sampling in which 15 additional grab samples were collected per site. After collecting 25 total samples from each of these sites, two sites were ruled out from further investigation, and the other three sites were selected for inclusion in the Tier 3 studies described below. These three were Sites 8, 1 and 5 which had the highest rankings (i.e., densities of oysters) in both sampling rounds. All three sites had an average depth of at least 12 feet, which reduced their exposure to extended periods of low salinity and increased the likelihood of oyster survival.

TIER 3: SUBSTRATE EFFECTIVENESS, SPAT COLLECTORS, AND WATER QUALITY

Substrate Study

A study was designed to compare oyster density, growth, and survival between a natural (oyster shell) and artificial (concrete) substrate type (See Appendix D for study details). The study included three treatments: 1) metal gabion cages containing natural oyster shell, 2) small concrete reef balls (“Lo-pro” style), and 3) larger concrete reef balls (“Mini-bay Ball” style). Sampling for oyster density and growth on these substrates was conducted in the fall of 2015, 2016 and 2017 by a team led by the Hudson River Foundation and included scientists from the Billion Oyster Project and the University of New Hampshire. During the sampling events, oysters were counted and measured from randomly selected quadrats on the reef balls and gabions.

While all sites showed evidence of successful oyster settling and growth, results at Site 8 suggested that it has the greatest potential for consistent recruitment (See Appendix D). There were higher densities of oysters on the gabion blocks than on the small and large reef balls, although the comparisons of gabions to reef balls may have been somewhat confounded by the three dimensional nature of the gabion surface and two dimensional nature of the reef ball surface. Overall, it was concluded from the study that oyster recruitment and growth are comparable between gabions and reef balls, and both are suitable substrates for consideration for oyster restoration in the Tappan Zee region of the Hudson River. It was also concluded that good oyster growth can be expected at all three sites, but the highest probability for good recruitment is at Site 8.

Spat Collector and Water Quality Study

Concomitant with the study of the effectiveness of oyster shell gabions and reef balls, probes and spat collectors were deployed at Sites 1, 5, and 8 as well as Site 0 (i.e., “the Glove”) to record dissolved oxygen (DO) and salinity, and investigate the timing and magnitude of spat-fall in 2015 and 2016. Site-specific salinity and DO data were collected to provide context in which to interpret the findings of the substrate study, and the spat collectors were deployed to compare larval availability among sites while also providing information on the timing of wild oyster spat-fall in this section of the river. DEC requested the continuation of the water quality monitoring at the sites into October 2017, concurrent with the duration of the substrate study. Sondes were deployed in April 2017 and retrieved in October 2017 and data from the sondes were downloaded monthly during the seven month period.

In 2015 and 2016, oysters were observed on the spat collectors for the first time during the September monitoring event. Oysters were found in September on spat collectors at all study sites. Based on their size, they were estimated to have set approximately 1 month prior, shortly after the August monitoring events.

TIER 4: HARD BOTTOM RESTORATION AND MONITORING

Site Selection

Findings from the spat collector and substrate studies indicated that Site 8 has suitable conditions and larval availability to support an oyster reef if hard substrate were provided. However, by being farthest north and near the limit of the salinity gradient in the Hudson River, Site 8 is most vulnerable to frequent and prolonged periods of low salinity which are projected to increase in the coming decades as a result of global climate change. In the Tier 3 water quality study, Site 8 was found to have the lowest mean salinity levels among the four study sites, and was also found to experience long periods of low bottom dissolved oxygen levels that could potentially reduce survival of larval oysters. While the substrate study indicated good oyster survival at Site 8, concerns were raised as to whether oysters of reproductive size would survive longer term there.

For these reasons, the OWG and the Authority recommended including more southern sites, Site1 and to a lesser extent, Site 0 (“the Glove), as additional areas for restoration in Tier 4. Although Site 0 was not included in the substrate study, this area is known to currently contain a naturally sustaining oyster reef that may only be constrained in size by the availability of hard substrate beyond its current boundaries. The reconnaissance grab sampling that was conducted in the vicinity of the bridge found oyster density around Site 0 to be the highest of any area explored. Adding hard substrate beyond the extent of the existing reef at Site 0 might allow it to expand in size and increase the population of oysters in this region of the river. Because it is well south of Site 8 and is deeper than any of the other study sites, Site 0 would also be likely to maintain the highest salinity levels of any site in the face of climate change. The extent of the restoration at Site 0 was relatively small due to concerns that too much alteration of the area could have unintended negative consequences for the existing reef, which is believed to be thriving. As such, restoration at Site 0 was limited in size, while Sites 1 and 8 had much more acreage of hard substrate added to them. Site 1 was selected as field studies ranked it second in oyster densities (exceeded only by Site 8), and reported several relatively large oysters (at least 3 years old, based on size) occurring there. Additionally, the Tier 3 studies showed there is natural recruitment and growth of oysters in this area, and salinity levels appear to be sufficient to sustain the population.

Substrate selection

Overall, it was concluded from the study that oyster recruitment and growth are comparable between gabions and reef balls, and both are suitable substrates for oyster restoration in the Tappan Zee region of the Hudson River. As such, it was recommended that a mix of gabion blocks and reef balls be used in the Tier 4 restoration effort. Gabion cages may be slightly superior to reef balls as a substrate for oyster attachment, while reef balls may be more likely to attract and provide habitat to support recreationally and commercially important fish species as well as other secondary benefiters. The larger (Mini-bay) reef balls were recommended over the smaller (Lo-pro) reef balls because they would be expected to have greater durability and ability to remain in place in the dynamic conditions of the river.

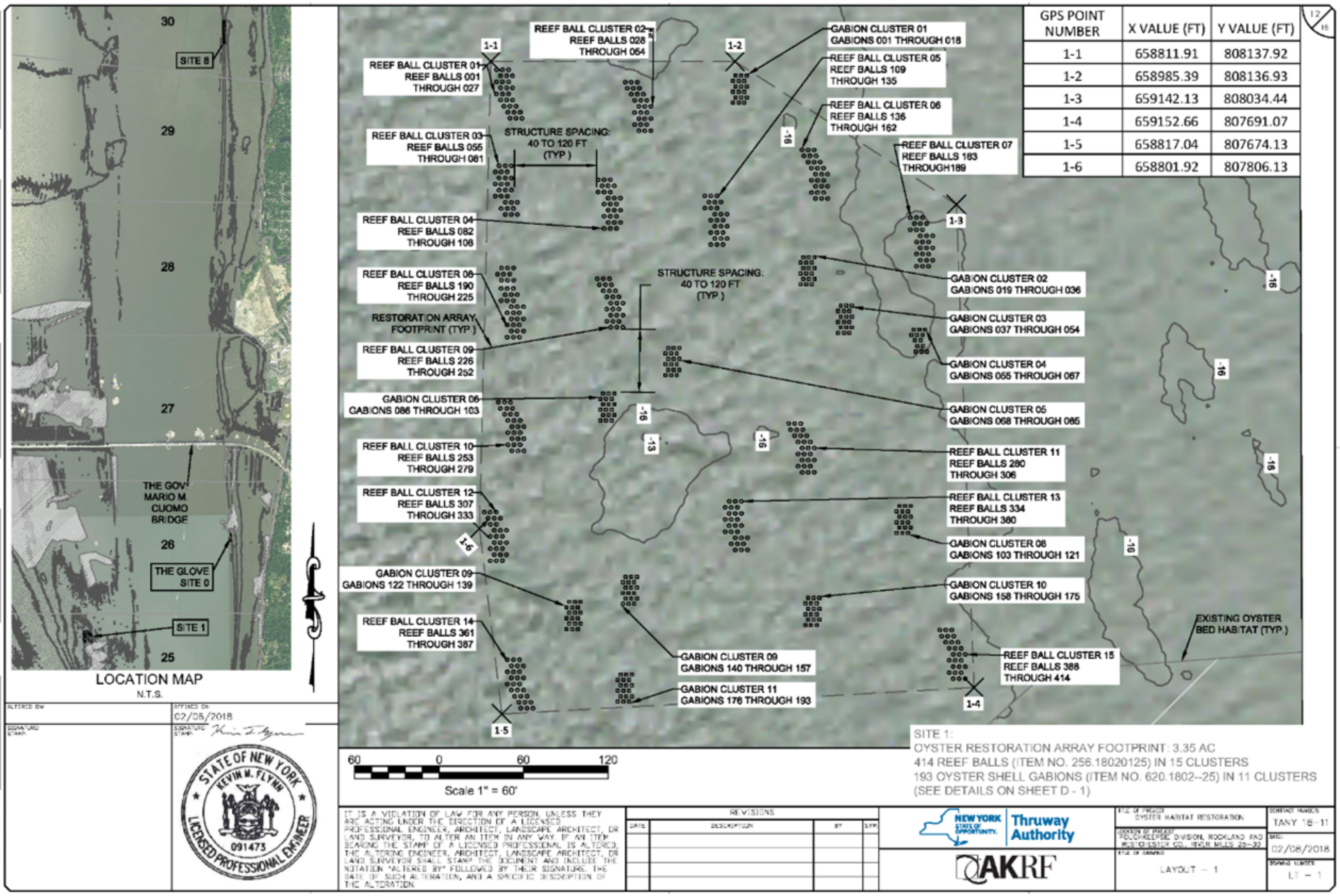
Construction Activities

A contractor, The Arben Group, was retained for implementing the substrate deployment for the restoration effort, which took place in the summer of 2018. The substrates proposed for the oyster restoration were manufactured off-site and delivered ready for deployment. The Billion Oyster Project (BOP) was retained to construct 422 metal gabion cages containing shell material. The metal gabion cages containing natural oyster shell and the reef balls were placed in the selected locations in Sites 0, 1, and 8. Site 1 contained 414 concrete Mini Bay Reef Balls and 193 oyster-shell gabion cages distributed over 3.35 acres of river bottom. Deployment at Site 8 consisted of 413 concrete Mini Bay Reef Balls and 193 oyster-shell gabion cages distributed over 2.57 acres of river bottom. At Site 0 (i.e., the Glove), 54 Reef Balls and 36 gabion cages were distributed over a smaller area (0.07 acres).

Shortly after substrate deployment a contractor, Prudent Engineering, was retained to verify that the location, number, and type of substrates (i.e., reef ball and gabion) were deployed as intended. This was accomplished using multi-beam sonar which ensured that the substrates were located at the proper coordinates and also provided visual images of each of the gabions and reef balls.

The sampling duration, methods, and further details of the post-construction substrate and water quality monitoring plan is provided in Appendix E.

The locations and spatial arrangements of the deployed substrates at the three sites are depicted in the layout sheets below.



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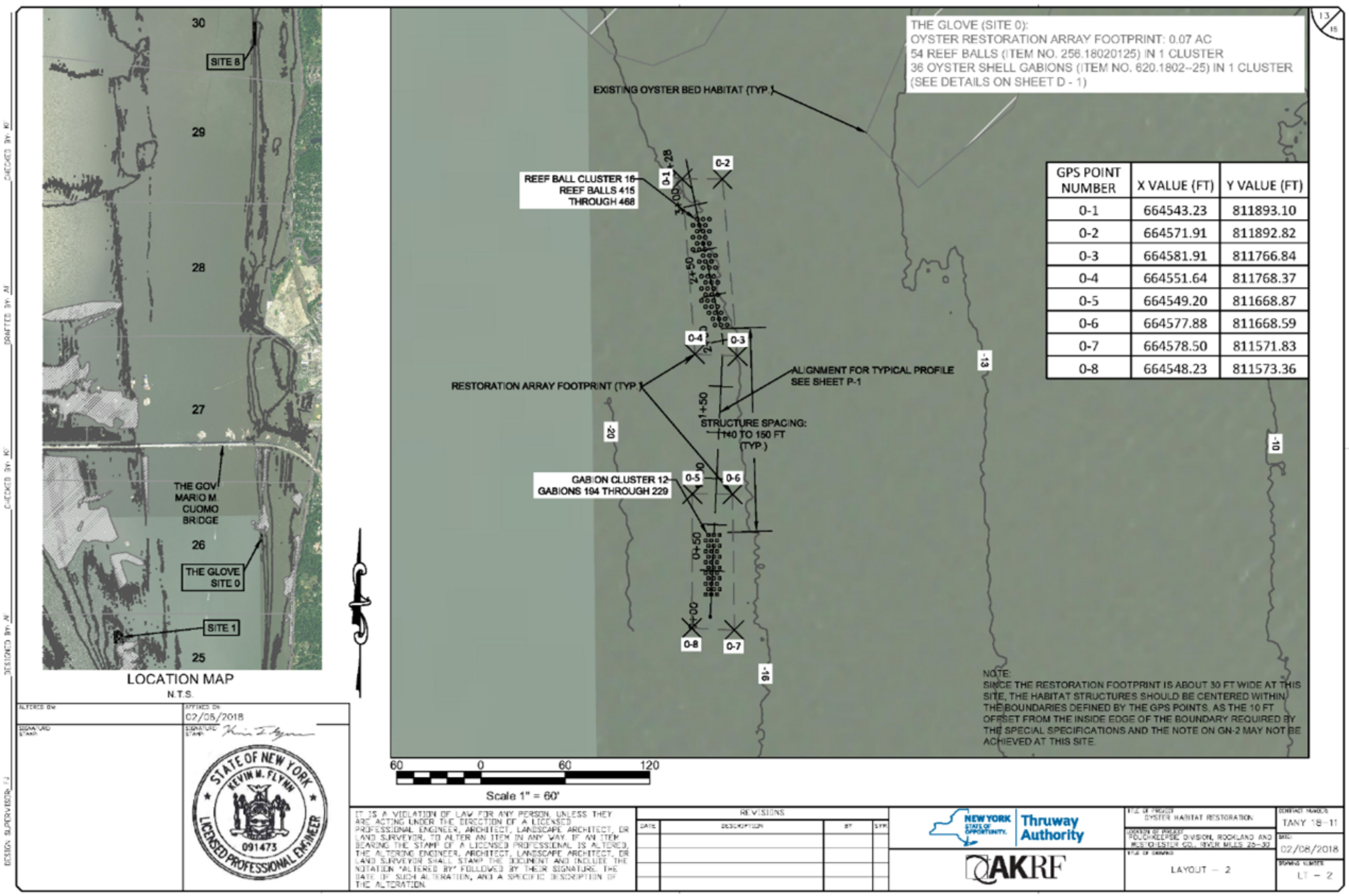
1-5	658817.04	807674.13
1-6	658801.92	807806.13



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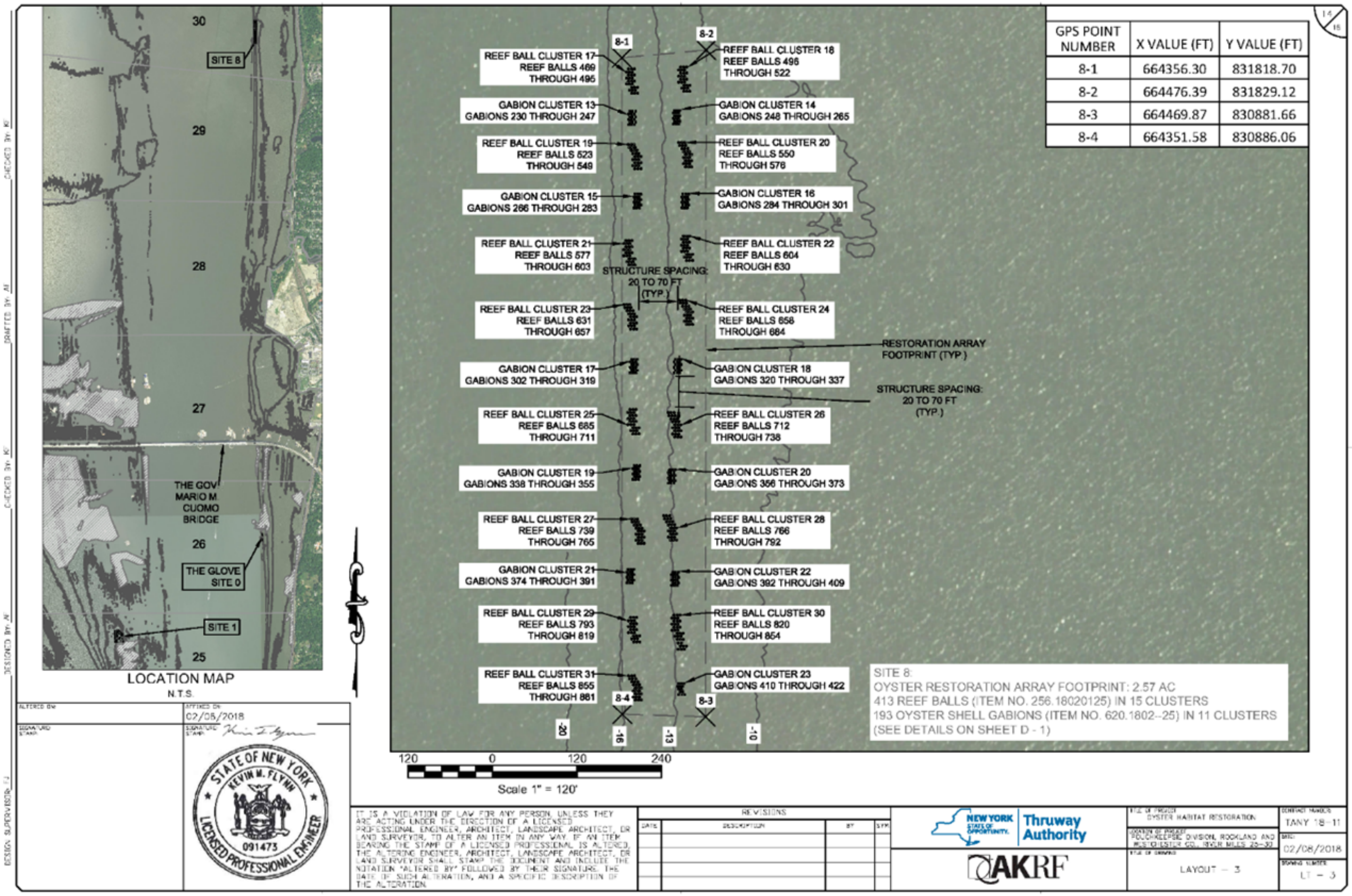

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8-3	664469.87	830881.66
8-4	664351.58	830886.06

ATTACHMENT A: 2019 & 2020 OYSTER SUBSTRATE MONITORING

The Governor Mario M. Cuomo/New NY Bridge Project at Tappan Zee

Oyster Habitat Restoration Study – Oyster Monitoring

March 24, 2021

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Introduction and Background

The Hudson River Foundation (HRF), the University of New Hampshire (UNH), and Billion Oyster Project (BOP) partnered to conduct monitoring of an oyster mitigation project resulting from construction of the new Governor Mario M. Cuomo Bridge. The monitoring project was conducted under the direction of AKRF, Inc., and the New York State Thruway Authority (NYSTA). Mitigation was accomplished by constructing new oyster reef habitat at three sites (Figure. 1) and involving two treatment types (=substrate types): 1) metal gabion cages containing recycled oyster shells, and 2) Reef Balls ("Mini-Bay" style).

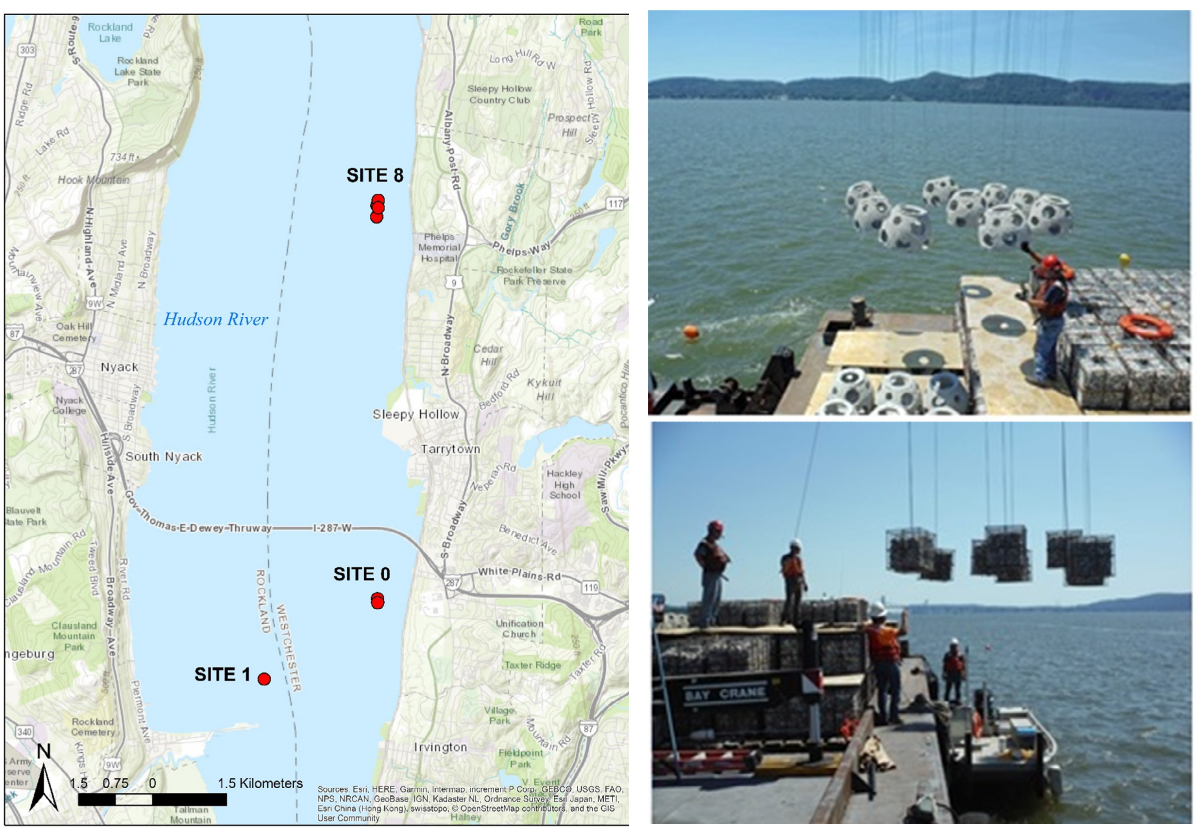


Figure. 1. Locations of the three oyster reef mitigation sites and deployment of the two substrate types in July 2018.

[1] Hudson River Foundation, [2] University of New Hampshire, [3] New York Harbor Foundation

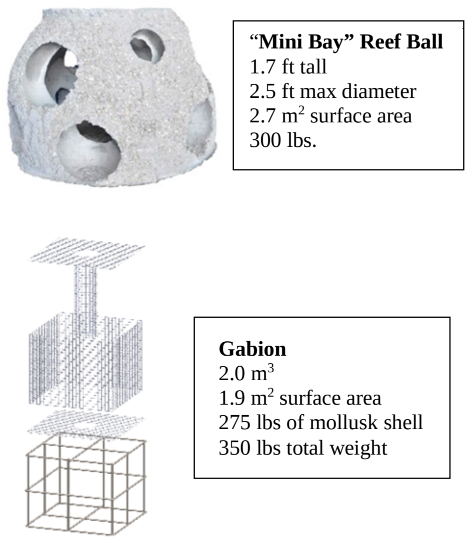


Figure. 2. Reef Ball and Gabion Sizes

The three sites for full-scale mitigation (oyster reef restoration) were chosen based on earlier studies that characterized the occurrence of natural reefs with live oysters (Princeton Hydro 2015) and were among the sites recommended for further study based on overall environmental characteristics (AKRF 2016a, b). These initial studies were followed by a 3-year (2015-2017) pilot study that assessed the performance of three potential restoration substrates at several potential restoration sites (Lodge et al. 2020). The performance metrics included attracting (recruiting) oysters, supporting oyster growth and survival, and the longevity and sustainability of the three different substrates and construction techniques: 1) metal gabion cages containing oyster shells; 2) small Reef Balls ("Lo-Pro"); and 3) larger Reef Balls ("Mini-Bay"). The pilot study determined that Mini-Bay reef balls and shell-filled gabions provided effective substrates, and were chosen for the full-scale reef restoration efforts. The reef balls are 1.7 feet tall, 2.5 ft wide at the base, and weigh approximately 300 lbs. The gabions were fabricated using ½" steel rod and 12.5 gauge wire stainless steel 1" mesh. The gabions are 2^3 feet and weigh approximately 350 lbs. (Figures 2 and 3). The gabions were filled with approximately 5 cubic feet of cured mollusk shell (approximately 85% oyster, 15% hard clam). Installation of the substrates occurred in July 2018.

Figure 3. 422 Gabions pre-deployment.

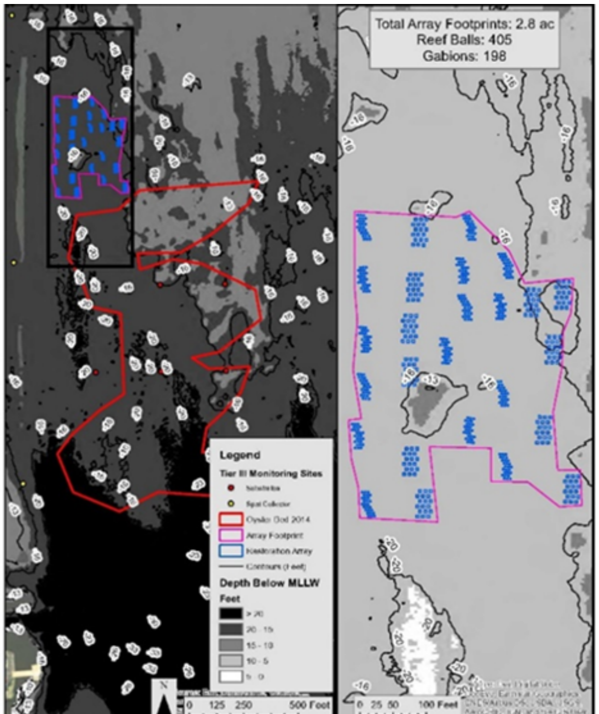


Figure. 4. Site 1 Locations of reef balls and gabions

Project Site Location and Description:
The oyster mitigation project consists of three site areas: Site 1 (~2 km south of the bridge on the western side of the Hudson River channel, average depth 13 ft), Site 0 “The Glove” (~1 km south of the bridge (eastern side of the Hudson River, average depth 15 ft), Site 8 (~5 km north of the bridge (eastern side of the Hudson River, average depth 12 ft), (Figures. 4 - 6).

Site 1. Site 1 encompasses an area of 3.35 acres and consists of 414 reef balls arranged in 15 clusters and 193 gabions arranged in 11 clusters (Figure. 4).

Site 8. Site 8 encompasses an area of 2.57 acres and consists of 413 reef balls in 15 clusters and 193 gabions in 11 clusters (Figure. 5).

Site 0. Site 0 “The Glove” encompasses an area of 0.07 acres and consists of 54 reef balls and 36 gabions, each in a single cluster (Figure. 6).

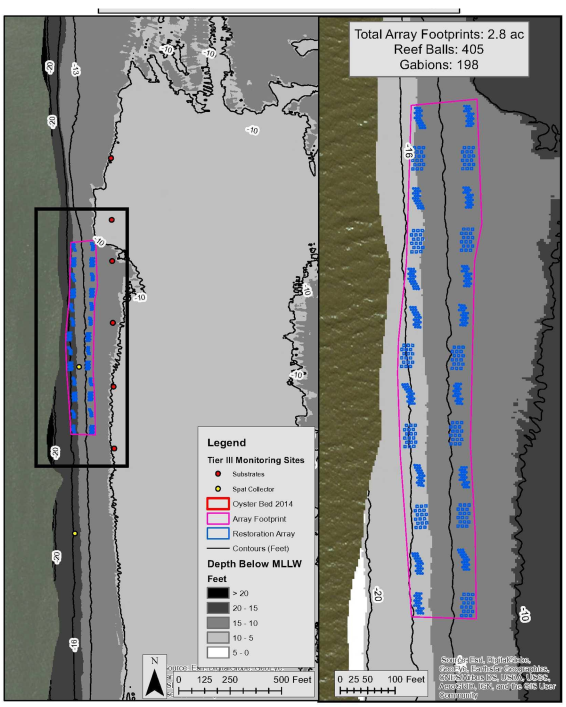


Figure. 5. Site 8

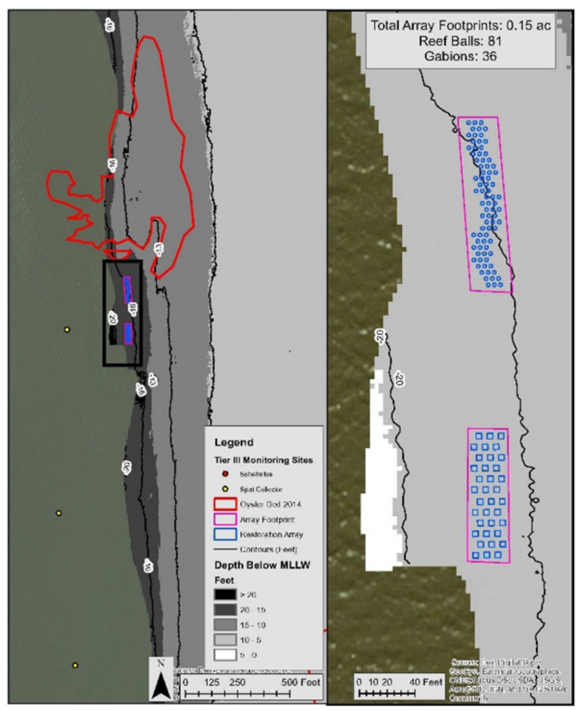


Figure. 6. Site 0 “The Glove”

Monitoring Methods

The primary objective of the monitoring portion of the project was to quantify oyster recruitment, density, growth, and survival at the three study sites and on the two substrate types by annual sampling in the fall of 2019 and 2020. The clusters targeted for sampling were spatially distributed within each site and the clusters monitored in 2019 were avoided in 2020. After each monitoring event, the reef balls and gabions were placed at a new location within the restoration site to avoid resampling during future monitoring events. Side-Scan Sonar and GPS were used to locate the substrates selected for monitoring. After locating the substrates, SCUBA divers attached harnesses and lines to the reef balls and gabions which were lifted from the water using the vessel's A-frame and winch.

In 2019, sampling occurred on six days over two periods (September 30 - October 2, and October 29 – October 30). A total of 37 reef balls and 20 gabions were monitored from the three sites (16 reef balls and 8 gabions from Site 1, 17 reef balls and 8 gabions from Site 8 and 4 reef balls and 4 gabions from Site 0. In 2020, sampling occurred on October 5 and October 6. A total of 36 reef balls and 20 gabions were monitored from the three sites: 16 reef balls and 8 gabions from Site 1, 16 reef balls and 8 gabions from Site 8 and 4 reef balls and 4 gabions from Site 0. Over the two years of monitoring, 73 reef balls (8.2%) and 40 gabions (9.3%) were sampled (Table. 1).

Substrate	Site 1	Site 8	Site 0	Total Sampled	Total Deployed	Percent Sampled
Reef Balls	32	33	8	73	891	8.19%
Gabions	16	16	8	40	432	9.26%

Table 1. Total number of Reef balls and gabions sampled

Oyster Metrics: Standard sampling methods for oysters were used following the general recommendations in Baggett et al. (2014), previous studies in the region (Grizzle et al. 2013) and as refined in the pilot study (Lodge et al. 2015). After the test substrates were removed from the water, the number and size (shell height measured with calipers or ruler to nearest 1 mm) of individual, live oysters were determined following the detailed methods below for each substrate type.

Reef Balls: In 2019, if the number of oysters and oyster spat for the entire reef ball was <50, all oysters and oyster spat on the exterior and interior surfaces were counted and measured. If the number of oysters and oyster spat for the entire reef ball was >50, individual live oysters in four replicate 0.04 m^2 (20 cm x 20 cm) quadrats placed randomly at multiple locations on the exterior of the reef ball were measured. Two quadrat samples from one side and two samples from the opposite side of the reef balls were sampled. A random number generator was used to determine the positions of the quadrats. The same haphazard photographic sampling method was used to characterize the non-oyster epibenthos for all reef balls. In 2020, all counts and measurements were made using duplicate 0.04 m^2 quadrats placed at random locations on opposite sides of each reef ball.

Gabions: In both years, a section of the wire mesh from the tops of the gabion cages in two areas was opened using wire cutters and two 0.04 m^2 (20 cm x 20 cm) quadrats were placed haphazardly. A photograph was taken of the quadrat, and after photographing shell/cultch was excavated from the upper 2 cm (approximately 2 shells depth). All oysters were counted on the excavated cultch material and shell height (to nearest 1 mm) from all live oysters was measured.

Non-oyster Epibenthos: Although oysters were the focus of the project, other species colonized the restoration substrates. The non-oyster taxa were characterized using quantitative "photographic quadrat sampling" using the photos taken of each 0.04 m^2 quadrat sample on both types of substrates, as described above. The methods described in Berman et al. (1992), Stachowitsch et al. (2002) and Grizzle et al. (2016) were followed. The photos were processed in the laboratory, identifying each taxon to the lowest level practical (species where possible). This process provides data on the number of taxa present (taxonomic richness) and the density of each taxon. To ensure correct identification in the photo quadrats, representative specimens of each taxon were removed in the field, placed in isopropanol, and returned to the laboratory for identification using standard taxonomic keys (Weiss 1995; Pollack 1998).

Figure. 7. Photos of typical substrates retrieved from the three mitigation sites during 2019 (left) and 2020 (right).

Results and Discussion

Both substrate types were heavily colonized by oysters and other species at all three sites, essentially duplicating the general findings of the 3-year pilot study (Lodge et al. 2017). Overall, the pilot study and the present full-scale mitigation efforts provide a 5-year record of consistent natural oyster recruitment and early reef development.

These studies suggest that there are natural populations in the general area to provide adequate recruitment for successful oyster reef restoration efforts involving only addition of appropriate hard substrates. Significant reef development was observed on most substrates in 2020 (Figure. 7). At Site 0, oysters had achieved close to 100% areal coverage on some of the reef balls (Figure. 8) and some oyster clusters projected >10 cm above the surface of the gabions (Figure. 9). Less oyster areal coverage and vertical height occurred at Sites 1 and 8, but reef development at both sites was substantial. These differences were quantified using standard oyster metrics (quadrat samples for density and size) and assessment of photo-quadrats to characterize species other than oysters that made up the reef communities.

Figure 8. Reef Balls from Site 0

Figure. 9. Gabion from site 0

Among-site differences in oyster metrics: There were marked differences in oyster density and mean size among the sites for both years of the study. Both annual datasets (2019 and 2020) showed the same by-site (data from both substrate types combined at each site) trends for live oyster density: Site 0 > Site 8 > Site 1 (Figure. 10). Two-way analysis of variance (ANOVA) of the 2020 dataset indicated significant differences ($p<0.0001$) among the three sites for both density and size. For both density and size, t-tests indicated Site 0 was significantly ($p<0.05$) greater than Sites 1 and 8. These data suggest better conditions for individual oyster growth and perhaps survival at Site 0. It should also be noted that mean oyster density increased from 2019 to 2020 at all three sites but mean oyster size did not show a similar increase; rather a decrease in size was observed at two of the three sites. However, oyster size data are best interpreted in the context of size-frequency distributions which provide information on the contribution of each age class to the overall mean value (see discussion below).

There are few data on live oyster densities from natural reefs in the Hudson River Estuary because most of the historical reefs are thought to have long been decimated (Kurlansky 2006; Levinton and Waldman 2006). Preliminary sampling of oyster bottom in the Tappan Zee study area indicated multiple year classes but average densities <50 live oysters/m^2 (Princeton Hydro 2015). The range of mean densities observed in 2020 (~1,500 – 2,500/m^2; Figure. 10) far exceeded those reported from other studies in the region. For example, annual sampling of natural reefs in New Hampshire since the early 1990s indicate that live oyster densities only rarely exceed 100/m^2 (Eckert 2016). The disparity may be due to the fact that both substrate types provide potential recruitment space that projects nearly a meter above the seafloor. The range of oyster sizes, however, were comparable to those of previous studies in the region (see discussion below in size distribution section).

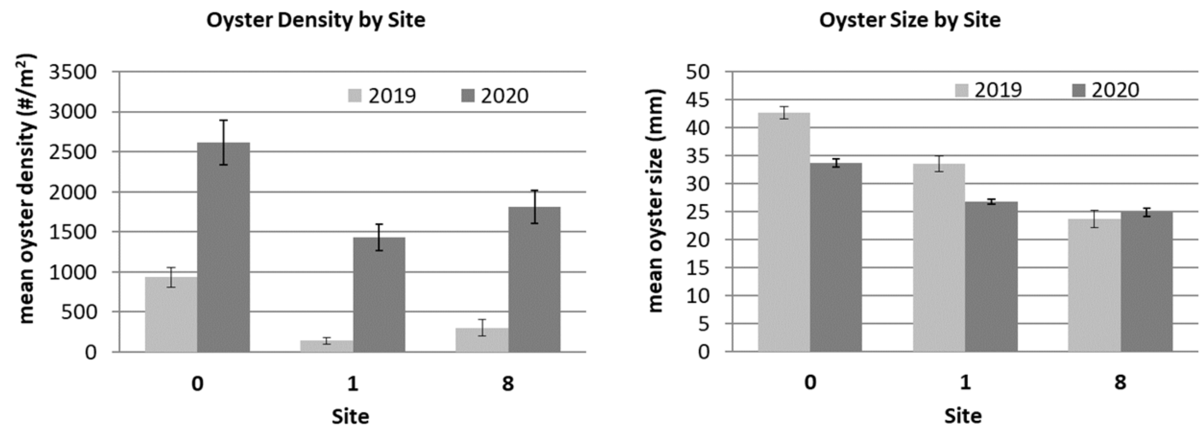


Figure. 10. Mean (±1SE) live oyster densities (left) and live oyster shell height (right) by site when data from both substrate types (gabions and Reef Balls) were combined.

Substrate type and oyster metrics: The effect of substrate type on oyster metrics was assessed on an overall basis after combining the data from all three sites (Figure. 11). The same relative trends were observed in 2019 and 2020. T-tests on the 2020 data indicated no significant ($p>0.05$) differences in density or size on the two substrates. It should be noted that the greater densities on the gabions compared to the Reef Balls in 2019 – which represented initial recruitment – may indicate that the magnitude of the differences between the two substrates decreased as the reef develops. Longer-term studies are needed to assess this as well as other aspects of reef development.

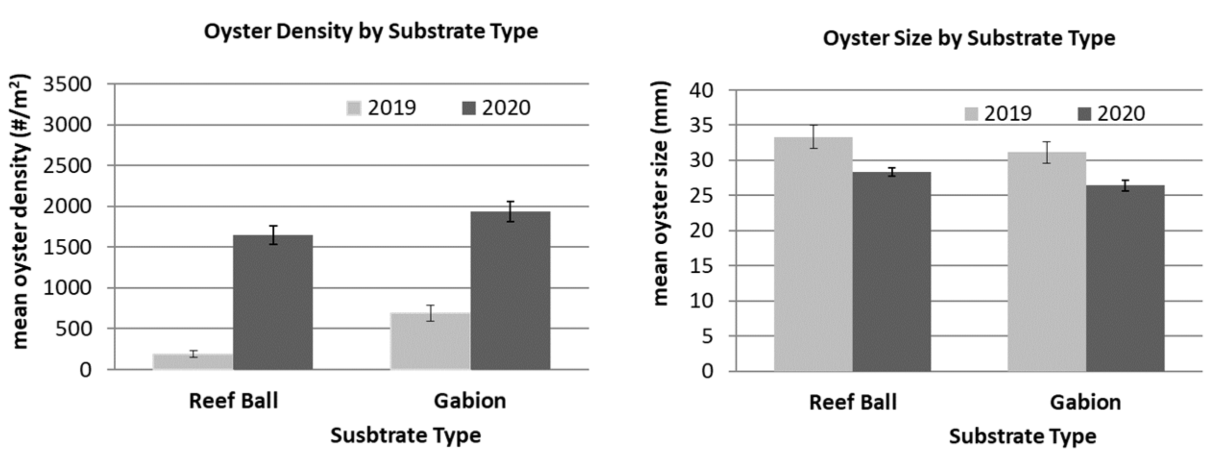


Figure. 11. Mean (±1SE) oyster densities (left) and oyster shell height (right) by substrate type when data from all three sites were combined.

Potential interactions between site and substrate: This assessment provided information on how oyster metrics on the two substrates may have varied among the three sites. Two-way analysis of variance (ANOVA) of the 2020 dataset on oyster density and size indicated no significant interaction ($p>0.05$) between sites and substrate types (Figure. 12).

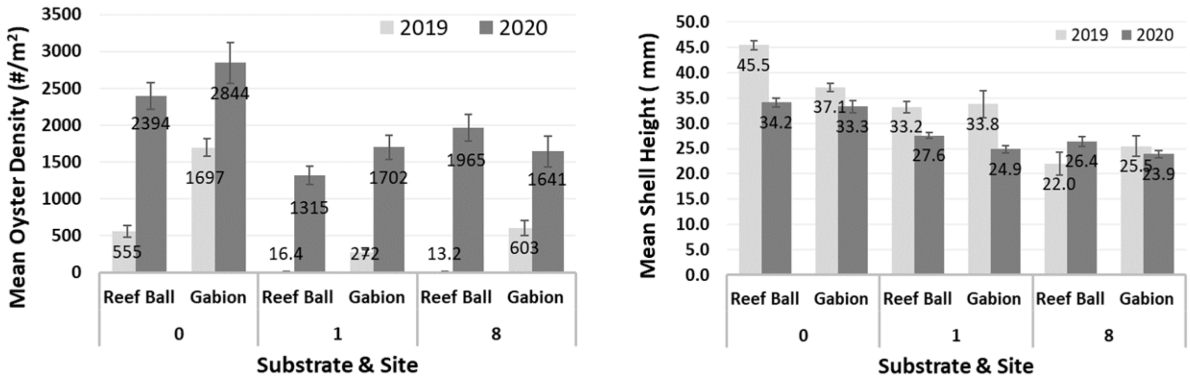


Figure. 12. Mean (±1SE) oyster densities (left) and oyster shell height (right) by site and substrate.

Oyster size distributions by site and substrate: Three size/year classes of oysters were expected on the substrates sampled in October 2020 because their deployment in July 2018 allowed for three summer reproduction periods. Size-frequency plots of the 2019 data indicated two size/year classes and the 2020 data clearly indicated three classes at Site 0, where the largest oysters in 2020 exceeded 120 mm shell height (Figures 13 and 14). Because of variability in oyster growth, it is unclear whether some of the larger oysters (range of 70-85 mm shell height) collected at Site 1 and Site 8 were representative of two (2018-2019) or three (2018-2020) size/year classes. Higher mortality losses at Sites 1 and 8 could potentially explain the lack of larger oysters at those sites in 2020.

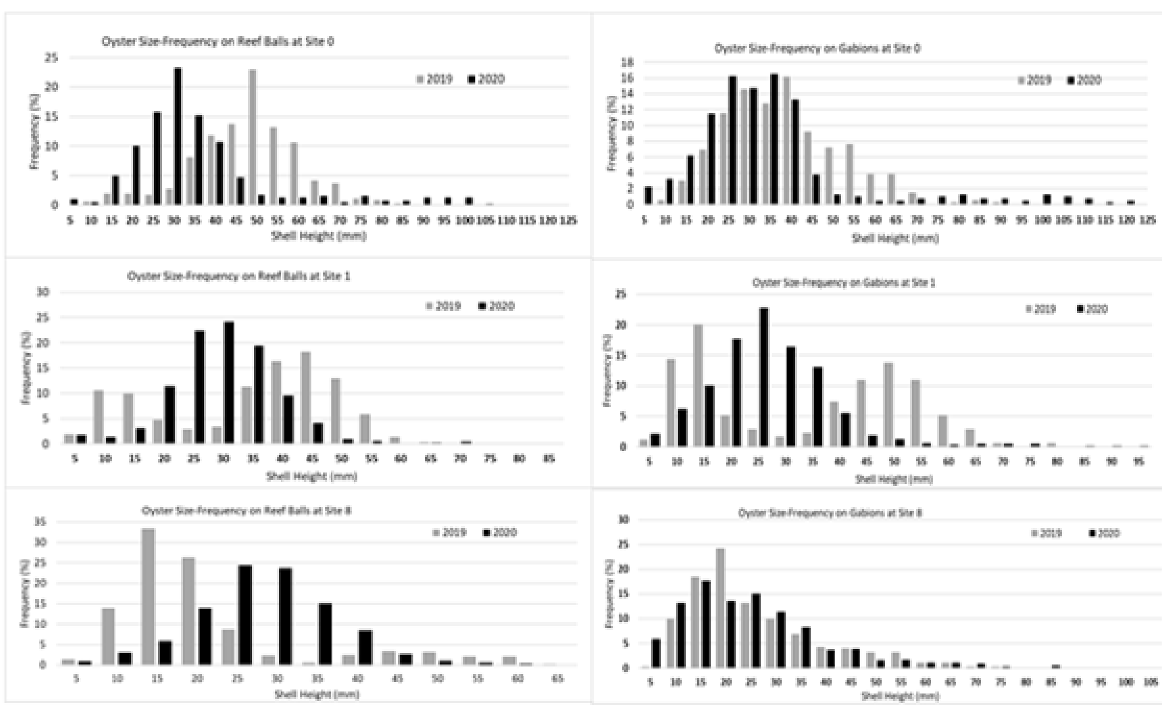


Figure. 13. Size-frequency distributions by site and substrate type for fall 2020 oyster data.

Growth rates of 25 to 40 mm/year for the first few years have been reported in earlier studies in the region (Cerrato 2006; Medley 2010; Levinton and Doall 2011; Grizzle et al. 2013, 2016; Levinton et al. 2013). Although growth rates can vary widely from site to site, using 35 mm/year as an approximate mean value, the size-frequency data from Site 0 for both years indicates two-year classes in 2019 and three in 2020. Data from the other sites and substrates were more variable, which may indicate variations in growth and/or survival rates among the sites and between the substrates. Therefore, as stated above, it is unclear whether some of the larger oysters collected at Sites 1 and 8 are representative of the two or three year classes. One major difference in patterns between the two years was strong small size classes (10 – 15 mm) at Sites 1 and 8 in 2019 but not 2020. Since there already was a relatively dense oyster population of various sizes at Site 0 prior to the restoration effort, it's possible that environmental conditions there are better for oyster recruitment, but additional years of data would be needed to test this.

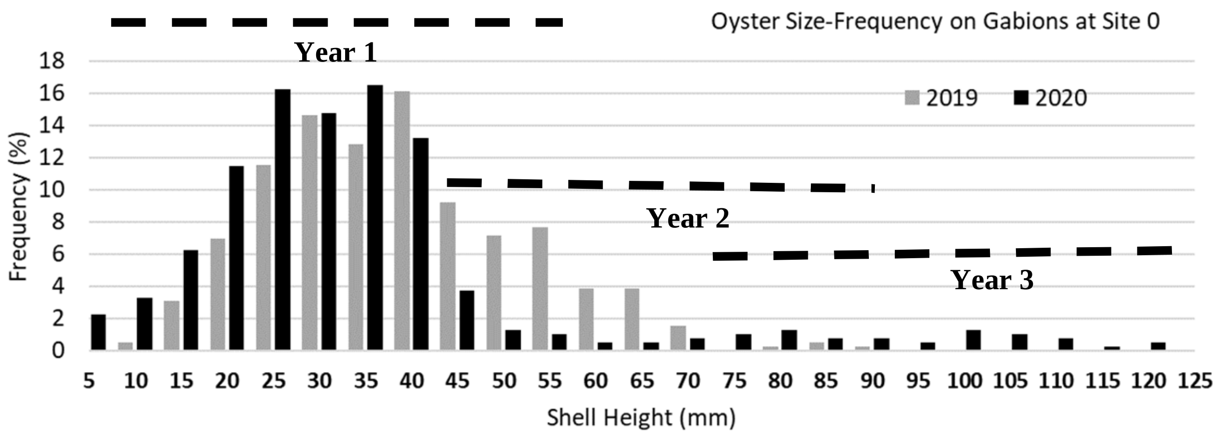


Figure. 14. Size-frequency distributions for gabions only at Site 0 in 2019 and 2020. Dashed lines denote probable size/age classes based on previous studies in the region (see text).

Regardless of variations in growth and survival, an important finding for future restoration efforts in the region was consistent annual recruitment among the sites and on both substrates. When considering datasets from the present study (2019-2020), the 3-year pilot study (2015-2017; Lodge et al. 2017), and a preliminary recruitment study in the same area (2015-2016; AKRF 2016a, b) substantial annual spat sets have been recorded throughout the Tappan Zee study area for the past 5 years.

Non-oyster Epibenthos: In addition to oysters, four species of epifauna made up the overall fouling community on the test substrates during the pilot studies and in 2019 and 2020: the encrusting bryozoan *Membranipora* sp. which was associated with an unidentified hydroid, the hooked mussel *Ischadium recurvum*, and the bay barnacle *Balanus improvisus*. In 2020 only the mussel and barnacle were abundant on the substrates (Figure 15), though some *Membranipora* colonies were observed. Although we are aware of no studies on these taxa in the region, species of *Membranipora* and *Balanus* have been shown to be early colonists in fouling communities (Bram et al. 2005). Thus, wide variations in seasonal and year-to-year abundances of both taxa are typical (e.g., Gosner 1978; Saunders and Metaxas 2009). The relationships among species in fouling communities is complex and includes the obvious competition for space as well as predation on settling oyster larvae (Kochman et al. 2008; Barnes et al. 2010; Boudreaux et al. 2009). This should be an important topic in future studies that might yield relevant information for interpreting oyster reef development patterns. Overall there appears to be an increase in mussel and barnacle densities between 2019 and 2020 but the increase was not always consistent among sites or between substrates.

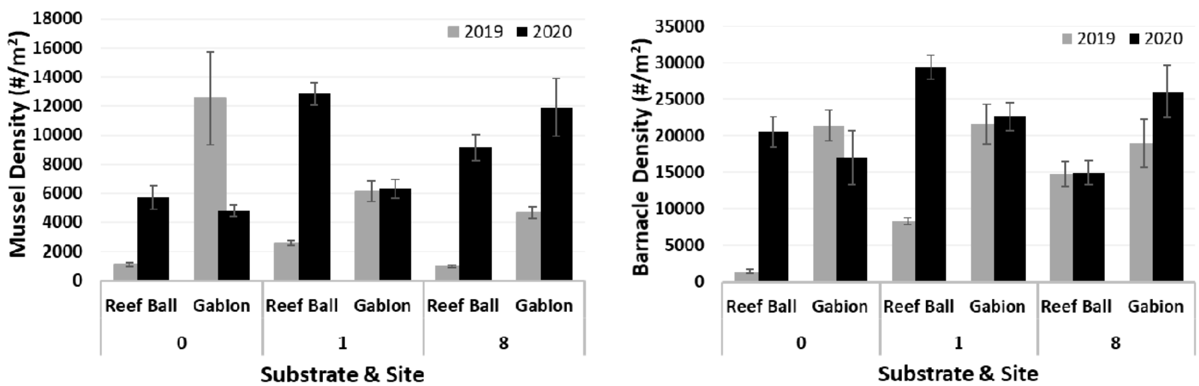


Figure. 15. Non-oyster invertebrate densities by substrate type and year.

Assessment of overall mitigation effort: Table 2 below summarizes the results of the overall mitigation effort with respect to abundances of live oysters. Based on the October 2020 sampling results, an estimated total of approximately 5.8 million live oysters were on the deployed substrates at the three mitigation sites. Although most of the oysters were recent recruits (see Figure 13), substantial numbers of 2nd and some 3rd year individuals were present., indicating good survival for the 2-year study period. While very encouraging, particularly when considering similar results for the 3-year pilot study, longer-term monitoring is needed to better assess the sustainability of the new reefs.

Table 2. Estimated abundances of live oysters in 2020 by site and substrate type.

Site	Substrate Type	Total # Substrates Deployed	Surface Area of Each Substrate (m^2)	Mean Live Oyster Density (#/m^2)	1 SE	Estimated # of Live Oysters	1 SE
0	Reef Ball	54	2.74	2394	186	354,216	27521
0	Gabion	36	1.94	2844	275	198,625	19206
1	Reef Ball	414	2.74	1315	125	1,491,683	141795
1	Gabion	193	1.94	1702	165	637,263	61779
8	Reef Ball	413	2.74	1965	185	2,223,633	209350
8	Gabion	193	1.94	2311	522	865,285	195447
					Total	5,770,705	

The total restoration area of the three sites is about 6.0 acres. The reef balls and gabions used to construct the reefs cover <5% of the total area but they provide over an acre (~14% of the total area) of "hard substrate" potentially suitable for oyster reef development because of their structural complexity. Both substrates project nearly a meter above the bottom and provide 2.8 m^2 (reef balls) to 1.9 m^2 (gabions) of surface area. It's important to note that the haphazard placement of the quadrats when monitoring the reef balls and gabions was limited to the outside surfaces. We did consistently observe oysters on the inside surfaces, but we didn't develop separate density numbers to account for the potential of reduced settlement on the inside surfaces. Additionally, the gabions have much more small-scale surface area than the reef balls due to the rough surface provided by the seasoned oyster shells, but this also was not accounted for in the calculations. Reef Balls have been used extensively, and their effectiveness is well-documented (http://www.reefball.org). In contrast, shell-filled gabions have only recently begun to be used for oyster reef restoration (e.g., Safak et al. 2020) and their general effectiveness as well as sustainability in the long-term remain to be tested. And as discussed above, the magnitude of the differences between the two substrates decreased as the reef develops. Variable and sometimes high amount of sedimentation was observed by the divers and during the monitoring at the surface. While it is plausible that high levels of sedimentation could have affected the substrate surface available for settlement and growth, this study was not designed to determine the extent of that effect. Longer-term studies are needed to assess this as well as other aspects of reef development.

Conclusions

The present mitigation project represents the most successful oyster reef restoration project in the Hudson River Estuary in recent decades from the perspective of restoration area and several metrics of early restoration success. It also strongly indicates good prospects for additional oyster reef restoration efforts. Overall, the pilot study (Lodge et al. 2017) and the present full-scale mitigation effort provide a 5-year record of consistent natural oyster recruitment and early reef development. As this study and previous work demonstrate, there are sufficient natural populations in the general area to provide adequate recruitment for successful oyster reef restoration efforts involving only addition of appropriate hard substrates.

While this study demonstrates that seeding of oysters may not be necessary in the general Tappan Zee area, detailed knowledge of specific site conditions (e.g., depth, sediment type and stability, salinity, proximity to the channel) must be carefully evaluated to identify locations where the greatest likelihood of success may occur. Early investigations for this restoration effort indicated that even at locations where these environmental conditions appeared favorable, oysters often occurred at extremely low densities, or not at all. Furthermore, additional monitoring of the present project would be needed to assess long-term (>5 years) sustainability of the reef communities and substrates.

The major focus of the monitoring effort was oysters, but other species occurred on the substrates and two were at much higher densities (Figure 15) than the oysters. Thus, the newly developing reefs provided substantial habitat for other sedentary species, and *presumably* other motile species of invertebrates and fish that typically are associated with oyster reefs in the region (Peterson and Kulp 2013). Although unmeasured, the new reef communities also provided water filtration due to the abundances of at least three filter feeding species (oysters, mussels and barnacles). The provision of these and other ecosystem services by the new reefs could be important topics for future research.

The success of the present mitigation project has important implications for designing future restoration projects. Previous work in this area documented the rapid reduction in oyster spat recruitment as distance down-stream increased (McFarland and Hare 2018). This suggests that larval transport or suitable substrate may be limiting recruitment only a few kilometers south of the Tappan Zee. Reproductive metrics including gonad condition data were not collected as part of this study. As such the potential larval output or contribution to recruitment that the restored reefs are providing is not known. Furthermore, it would also be useful to characterize the reproductive condition of oysters along a distance gradient in the general area. Such data might yield information on larval sources and thus locations of where reef substrate construction would have the highest probabilities of long-term success. Overall, future pilot studies should be designed to investigate the southerly expansion of oyster populations in the Tappan Zee.

The present project also provides additional data on surprisingly robust oyster performance in waters of very low salinity. During the 5-year study period, spring and early summer (April – July) salinity measurement were typically less than 5 PSU and sometimes zero for several days to weeks (Figure 16 and Attachment B). Strong oyster performance despite these apparently extreme conditions has implications for restoration practitioners utilizing habitat suitability models and suggests careful consideration be given to using data and models from outside of this region.

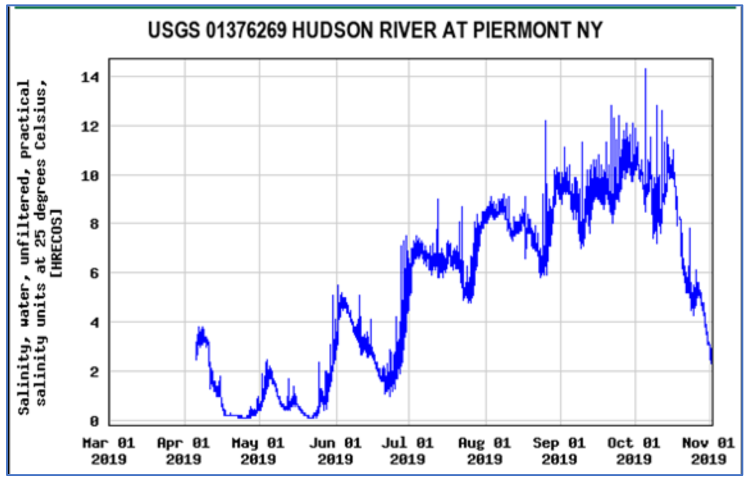


Figure. 16. Salinity data from Piermont HRECOS station near Site 1, May-November 2019 (https://hrecos.org/).

References

AKRF. 2016a. Tier 3 Progress report, Oyster research and restoration plan, New NY Bridge Project. AKRF, Inc., New York City. Submitted March 16, 2016

AKRF. 2016b. Tier 3 Progress report, Oyster research and restoration plan, New NY Bridge Project. AKRF, Inc., New York City. Submitted November 30, 2016.

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock, and S. Morlock. 2014. Oyster habitat restoration monitoring and assessment handbook. The Nature Conservancy, Arlington, VA, 96 pp. see http://www.oyster-restoration.org/wp-content/uploads/2014/01/Oyster-Habitat-Restoration-Monitoring-and-Assessment-Handbook.pdf

Barnes, B.B., M.W. Luckenbach, and P.R. Kingsley-Smith. 2010. Oyster reef community interactions: the effect of resident fauna on oyster (*Crassostrea* spp.) larval recruitment. *Journal of Experimental Marine Biology and Ecology* 391:169-177.

Berman, J., L. Harris, W. Lambert, M. Buttrick, and M. Dufresne. 1992. Recent invasions of the Gulf of Maine: three contrasting ecological histories. *Conservation Biology* 6:435-441.

Boudreaux, M.L., L.J. Walters, and D. Rittschof. 2009. Interactions between native barnacles, non-native barnacles, and the eastern oyster *Crassostrea virginica*. *Bulletin of Marine Science* 84:43-57.

Bram, J.B., H.M. Page, and J.E. Dugan. Spatial and temporal variability in early successional patterns of an invertebrate assemblage at an offshore oil platform. *Journal of Experimental Marine Biology and Ecology* 317: 223-237.

Cerrato, R.M., 2006. Long-term and large-scale patterns in the benthic communities of New York Harbor. Pp. 242-265. In: *The Hudson River Estuary*, J.S. Levinton and J.R. Waldman (Eds.), Cambridge University Press.

Eckert, R.L. 2016. Oyster (*Crassostrea virginica*) recruitment studies in the Great Bay Estuary, New Hampshire. MS thesis, University of New Hampshire, Durham, NH. Available at: https://scholars.unh.edu/thesis/874.

Gosner, K.L. 1978. A field guide to the Atlantic seashore, from the Bay of Fundy to Cape Hatteras. Houghton Mifflin, Boston.

Grizzle, R., K. Ward, J. Lodge, D. Suszkowski, K. Mosher-Smith, K. Kalchmayr, and P. Malinowski. 2013. Oyster Restoration Research Project Final Technical Report, Phase I: Experimental Oyster Reef Development and Performance Results. 2009-2012. Available from: http://www.hudsonriver.org/download/ORRP_Phase1.2013.pdf

Grizzle, R.E., K.M. Ward, C.R. Peter, M. Cantwell, D. Katz, and J. Sullivan. 2016. Growth, morphometrics, and nutrient content of farmed eastern oysters, *Crassostrea virginica* (Gmelin), in New Hampshire, USA. *Aquaculture Research* 2016:1-13. Doi:10.1111/are.12988.Kochman, J., C. Buschbaum, N. Volkenborn, and K. Reise. 2008. Shift from native mussels to alien oysters: differential effects of ecosystem engineers. *Journal of Experimental Marine Biology and Ecology* 364:1-10.

Kurlansky, M., 2006. The big oyster: history on the half shell, Ballantine Books, New York, N.Y., 320pp.Leaf, R., 2010. City of New York Parks & Recreation, Natural Resources Group WCS-NOAA Fish and Shellfish Habitat Creation and Seeding Project: Bronx River Pilot Oyster Reef Placement Report. Annual Summary Report. NYC Department of Parks and Recreation. July 2010, 38pp.

Levinton, J.S., and J.R. Waldman, 2006. The Hudson River Estuary. Cambridge University Press, New York, 471 pp.

Levinton, J.S. and M. Doall, 2011. Guiding oyster restoration: growth, condition and spawning success of experimental populations of oysters throughout New York-New Jersey Harbor. Final Report to the Hudson River Foundation, New York, NY.

Levinton, J., M. Doall, and B. Allam, 2013. Growth and mortality patterns of the eastern oysters *Crassostrea virginica* in impacted waters in coastal waters in New York, USA. Journal of Shellfish Research 32:417-427.

Lodge, J., Grizzle, R., Coen, L., Mass Fitzgerald, A., Comi, M., Malinowski, P., 2015. Community Based Restoration of Oyster Reef Habitat in the Bronx River: Assessing Approaches and Results in an Urbanized Setting. Final Report of the NOAA/WCS Regional Partnership Grant, New York, NY Available from http://www.hudsonriver.org/download/HRF%20_%20NOAA-WCS%20Final%20Report%20Web%20Version.pdf

Lodge, J., Grizzle, R., Ward, K., Malinowski, P. 2017. FINAL REPORT - Tier 3 Tappan Zee Bridge Oyster Restoration Pilot Study. Submitted to: Fred Jacobs, AKRF, Inc.

Lodge, J., R. Grizzle, K. Ward, K. Mosher and L. Burmester. 2020. PROGRESS REPORT #1 – Preliminary Data Assessment The Governor Mario M. Cuomo/New NY Bridge Project at Tappan Zee Oyster Habitat Restoration Study – Oyster Monitoring. Submitted to: Fred Jacobs, AKRF, Inc.

McFarland K, Hare MP, 2018. Restoring oysters to urban estuaries: Redefining habitat quality for eastern oyster performance near New York City. PLoS ONE 13(11): e0207368. https://doi.org/10.1371/journal.pone.0207368

Medley, T.L. 2010. Wild oysters, *Crassostrea virginica*, in the Hudson River estuary: Growth, health and population structure. PhD Dissertation submitted to The City University of New York.

Peterson, B., and R. Kulp, 2013. Investigating ecological restoration: enhancement of fisheries due to the presence of oyster reefs in the Hudson River 2011-2012. See http://www.oyster-restoration.org/wp-content/uploads/2012/06/HRF-final-report_Peterson_2013-small.pdf

Pollack, L.W., 1998. A practical guide to the marine animals of northeastern North America. Rutgers University Press.

Princeton Hydro. 2015. Tier 2 Oyster sampling report, Tappan Zee Bridge Hudson River crossing project, Westchester and Rockland Counties, New York. Submitted to: AKRF, Inc. Hanover, Maryland.

Safak, I., P.L. Norby, N. Dix, R.E. Grizzle, M. Southwell, J.J. Veenstra, A. Acevedo, T. Cooper-Kolb, L. Massey, A. Sheremet, and C. Angelini. 2020. Coupling breakwalls with oyster restoration structures enhances living shoreline performance along energetic shorelines. *Ecological Engineering* 158(2020)106071. https://doi.org/10.1016/j.ecoleng.2020.106071

Saunders, M.I. and A. Metaxas. 2009. Population dynamics of a nonindigenous epiphytic bryozoan *Membranipora membranacea* in the western North Atlantic: effects of kelp substrate. *Marine Ecology Progress Series* 8:83-94.

Shumway, S. 1996. Environmental factors. pp. 467-514 In: The Eastern Oyster *Crassostrea virginica*. Eds: V.S. Kennedy, R.I.E. Newell, A.F. Eble. Maryland Sea Grant College, University of Maryland System, College Park.

Stachowitsch, M., R. Kikinger, J. Herler, P. Zolda, and E. Geutebrück. 2002. Offshore oil platforms and fouling communities in the southern Arabian Gulf (Abu Dhabi). *Marine Pollution Bulletin* 44:853-860.

Weiss, H.M., 1995. Marine animals of southern New England and New York: Identification keys to common nearshore and shallow water macrofauna. Bulletin, vol. 115. State Geological and Natural History Survey of Connecticut. Department of Environmental Protection.

ATTACHMENT B: 2020 WATER QUALITY MONITORING REPORT

The Governor Mario M. Cuomo/New NY Bridge Project at Tappan Zee

Oyster Habitat Restoration Study – Oyster Monitoring

January 29, 2021

This section of the 2020 Monitoring Report presents the results of measurements of conductivity (converted to salinity), dissolved oxygen (DO), and temperature associated with Tier 4 of the four-tiered oyster research and restoration plan that was developed by the New York State Thruway Authority (the Authority), New York State Department of Environmental Conservation (NYSDEC) and other members of the Oyster Work Group (OWG) for the Governor Mario M. Cuomo Bridge Project. The 2020 water quality monitoring effort was performed as described in the Post Construction Monitoring Plan (originally prepared on 6-19-17 and revised on 3-25-2019) and collected salinity, dissolved oxygen (DO), and temperature monitoring data following deployment of oyster shell gabions and reef balls at the three sites that were selected for restoration by the OWG and NYSDEC under Tier 4. The primary objective for the collection of salinity, DO, and temperature data collected at these three sites (Sites 0 [i.e., the Glove], 1, and 8; **Figure 1**) is to provide some additional context in which to interpret the results of the Tier 4 oyster density and growth rate monitoring that was conducted by the Hudson River Foundation Team (HRF) because salinity and DO are potential factors limiting oysters in this section of the Hudson River.

STUDY DESIGN AND SAMPLING FREQUENCY

The study design and sampling frequency during 2020 was similar to the previous year with the exception that the monitoring period began one month later than in 2019 due to work stoppages caused by the Covid-19 pandemic. Two conductivity loggers and two DO loggers were deployed at each of the three study sites, in the same approximate locations as in 2018 and 2019 (**Figures 2-4)**, although some locations were temporarily missing loggers or missed data during parts of the season due to equipment failure. Depths of the loggers and substrate arrays are indicated on **Table 1.** The temperature data reported herein were obtained from the DO loggers, which record temperature in concert with DO. The monitoring locations were originally selected to be as close to the restoration areas as possible to be representative of the conditions experienced by colonizing oysters without directly interfering with the reef balls and gabions.

The same model of Onset HOBO conductivity loggers and PME DO loggers used from 2016-2019 were used in 2020. All units were factory calibrated prior to deployment. As in past years, the loggers were suspended by buoys approximately 2 feet off of the river bottom and programmed to record at 10-minute intervals. They DO loggers were deployed on April 28 and the conductivity loggers were deployed on May 5; they were then subsequently retrieved on a monthly basis to download data until their removal from the river at the end of the season on November 4. Upon each retrieval event, the sensors and the main body of the loggers were cleaned to remove fouling. As in all past years, the conductivity loggers were also calibrated by taking a reading while submerged in a standard solution (5,000 µs/cm at 25° C). These readings were then used in the HOBOware Pro software to adjust the raw conductivity measurements from each sampling period.

Table 1
Data Logger and Array Depths

Site	2018-2020 Data Logger Coordinates		2018-2020 Data Logger Depth (m)			Array Depth (m)		
	Latitude	Longitude	Min	Max	Mean	Min	Max	Mean
0	41.060319	-73.874146	-4.1	-4.5	-4.3	-4.2	-4.8	-4.6
	41.060589	-73.874273						
1	41.050008	-73.897081	-4.7	-4.8	-4.8	-2.9	-4.9	-4.0
	41.050292	-73.897037						
8	41.114499	-73.876102	-9.0	-9.2	-9.1	-2.8	-4.6	-3.6
	41.114812	-73.876006						

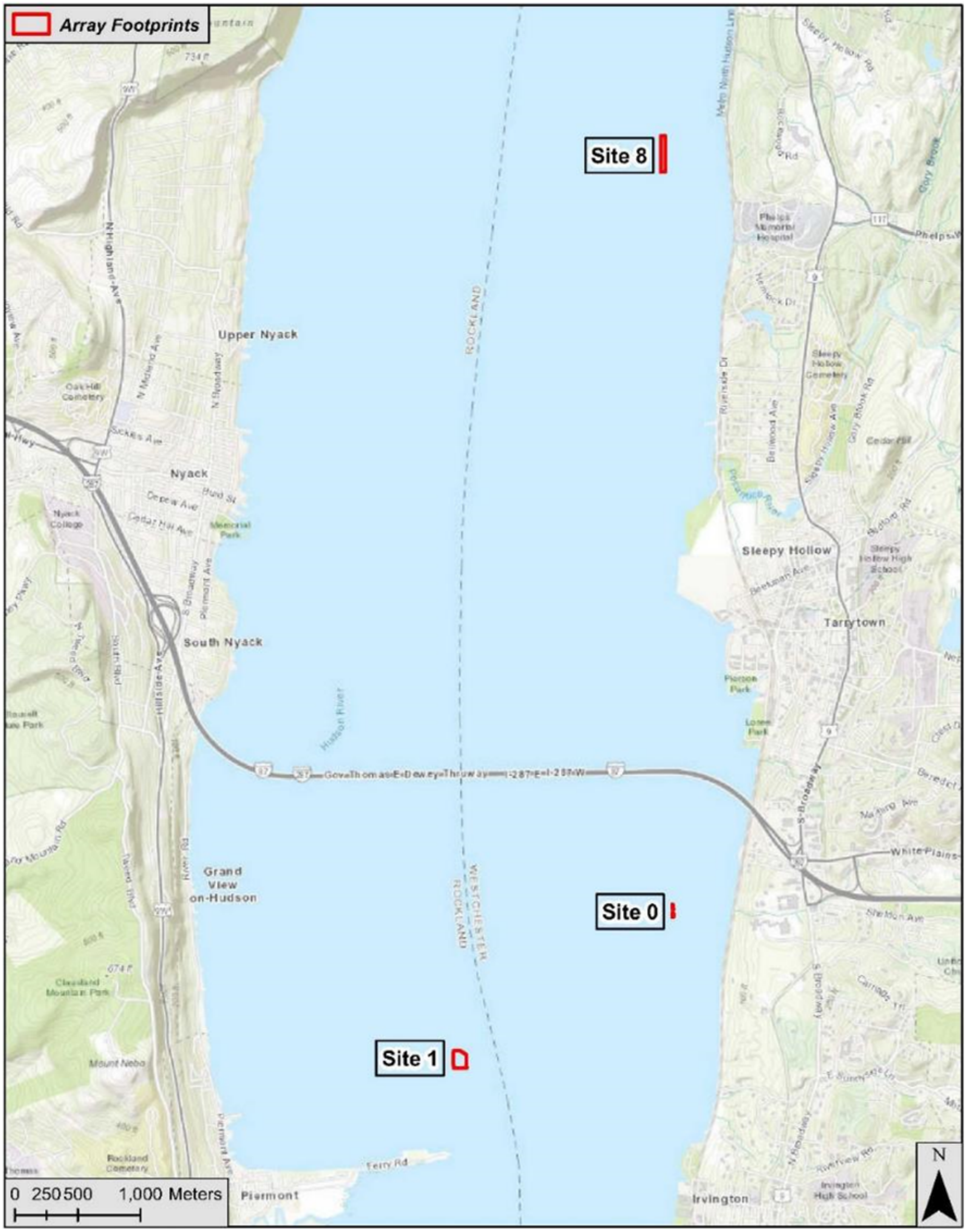


Fig. 1. Locations of Sites 0 (Glove), 1, and 8 for Tier 4 water quality monitoring.

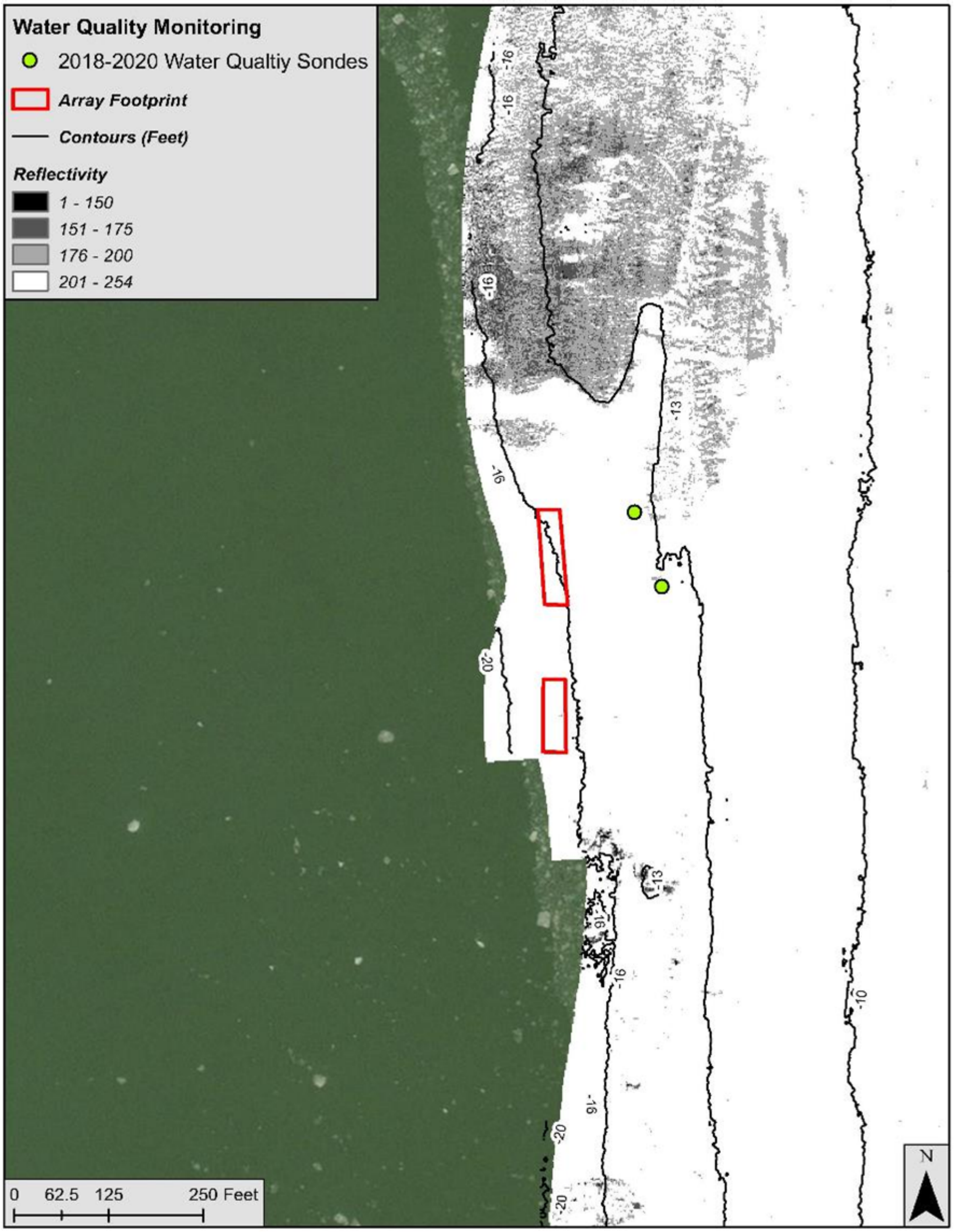


Figure 2: Site 0 Oyster Monitoring and Restoration Array Locations

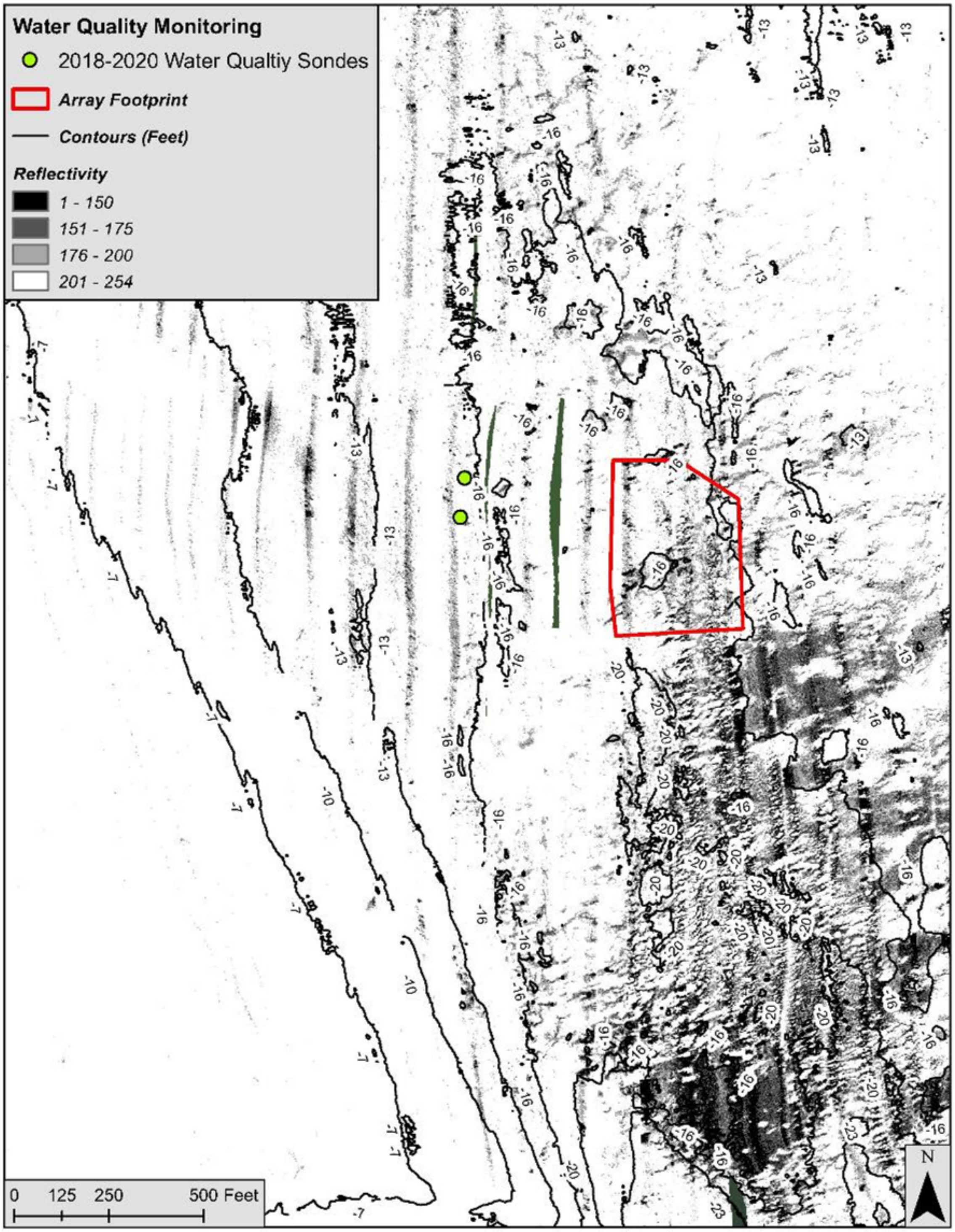


Figure 3: Site 1 Oyster Monitoring and Restoration Array Locations

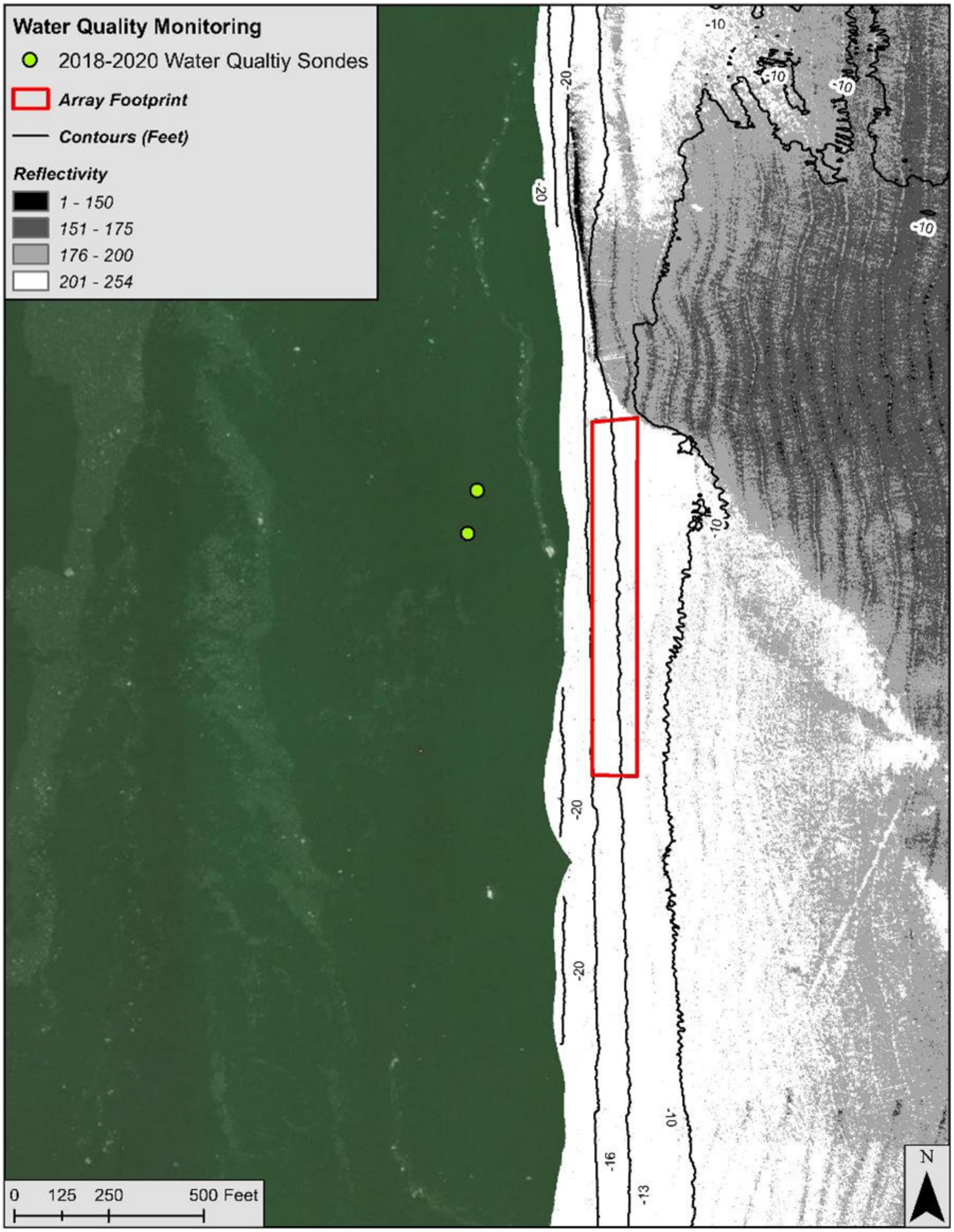


Figure 4: Site 8 Oyster Monitoring and Restoration Array Locations

RESULTS AND DISCUSSION

Following deployment on April 28 and May 5, the conductivity and DO loggers were retrieved and downloaded on June 2, July 2, August 1, September 2, September 30, and November 4. During some download events, one or more loggers could not be found, but were later retrieved during a subsequent download event. Some units had memory capacities that filled between downloads, failed to launch properly after a download, had batteries that died between downloads, or otherwise failed due to excessive fouling or other factors during the season, resulting in incomplete time series of data from some locations. These failures occurred more often than in past seasons because of the age and wear and tear of the instruments, and an error made by the manufacturer of the DO loggers. After being sent in for calibration, the DO loggers were returned from the manufacturer still in calibration mode, which affected the configurations and readings taken during the first month of deployment, and consumed battery life at a much faster rate than normal. The manufacturer notified us that upon initial deployment, there was no way for us to have known the units were still configured to calibration mode. The manufacturer was able to salvage some DO data from the calibration files, which are included here among the other DO data subsequently collected during the remainder of the season, and the issue was corrected after the first month of deployment. However, unbeknownst to us at the time, calibration mode consumes significantly more battery power than normal recording mode, and so we sometimes retrieved units throughout the season that had dead batteries and little to no data recorded since the prior download event even though the loggers had new batteries at the start of the season. This resulted in an incomplete time series of DO data from each site. The conductivity logger for Location 2 at Site 8 did not work properly at the beginning of the season and its replacement was first deployed on August 1. As such, no salinity data were obtained from that location earlier in the season, although salinity data were obtained from the duplicate location at Site 8. Finally, beginning with the September 2 download, there was excessive fouling on the instruments that was far more substantial than was observed from past seasons. The sensors of the instruments were heavily encrusted in multiple layers of barnacles, preventing them from collecting accurate conductivity and DO data. The data from the second half of each monthly sampling period, particularly from August onward, should therefore be interpreted with caution, as excessive fouling is expected to have begun interfering with data quality within about two weeks of the instruments being cleaned during each download event.

The most complete time series for salinity, DO, and temperature for each plot within each site are shown in **Appendices A, B, and C** respectively.

Salinity: Salinities observed across the three sites ranged from a minimum of 0.1 to a maximum of 20.5 PSU. Mean salinity was comparable among sites, with the highest and lowest means differing by only 1.4 PSU. In 2020, Site 0 had the highest mean salinity, followed by Site 1 and Site 8 (**Table 2**). Site 1 had the highest salinity on average in 2018 and 2019. Salinity at Site 0 averaged 1.1 PSU higher than in 2019 while averaging the same at Site 1 and 0.1 PSU higher at Site 8. The maximum salinity value recorded at Site 0 (20.5 PSU) was also considerably higher than in 2019 (15.7 PSU), whereas maximum salinities at the other two sites deviated by only 0.5 PSU or less from the maxima in 2019. Frequency distributions also show salinity to have been high on the most occasions at Site 0 followed by Site 1 and then Site 8 (**Appendix A**). For example, salinity was 10 PSU or greater 19% of the time at Site 0, 8% of the time at Site 1, and only 1% of the time at Site 8. Observations of low salinity did not follow the same pattern, however, and were comparable among sites (**Appendix A**). Salinity was less than 5 PSU 62% of the time at Site 0, 54% of the time at Site 1, and 64% of the time at Site 8. This is 5 to 12% less often than salinity was below 5 PSU at each site in 2019. This could be partly attributable to the later deployment of the conductivity loggers in 2020 (May 5) than in 2019 (April 2) since salinity levels in the river tend to gradually increase from spring into summer.

Table 2. Summary Statistics of Salinity Levels (PSU) at Sites 0, 1, and 8, May 5 – November 4, 2020

Site	Minimum	Maximum	Mean	10th Percentile	90th Percentile
0	0.1	20.5	4.8	0.4	11.6
1	0.1	20.3	4.4	0.1	9.6
8	0.1	14.9	3.4	0.2	8.3

The temporal trends in salinity during 2020 are difficult to discern and interpret due to the fouling that interfered with the measurements during the latter half of each month-long period between download events. This effect was most apparent from mid-July onwards, when fouling was the most extreme. Each site showed multimodal distributions in salinity over time, with the sharp rises coinciding with the cleaning of the instruments around the first day of each month, followed by steep declines as fouling began to accumulate again. Focusing on only the first week after each download event, when instruments were recently cleaned and likely the most accurate, one can see a general increase in salinity from the beginning of the monitoring period in early May, when it was consistently between 0 and 5 PSU, to late May/early June and through the end of July when it was between approximately 5 and 10 PSU. Salinity then decreased slightly at each site during August, rose during September, and then remained at similar levels in October (**Appendix A**). However, the effects of fouling were most extreme during August and September, making it difficult to compare salinity measurements from then to those from earlier in the season. Additionally, the loggers at Site 1 appear to have malfunctioned between the August 1 and September 30 downloads. The near-zero salinity levels recorded at this site from August 1 to September 30 are highly questionable given that salinities during that time period were considerably higher at Sites 0 and 8, and at the nearby USGS monitoring station off of Piermont Pier. The USGS data from Piermont show salinity to remain above 6 PSU from August 1 through October.

Dissolved Oxygen: The time series of DO from each location is illustrated in **Appendix B** and the mean, minimum, and maximum values are reported in **Table 3.** DO levels measured across the three sites ranged from a minimum of 0.03 mg/L to a maximum of 15.60 mg/L. Site 0 had the highest mean (8.67 mg/L) followed by Site 1 and then Site 8, but the highest and lowest means differed by only 0.58 mg/L. Compared to 2019, DO in 2020 averaged 45% higher at Site 0, 29% higher at Site 1, and 23% higher at Site 8. This may be due, in part, to the considerably colder water temperatures in 2020 than 2019 (see below) because DO is inversely related to water temperature.

DO at each site followed the same general trend of decreasing levels from May through the summer as water temperatures rose, followed by a gradual increase in the fall as the water began to cool again. As with salinity, the scatter plots of DO levels at each site show a multimodal distribution largely driven by the monthly cycles of fouling and cleaning of the instruments (**Appendix B**).

The low DO (< ~3 mg/L) at each site throughout August coincided with the peak in temperature, but also with the time when fouling was most extreme and prevented the DO loggers' sensors from making direct contact with the water. This raises uncertainty about the accuracy of the data. However, DO was also at its lowest from July through August, commonly reaching zero or near-zero, at the USGS monitoring station off of Piermont Pier. It is therefore likely that the three oyster monitoring sites also experienced a prolonged period of low DO during August. Otherwise, however, DO was seldom low and never for long amounts of time at other points in the season. Frequency distributions show that over the course of the sampling period, DO was measured at < 3 mg/L only 8% of the time at Site 0, 15% of the time at Site 1, and 17% of the time at Site 8. Likely because of colder water temperatures, this is less than what was observed in 2019, when DO was < 3 mg/L 24% of the time at Site 0, 22% of the time at Site 1, and 18% of the time at Site 8.

Table 3. Summary Statistics of Dissolved Oxygen Levels (mg/L) at Sites 0, 1, and 8, April 28 – November 4, 2020

Site	Minimum	Maximum	Mean	10th Percentile	90th Percentile
0	0.1	15.6	8.7	5.1	10.4
1	0.3	14.6	8.3	0.9	10.4
8	0.1	13.0	8.1	1.0	10.5

Temperature: The time series of temperature readings from each location are illustrated in **Appendix C** and summary statistics are reported in **Table 4.** Temperatures across the three sites during the monitoring period ranged from a low of 9.0º C to a high of 30.1º C. The three sites had similar mean temperatures over the course of the monitoring period, differing by only 0.7º C. The three sites also had similar minimum temperatures that ranged between 9.0 and 9.7º C, and maximum temperatures that ranged between 29.5 and 30.1º C (**Table 4**). All sites showed the same temporal pattern, with temperatures increasing from approximately 10º C at the start of the monitoring period on April 28 to a peak of nearly 30º C in late July/early August, and then steadily decreasing again towards the end of the monitoring period in early November (**Appendix C**).

Compared to 2019, minimum and maximum temperatures were greater at each site, but mean, 10^{th} percentile, and 90^{th} percentile temperatures were all lower. Temperature averaged 23% lower at Site 0, 24% lower at Site 1, and 15% lower at Site 8 in 2020 than in the previous year despite beginning the monitoring nearly one month later in the spring and ending it nearly one month earlier in the fall. As noted above, these colder water temperatures may largely explain the higher levels of DO observed in 2020 than in 2019.

Table 4. Summary Statistics of Temperature (ºC) at Sites 0, 1, and 8, April 28 – November 4, 2020

Site	Minimum	Maximum	Mean	10th Percentile	90th Percentile
0	9.4	29.5	16.3	11.0	26.6
1	9.0	29.5	16.6	11.2	26.1
8	9.7	30.1	17.0	11.0	26.6

Associations with Substrate Monitoring Results: Post-restoration monitoring conducted by the HRF in the fall of 2019 and 2020 found oysters to successfully colonize and survive at all three sites but with significant differences in oyster density and size among sites. In both years and across both substrate types (reef balls and gabions), oyster density and size were significantly greater at Site 0 than at Sites 1 and 8. Size class distributions indicated that Site 0 also had the highest recruitment of the three sites in 2020, although this was not the case the previous year. Collectively, the oyster monitoring results from 2020 suggest possible better conditions for recruitment, growth, and survival at Site 0 than at the other sites.

Site 0 had the highest mean salinity of the three sites in 2020. It also averaged higher salinity in 2020 than in 2019, while average salinity did not change from 2019 to 2020 at the other two sites. This may partly explain why Site 0 had better recruitment (as indicated by more small size classes) in 2020 than in 2019, and why density and size were greater at Site 0 than at the other sites. However, the frequency of low-salinity (< 5 PSU) events, which may be a more important factor affecting oyster performance than high-salinity events and a high average salinity, were comparable among sites in 2020.

DO in 2020 averaged the highest at Site 0, although the highest and lowest means of the three sites differed from each other by only 0.6 mg/L. DO was also low (< 3 mg/L) only half as frequently at Site 0 as at Sites 1 and 8. However, low-DO events were less frequent in 2020 than in 2019 at every site while recruitment improved only at Site 0. Therefore, the frequency of low-DO events is unlikely to account for the better recruitment at Site 0 than at the other sites.

There were no obvious site differences in salinity or DO in past years (2018 and 2019) to explain site differences in oyster metrics. Further, relative differences in salinity, DO, and oyster performance among sites have not been consistent from year to year. In 2020, salinity may have partly contributed to the better performance at Site 0, but overall, inter-site differences in salinity and DO have been minor each year, and all three sites have shown consistent, substantial recruitment and reef development over the monitoring period. Oysters appear to be thriving at all three restoration sites despite yearly, prolonged periods of low salinities that were previously believed to be too far below the salinity tolerance thresholds of eastern oysters to support viable populations. This is consistent with Matt Hare's molecular work demonstrating a genetic basis for greater tolerance of low salinities among Tappan Zee oysters than oysters in higher saline waters of the southern portions of the Hudson/Raritan estuary. Further monitoring will be needed to confirm long-term viability of the reefs forming at each of these sites, but observations thus far indicate the restoration effort has been highly successful and that water quality conditions at all three sites are suitable for supporting robust levels of oyster reproduction, development, and survival.

APPENDIX A

SALINITY FIGURES

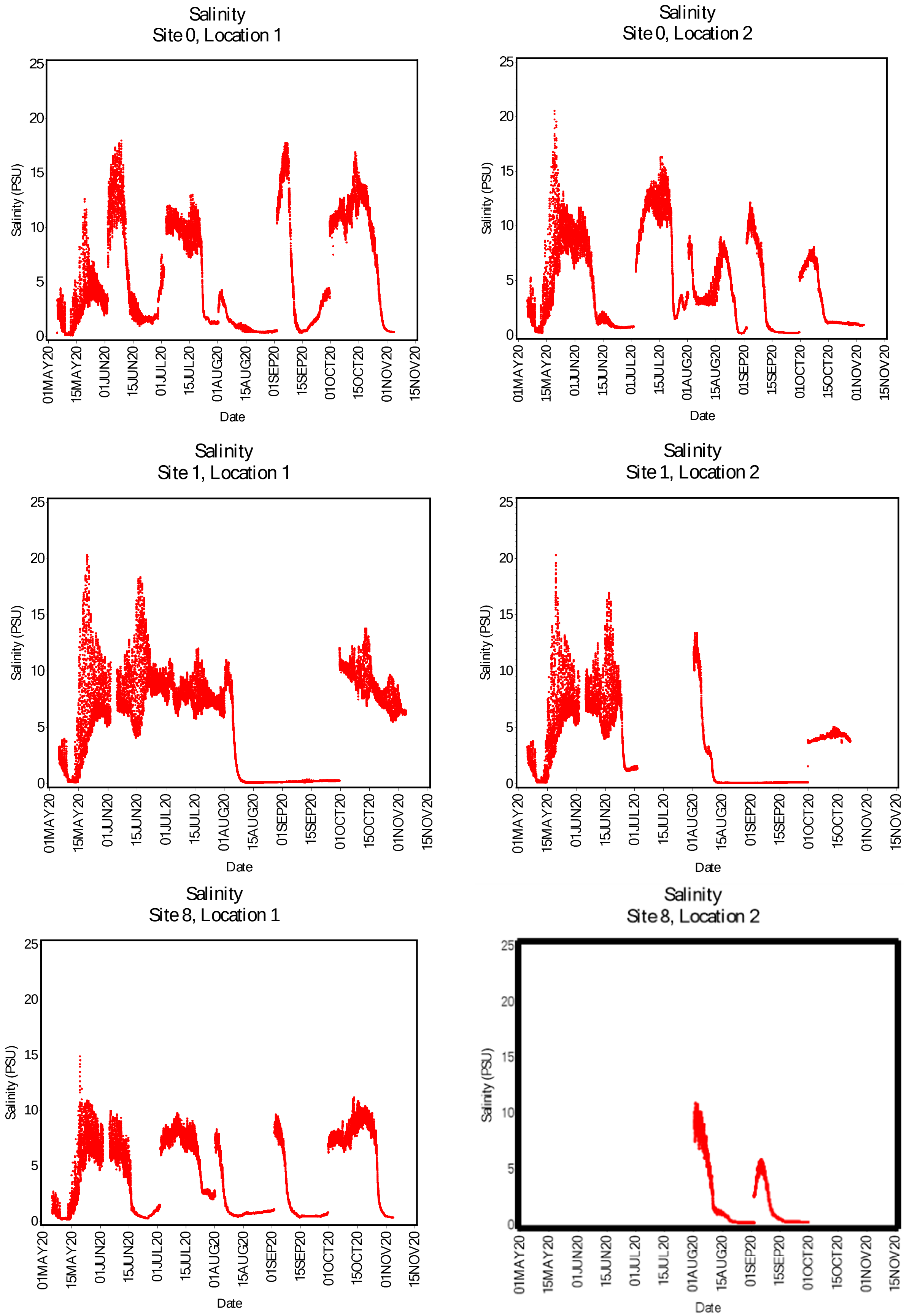


Figure A-1. Temporal trends in salinity at locations 1 (left) and 2 (right) at Sites 0, 1, and 8.

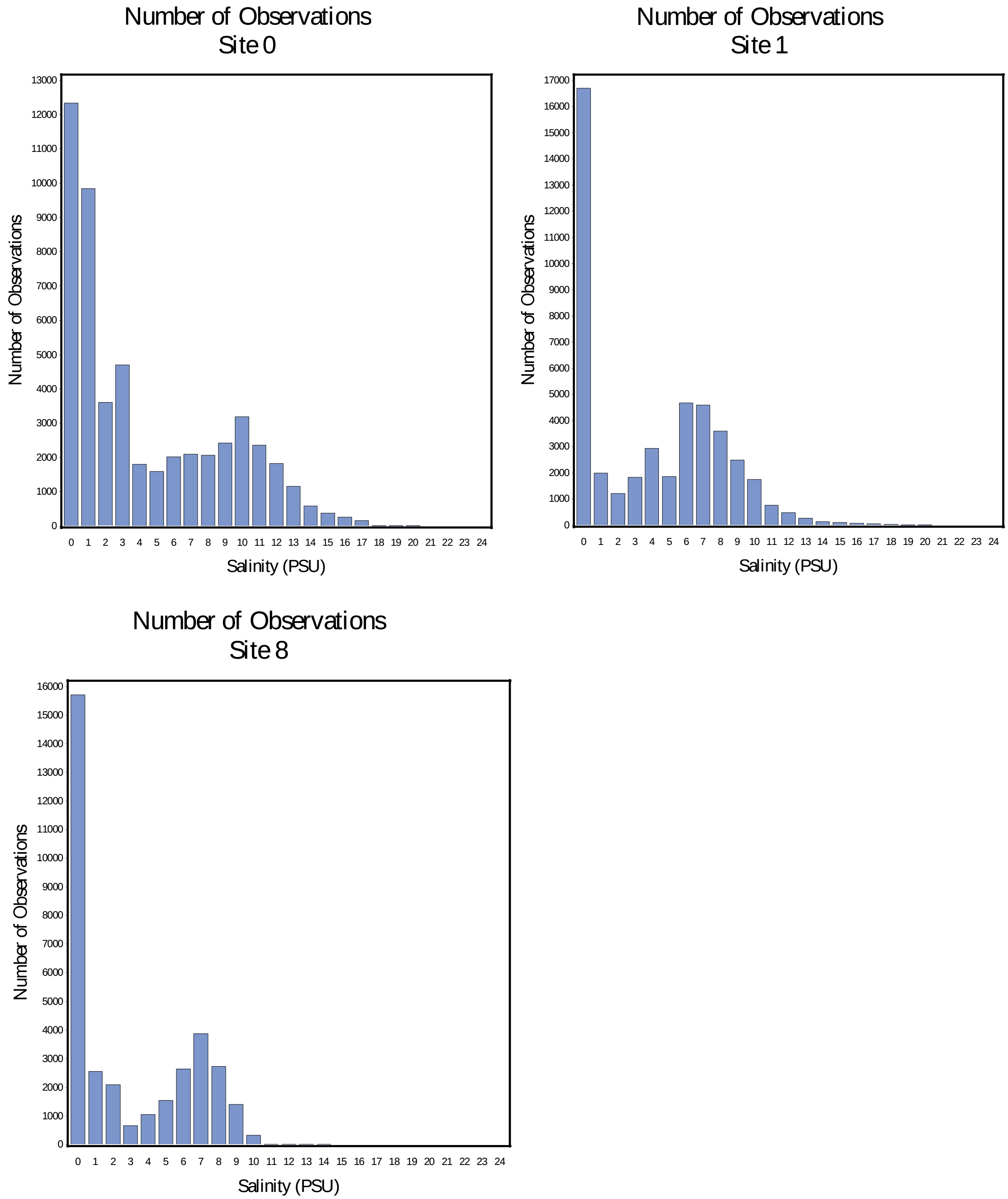


Figure A-2. Salinity frequency distribution at Sites 0, 1, and 8 (locations 1 and 2 combined)

APPENDIX B

DISSOLVED OXYGEN FIGURES

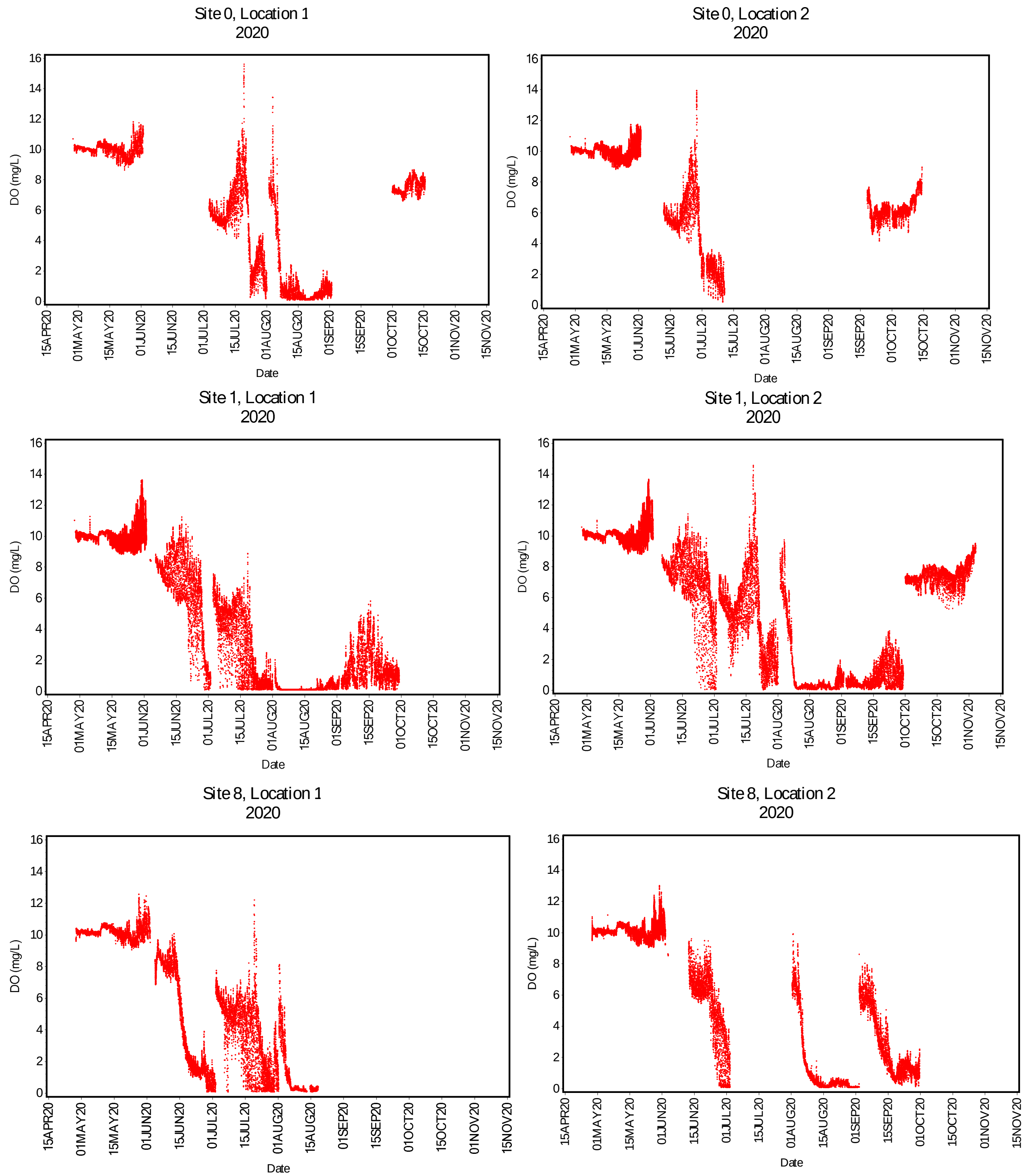


Figure B-1. Temporal trends in dissolved oxygen at locations 1 (left) and 2 (right) at Sites 0, 1, and 8

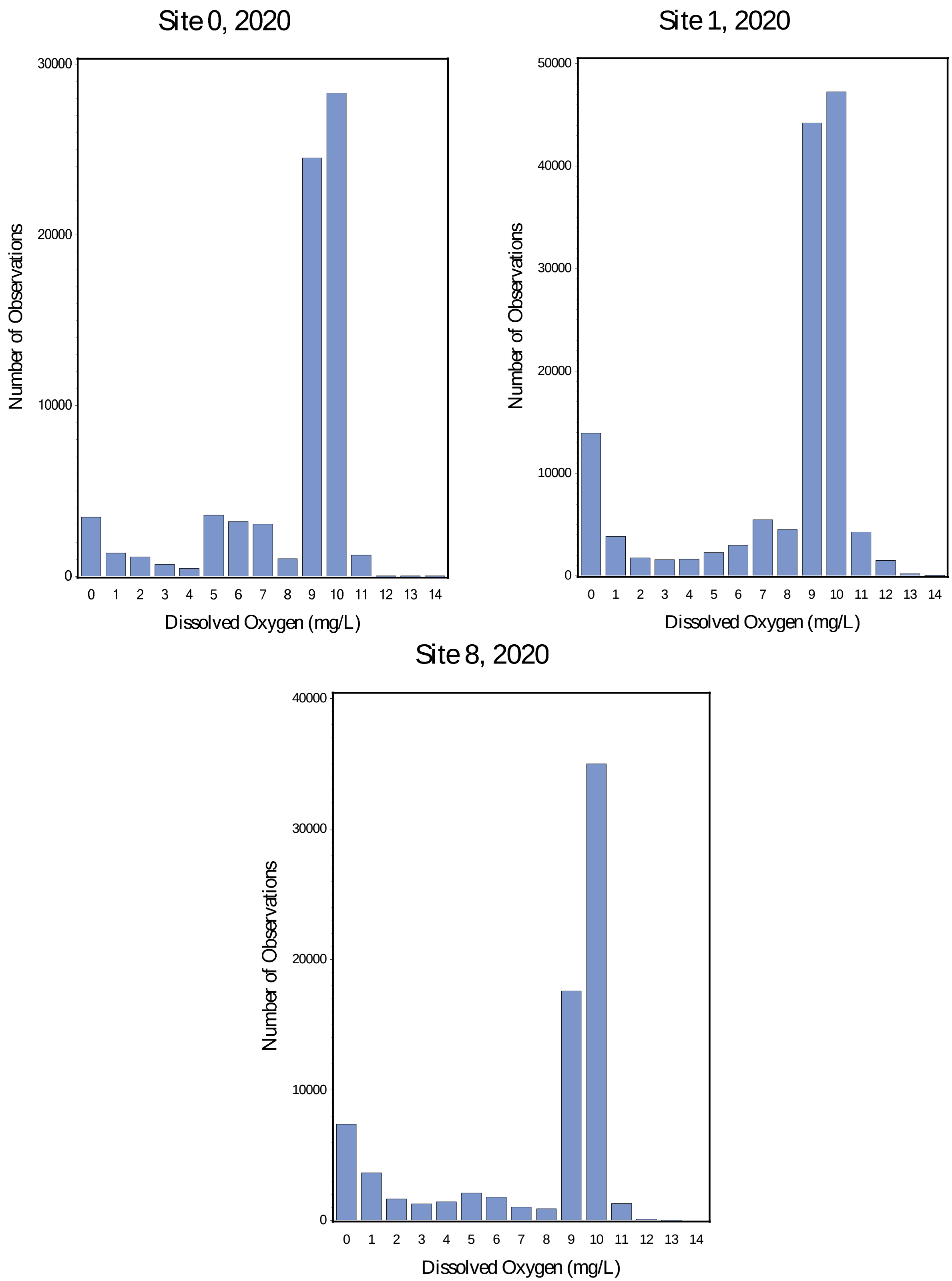


Figure B-2. Dissolved oxygen frequency distribution at Sites 0, 1, and 8 (locations 1 and 2 combined).

APPENDIX C

TEMPERATURE FIGURES

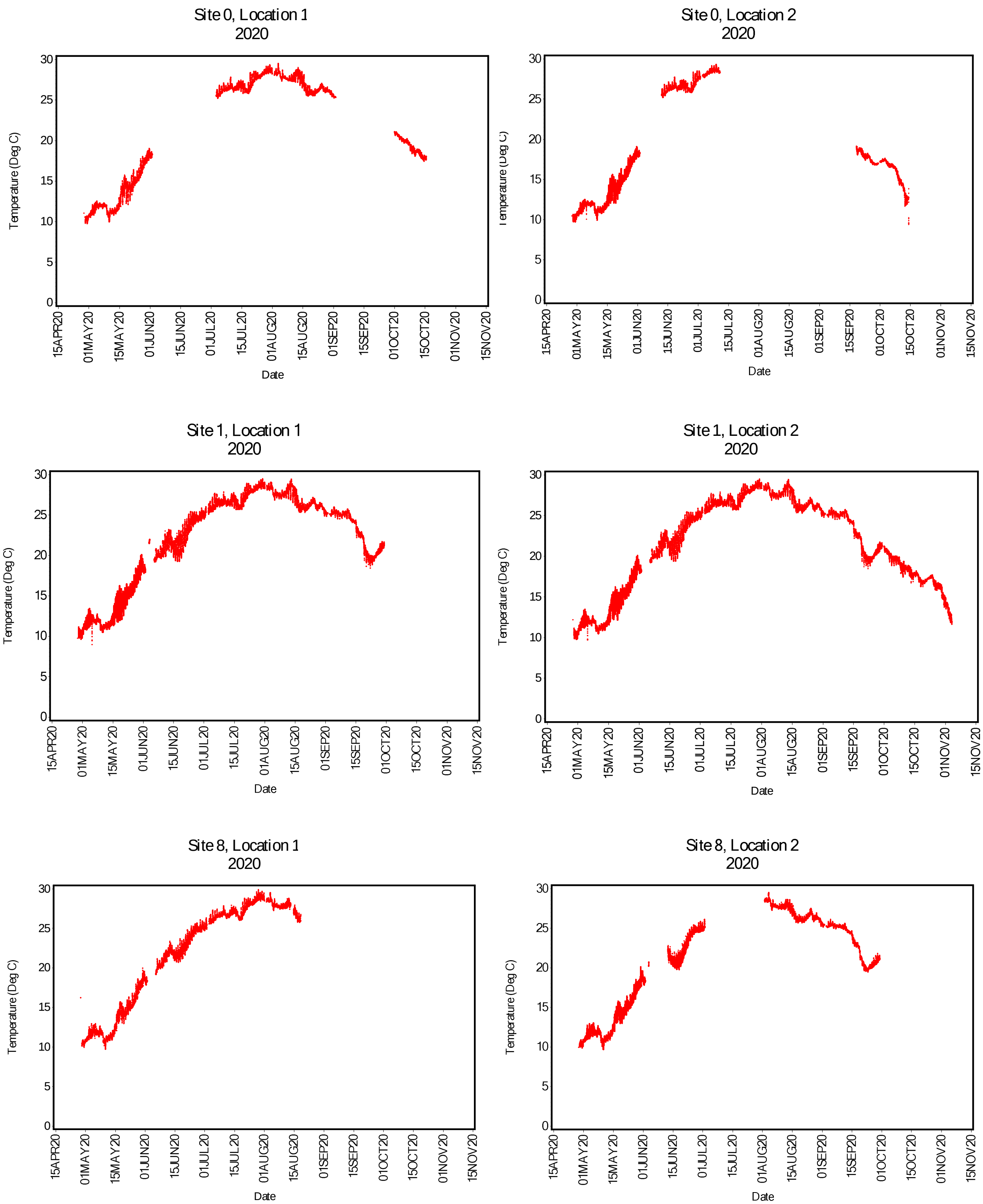


Figure C-1. Temporal trends in temperature (ºC) at locations 1 (left) and 2 (right) at Sites 0, 1, and 8.

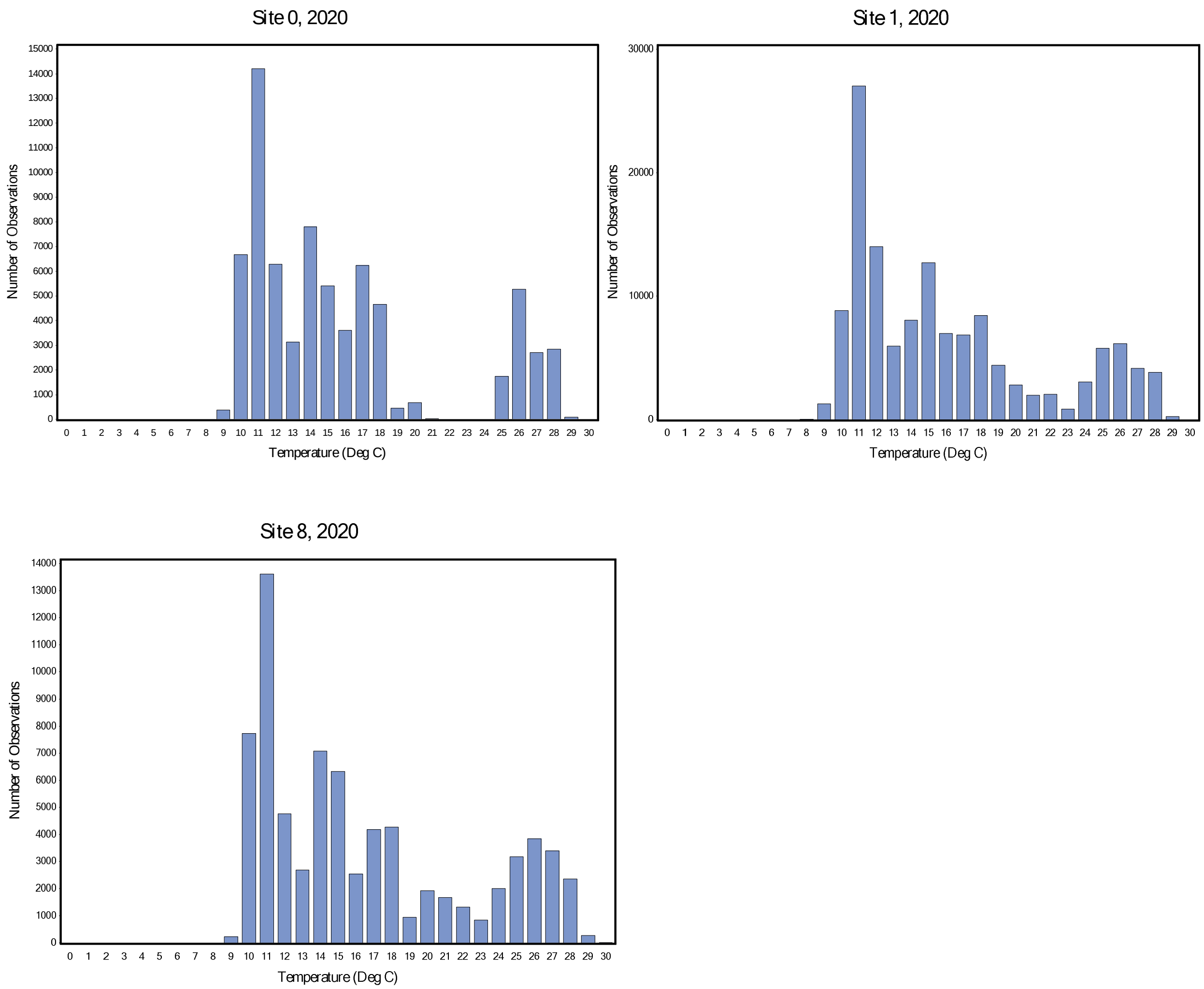


Figure C-2. Temperature frequency distribution at Sites 0, 1, and 8 (locations 1 and 2 combined).

APPENDIX D

FINAL REPORT TIER 3 TAPPAN ZEE BRIDGE
OYSTER RESTORATION PILOT STUDY

FINAL REPORT

Tier 3 Tappan Zee Bridge Oyster Restoration Pilot Study – University of New Hampshire

January 17, 2018

Submitted to: Fred Jacobs, AKRF, Inc.

Submitted by: Jim Lodge[1], Ray Grizzle[2], Krystin Ward[2], Pete Malinowski[3]
Katie Mosher Smith[3]

Introduction and Background

This report describes the results of a 3-year (2015-2017) pilot study conducted by the Hudson River Foundation (HRF) in partnership with the University of New Hampshire (UNH) and the NY Harbor Foundation under the direction of AKRF, Inc. and the New York State Thruway Authority (NYSTA). The goal of the study was to inform the design of the Tappan Zee Bridge Oyster Restoration Project by providing information on the performance of three potential restoration substrates at three potential restoration sites. The performance metrics included attracting (recruiting) oysters (*Crassostrea virginica*), supporting oyster growth and survival, and the longevity and sustainability of the three different substrates and construction techniques: 1) metal gabion cages containing oyster shells; 2) small Reef Balls ("Lo-Pro"); and 3) larger Reef Balls ("Mini-Bay").

Methods

Study Design

Three replicates of each of the three test substrates were deployed on June 22, 2015 at three sites in the general vicinity of the Tappan Zee Bridge (Fig. 1). Each replicate consisted of one of each of the test substrates attached by a line so that all three substrates could be retrieved in one effort. This design allowed comparisons to be made among substrates and among sites. The three sites were chosen based on a previous study that characterized the occurrence at all three sites of live oysters at densities comparable to other areas in the northeastern US, and were among the sites recommended for further study (Princeton Hydro 2015). The present study was done in conjunction with another Tier 3 study aimed at characterizing water quality conditions and oyster recruitment in the same study area (AKRF 2016a, b).

[1] Hudson River Foundation, [2] University of New Hampshire, [3] Billion Oyster Project

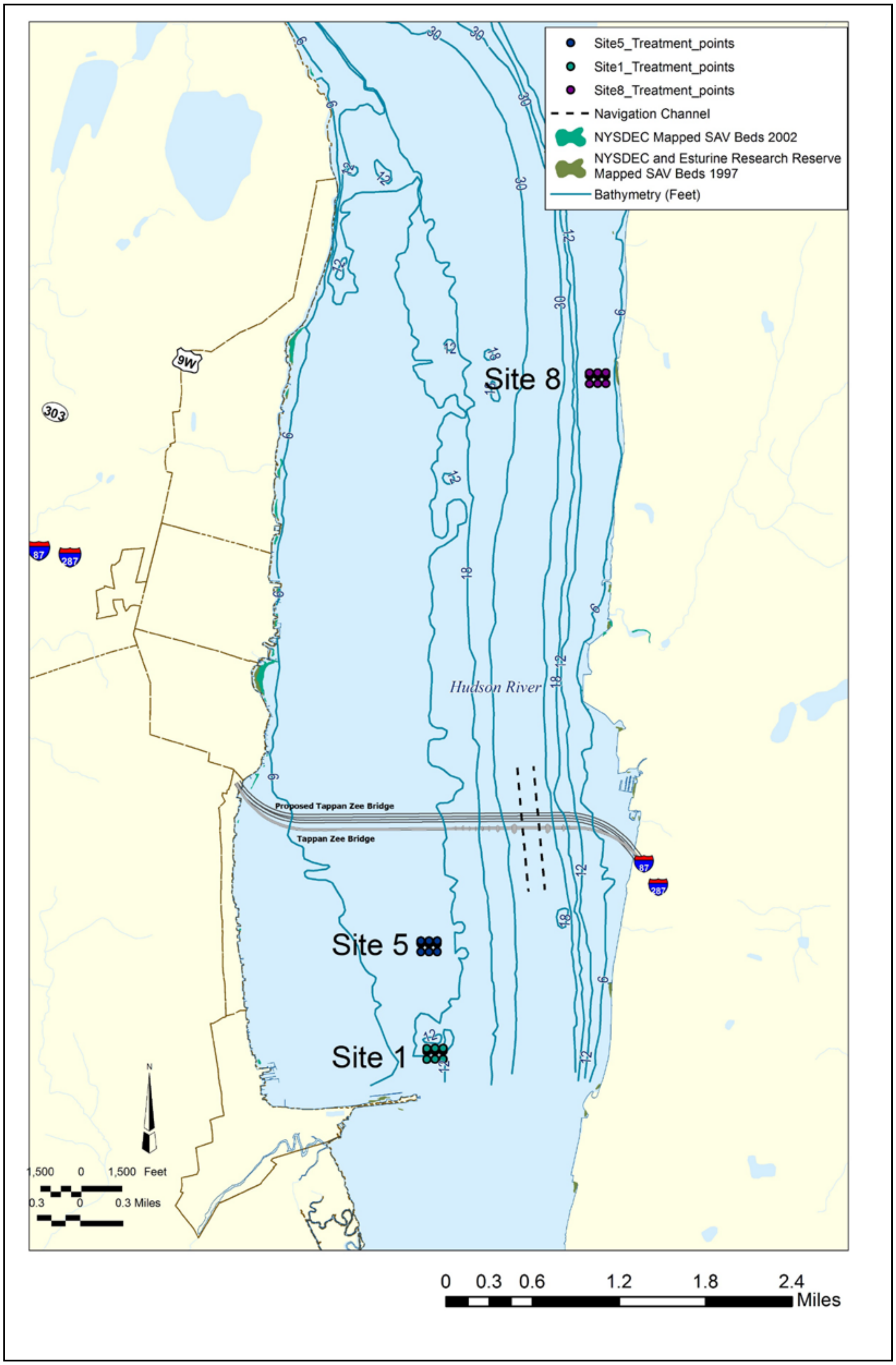


Fig. 1. Sites (1, 5, and 8) where test substrates were deployed.

Oyster Sampling

Similar sampling methods were used all 3 years of the study, but there were important variations among the years due to differences in the number of substrates retrieved for monitoring, differences in substrate characteristics that affected sampling effectiveness, and other issues (Table 1). In brief, the monitoring effort prioritized the collection of a minimum of one replicate at each of the three sites and when feasible, an additional replicate was retrieved for monitoring. The Gabions were sampled by extracting 1 or 2 of the 8 "mini-gabions" (~32 cm x 32cm x 32 cm cube) that were assembled to form each overall gabion substrate, removing the shell cultch material, and counting and measuring some subset of the live oysters on the cultch. Both types of Reef Balls were sampled by counting and measuring (shell height using calipers or ruler) all live oysters in replicate quadrats, except in 2017 when all live oysters on the outside of each Reef Ball were counted and measured. Details on the methods for 2015 and 2016 are described in the previous progress reports (Lodge et al. 2016, 2017). For 2017, the major change was counting all the live oysters on the outer surfaces of both types of Reef Balls, instead of quadrat sampling. This was done because of the low densities of oysters on the Reef Balls. This change insured that sufficient data were collected to adequately characterize the size and density of oysters, but also resulted in fewer replicates. For all 3 years and all 3 substrates the density data were expressed in per m^2 units.

Table 1. Summary of sampling methods for measuring oyster metrics.

Year	Site	Substrate Type	Sampling Method	# Samples Collected
2015	1	Gabion	mini-gabions extracted; live oysters counted; 50 oysters measured	2
		Mini-Bay	0.1 m^2 quadrats; live oysters counted and measured	4
		Lo-Pro	0.1 m^2 quadrats; live oysters counted and measured	4
	5	Gabion	mini-gabion extracted; live oysters counted; 50 oysters measured	1
		Mini-Bay	(no live oysters in quadrats)	4
		Lo-Pro	(no live oysters in quadrats)	4
	8	Gabion	mini-gabions extracted; live oysters counted; 50 oysters measured	2
		Mini-Bay	0.1 m^2 quadrats; live oysters counted and measured	4
		Lo-Pro	0.1 m^2 quadrats; live oysters counted and measured	4
2016	1	Gabion	mini-gabion extracted; live oysters counted; 50 oysters measured	1
		Mini-Bay	0.025 m^2 quadrats; live oysters counted and measured	4
		Lo-Pro	0.025 m^2 quadrats; live oysters counted and measured	3
	5	Gabion	mini-gabion extracted; live oysters counted; 50 oysters measured	1
		Mini-Bay	0.025 m^2 quadrats; live oysters counted and measured	4
		Lo-Pro	0.025 m^2 quadrats; live oysters counted and measured	7
	8	Gabion	mini-gabions extracted; live oysters counted; 50 oysters measured	4
		Mini-Bay	0.025 m^2 quadrats; live oysters counted and measured	8
		Lo-Pro	0.025 m^2 quadrats; live oysters counted and measured	7
2017	1	Gabion	(no substrate retrieved)	0
		Mini-Bay	all live oysters counted and measured	1
		Lo-Pro	all live oysters counted and measured	1
	5	Gabion	mini-gabions extracted; live oysters counted; 50 oysters measured	2
		Mini-Bay	all live oysters counted and measured	2
		Lo-Pro	all live oysters counted and measured	2
	8	Gabion	mini-gabions extracted; live oysters counted; 50 oysters measured	2
		Mini-Bay	all live oysters counted and measured	2
		Lo-Pro	all live oysters counted and measured	2

Fouling community

Oysters are typically only one of the species making up the overall (fouling) community of invertebrates that naturally develops on hard substrates in estuarine waters (i.e., the "oyster reef community"). The non-oyster component of the fouling community was characterized by taking replicate photographs of 0.025 m^2 quadrats placed randomly on each of the Reef Ball substrates and three of the gabions, and processing the photographs in the laboratory. All invertebrates were identified to the lowest taxonomic level practical (species in most cases; voucher specimens were returned to the laboratory for identification) and counted; data were expressed in per m^2 units.

Results and Discussion

Although there was wide variability in the numbers of replicate samples of the substrates collected each year (Table 1), sufficient data were collected to address the three major performance metrics: attracting (recruiting) oysters, supporting oyster growth and survival, and the longevity and sustainability of the three different substrates and construction techniques. Additionally, the overall fouling community that developed on the substrates was characterized all 3 years, focusing on how other species might affect development of oyster populations on the substrates.

One replicate (with all three substrate types) was retrieved from Site 8 on October 15, 2015 and from Sites 1 and 5 on October 16, 2015 (Table 1; Fig 2). These samples represented 4 months of development of the invertebrate communities on the test substrates. All three substrates from all three sites were in good condition. The major issue was in locating and connecting with the substrate lines, resulting in only one complete set of substrates being retrieved from each site. The gabion at Site 5 was also damaged.

One replicate (with all three substrate types) was retrieved from Site 8 on October 24, 2016 and from Sites 1 and 5 on October 25, 2016 (Table 1; Fig. 2). These samples represented 16 months of development of the invertebrate communities on the test substrates. All of the substrates were in good condition, except two of the mini-gabions had been lost from one of the gabions at Site 5 and the rebar used for framing the gabions showed signs of deterioration (Fig. 2).

Two complete replicates from Site 8 and one complete replicate from Site 5 were retrieved on October 17, 2017. One replicate was retrieve from Site 1 on October 18 but the gabion was missing (Table 1; Fig. 2). Most of the Reef Balls were in good condition, except some that may have been damaged in the sampling process. In contrast, most of the gabions showed signs of deterioration that in large measure appeared to be the result of failure of the rebar framing from broken welds.

Fig. 2. Retrieval of test substrates by year and site. Note damaged gabions all three years.

Oyster Metrics

Figures 3 – 5 below provide photographic documentation of the overall 3-year development of oyster reef communities (oyster populations and other fouling organisms) on the test substrates at each of the three study sites. Although substantial quantitative differences were evident (as discussed below), there was good oyster reef development on all three substrates and at all three sites.

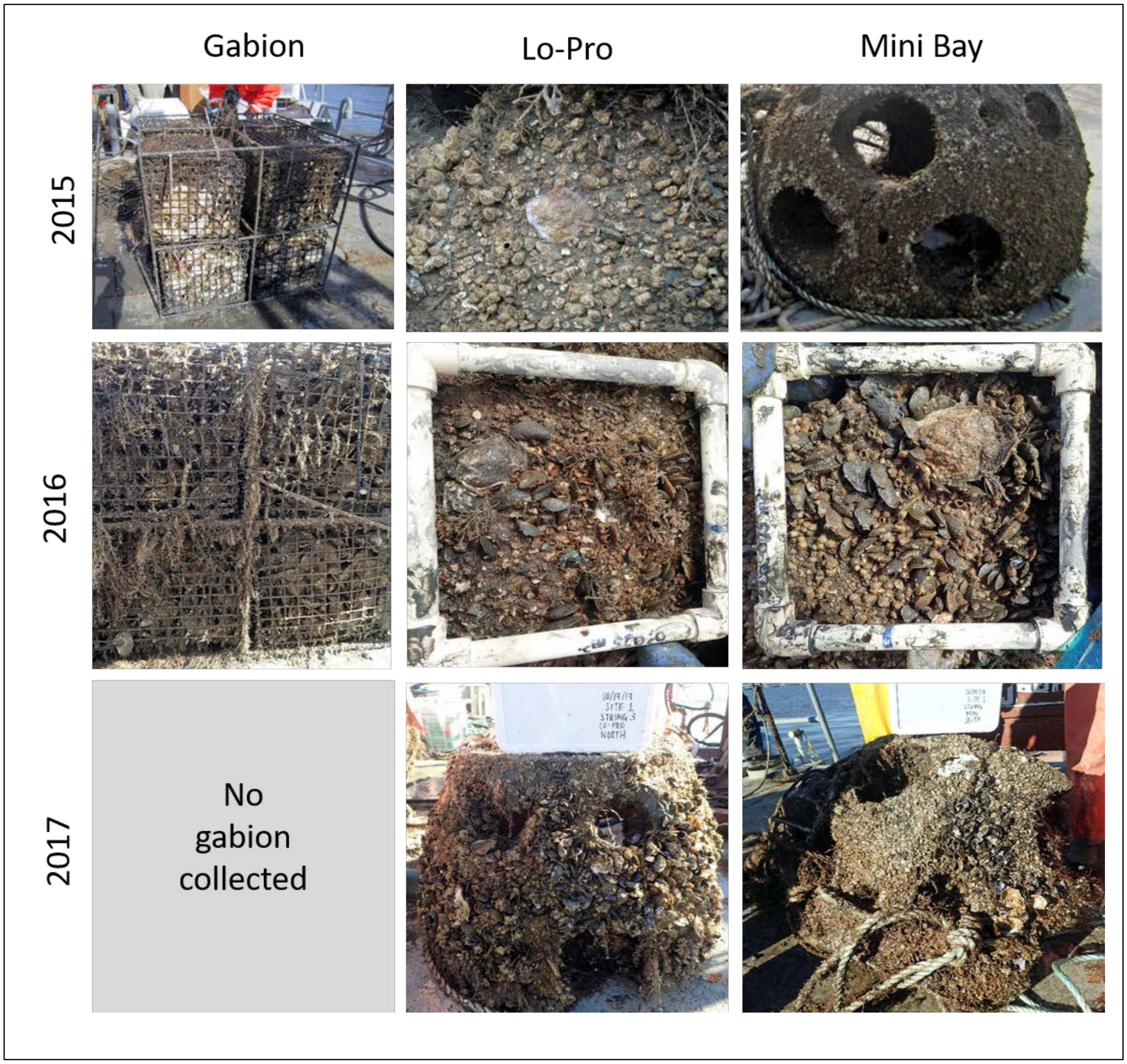


Fig. 3. Example photos of the oyster reef community on three substrate types each of the three years from Site 1.

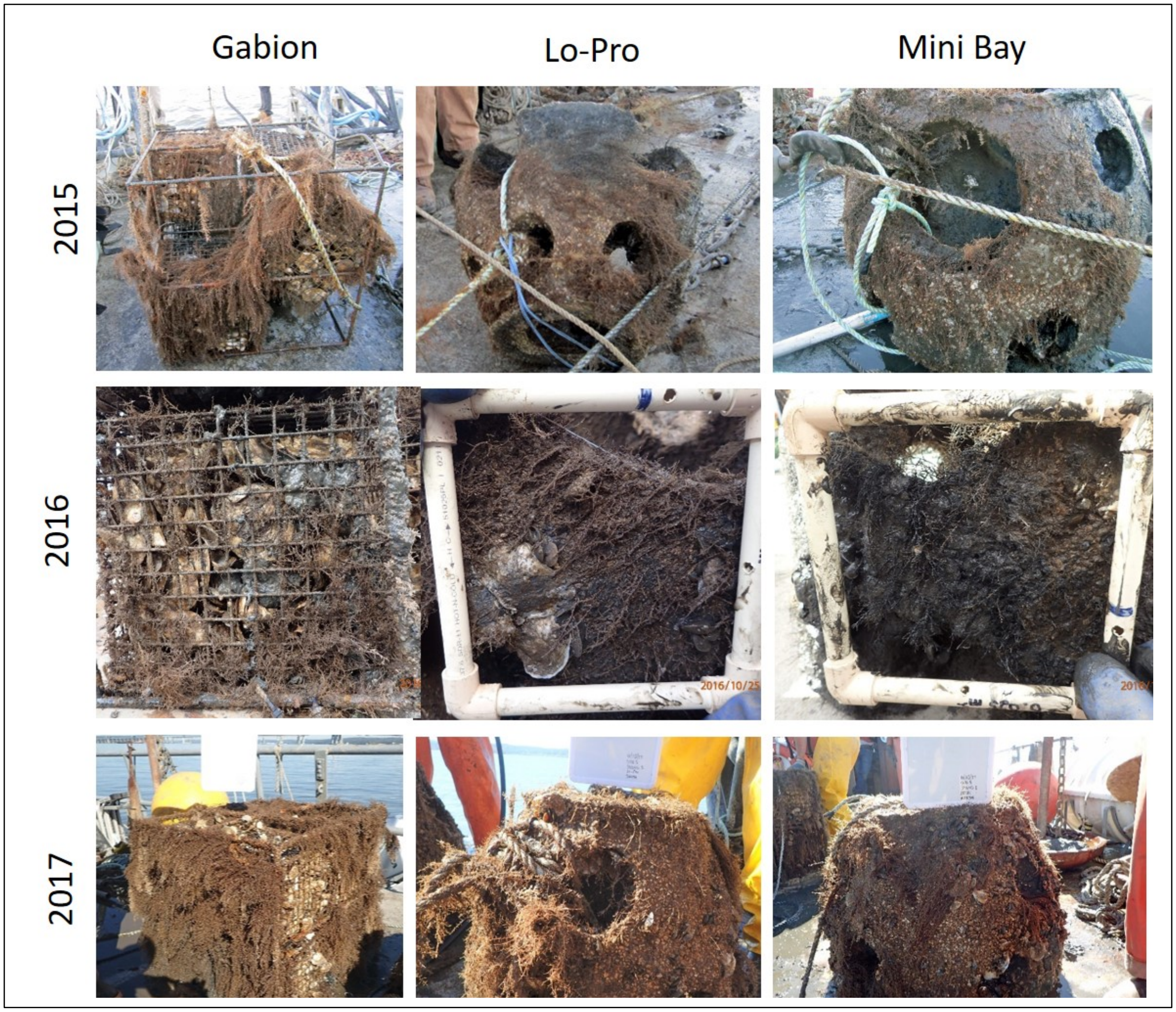


Fig. 4. Example photos of the oyster reef community on three substrate types each of the three years from Site 5.

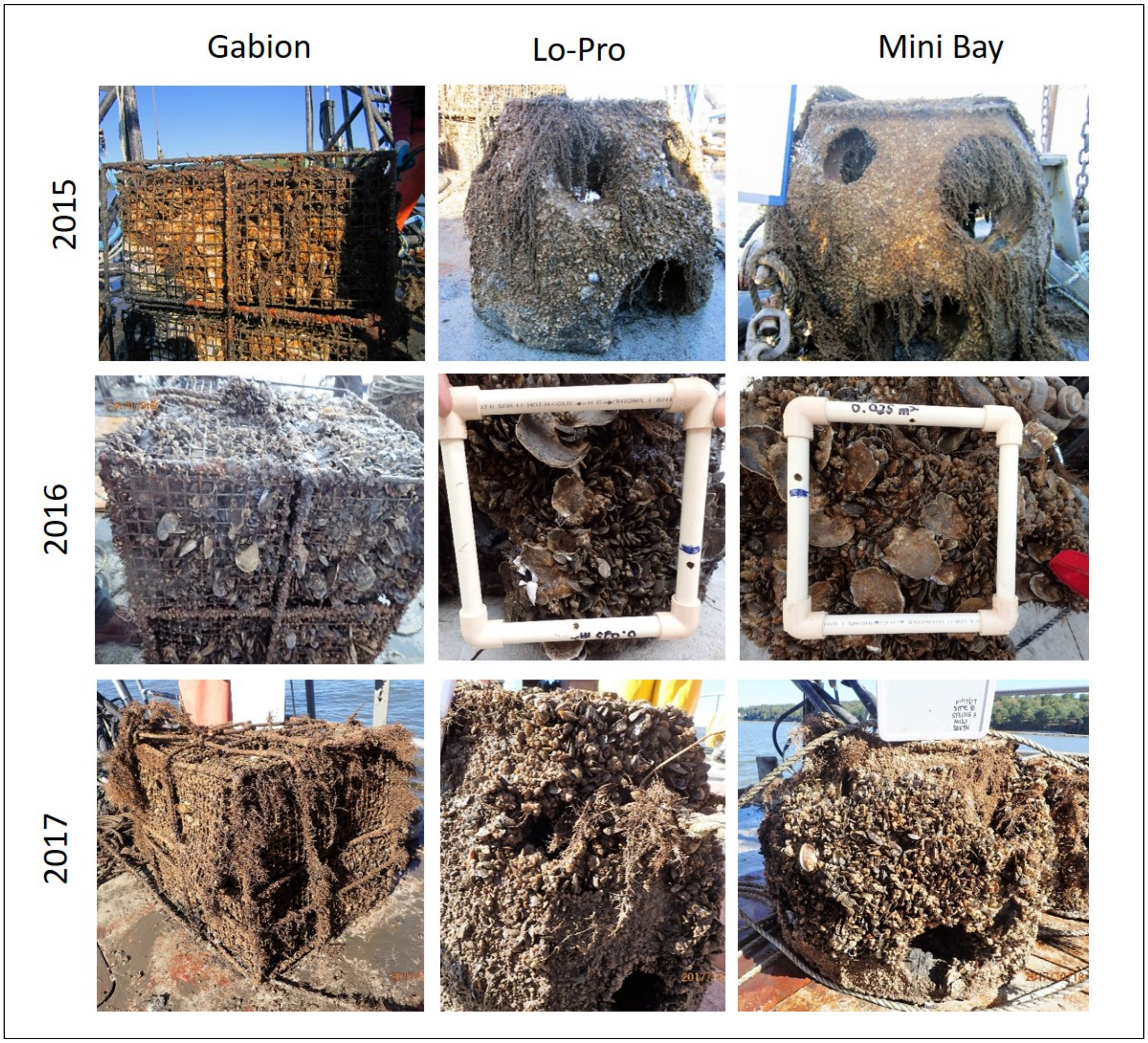


Fig. 5. Example photos of the oyster reef community on three substrate types each of the three years from Site 8.

The combined oyster size dataset (all substrates and sites) clearly showed one year class in 2015, two year classes in 2016, and three in 2017 (Fig. 6). Overall, this indicates successful recruitment all 3 years in the general study area, and suggests reasonable growth and survival. The data from all 3 years indicate oysters <40 - 45 mm can be considered spat when sampling occurs in the fall of the year. Although oyster size frequency data by site are not shown herein, spat (annual recruits) occurred at all three sites all three years. The spat collectors deployed in 2015 and 2016 in the concurrent study by AKRF also showed recruitment at all three sites (AKRF 2016a, b).

The 2016 and 2017 data indicate that year 2 oysters ranged from ~40 to 75 mm, with a mean of ~55 mm. These data compare well with published oyster sizes and growth rates in the northeastern US, including the New York Harbor region (Levinton and Doall 2011, Levinton et al. 2013; Grizzle et al. 2013, 2016; Lodge et al. 2016).

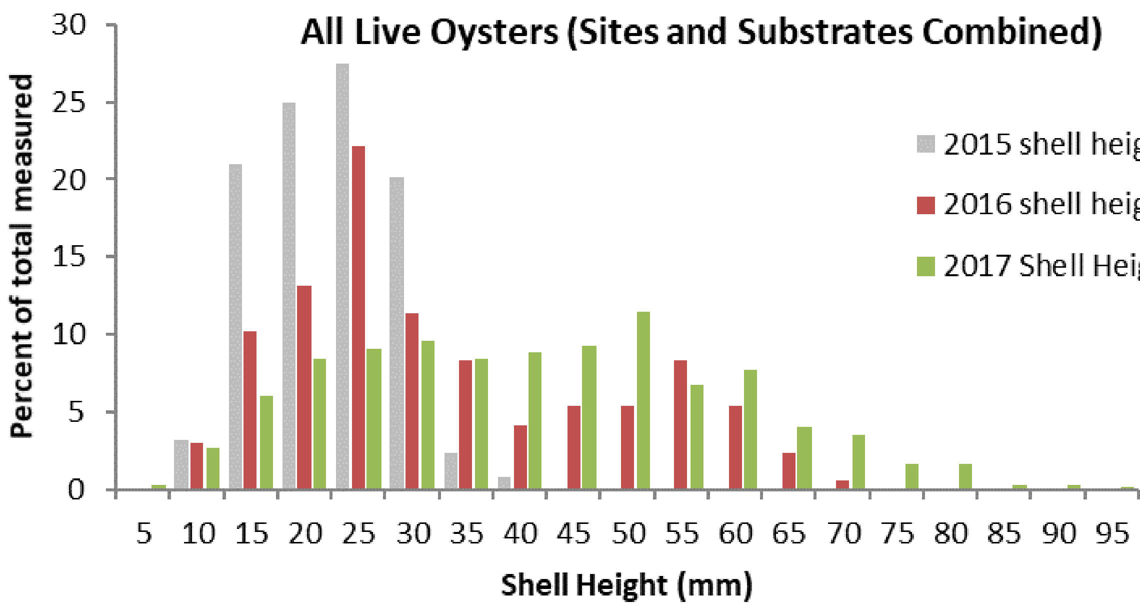


Fig. 6. Size-frequency histogram for all oysters measured on all three substrates and from all three sites.

Assessment of the oyster size data by site and year (combining all three substrates) indicates similar mean shell heights were at all three sites, suggesting similar environmental characteristics among the three sites that affect oyster growth (Fig. 7). Focusing on the 2017 data, ANOVA test indicated no significant differences in mean shell heights (P = 0.314) among the three sites. Mean oyster density differences were also non-significant (P = 0.637) among the three sites, though small sample sizes at some sites (Table 1) resulted in very high variances around each mean.

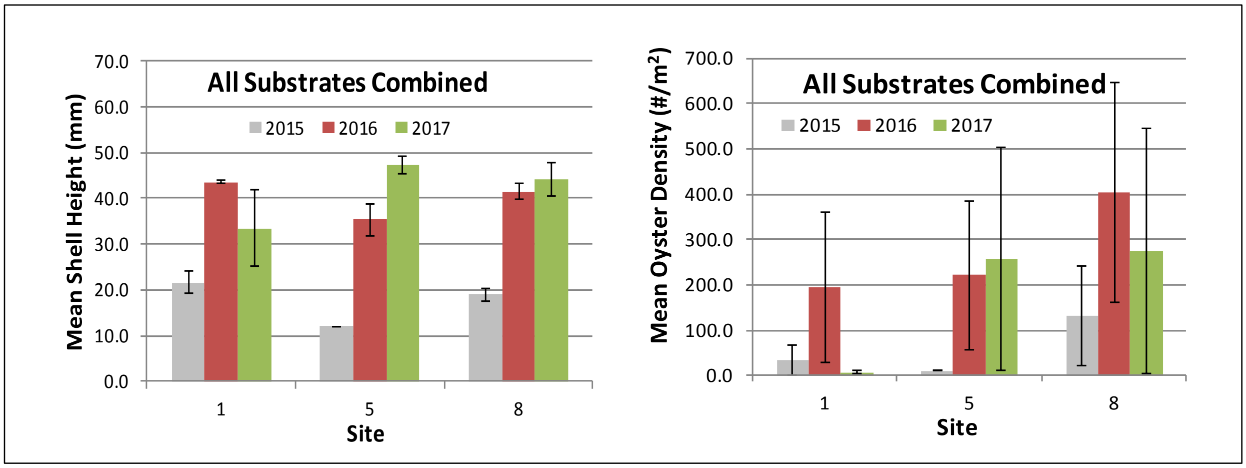


Fig. 7. Oyster mean size and mean density (±1 SE) by site and year (all substrates combined).

Assessment of oyster size by substrate (all sites combined) and year showed very similar mean sizes all three years on all three substrates, indicating the three substrates provide similar conditions for oyster recruitment and growth (Fig. 8). Focusing on the 2017 data, there were no significant differences in mean shell height among the three sites. In contrast, there were substantial differences among the three substrates with oysters occurring at much higher densities on the gabions. We emphasize, however, that the two substrate types (Reef Balls and gabions) differ substantially with respect to surface area potentially available for larval recruitment and subsequent reef development. Live oysters of a wide range of sizes were found on shell cultch material deep within each gabion, whereas only the surfaces of the Reef Balls were available as potential substrate. Thus, gabions provide a third dimension for reef development although the long-term survival of oysters deep within the gabions is unknown.

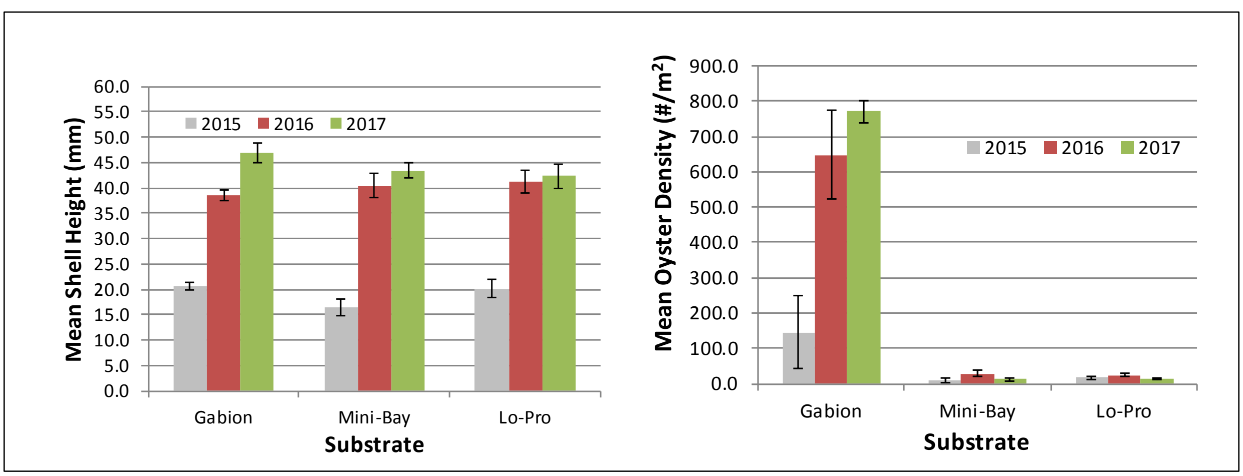


Fig. 8. Oyster size and density (±1 SE) by substrate and year, combining the data from all three sites.

Oyster size and density data were also assessed by site, substrate type, and year in order to visually inspect for interaction effects among the variables (Fig. 9). Shell height consistently showed similar mean values by year for all three substrates and all three sites; the only exception being the Lo-Pros at Site 1 in 2017, and this was perhaps due to small sample size (Table 1). Although oyster densities varied widely by both substrate and site, there were consistent trends such as the gabions consistently showing highest values across all three sites.

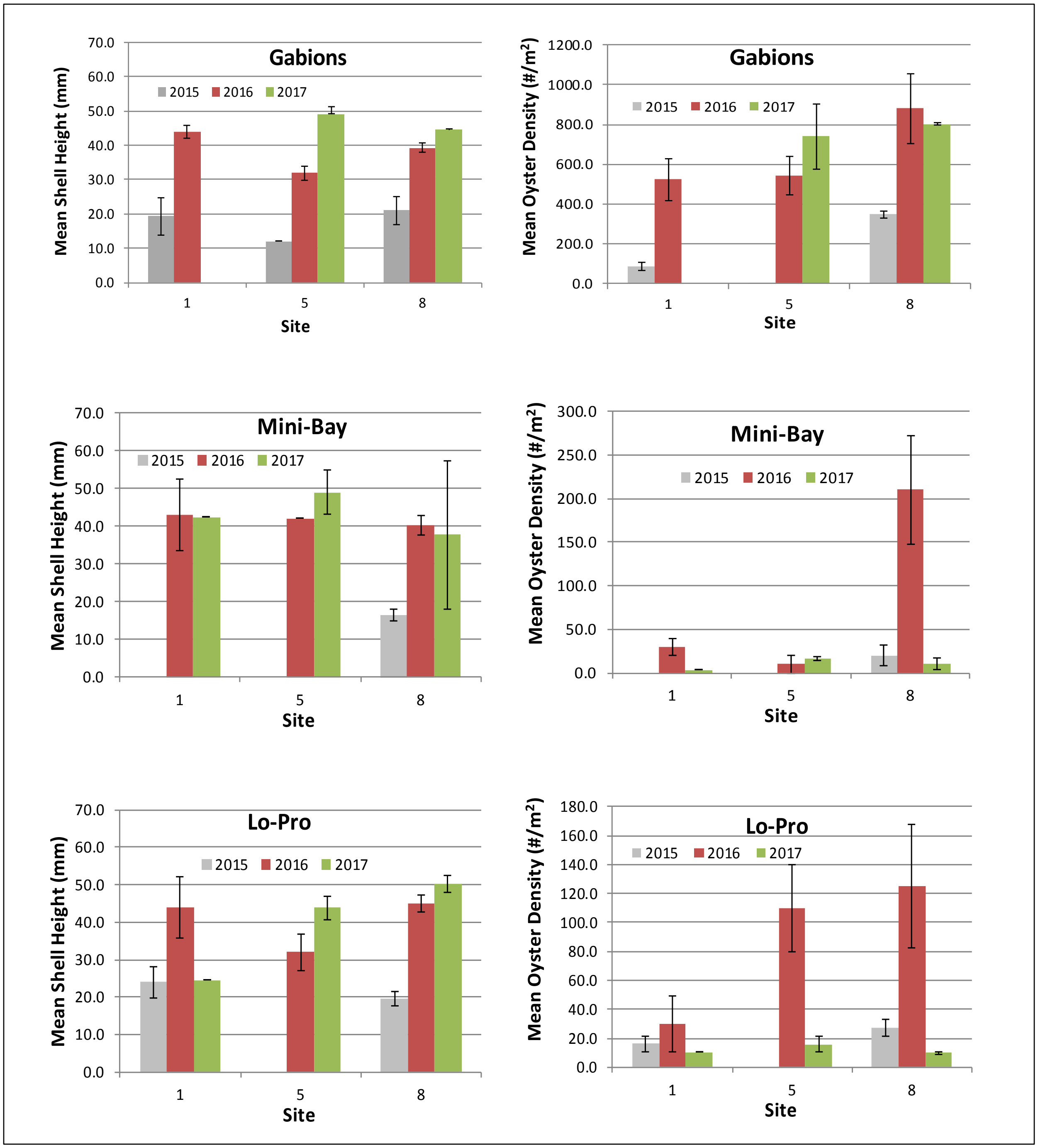


Fig. 9. Oyster mean size and mean density (±1 SE) by substrate type and site. Note different scales on oyster density charts.

A final topic to consider for oyster size and density is how our data compare to the ongoing studies by AKRF on water quality and oyster recruitment (AKRF 2016a, b). Perhaps the most important finding in 2015 and 2016 was that recruitment data from both efforts indicated higher spat densities at Site 8, suggesting that there is good potential for natural recruitment and thus sustainability of constructed reefs if located in that area. However, water quality data from Site 8 suggest caution in this respect because both salinity and dissolved oxygen have been well below levels considered stressful to the eastern oyster much of the monitoring period in 2015 and 2016 (see discussion in AKRF 2016b). The 2017 data, however, again showed substantial spat densities as well as growth and survival at Site 8 similar to the other two sites.

Fouling community development. In addition to oysters, four species of epifauna have made up the overall fouling community on the test substrates. Two species that occur as individuals were present all three years in sufficient abundances to determine density: the hooked mussel (*Ischadium recurvum*) and the bay barnacle (*Balanus improvisus*).

Mussels occurred at low to moderate densities at all sites and on all three substrate types in 2015, but greatly increased densities at Sites 1 and 8 in 2016, particularly on the two types of Reef Balls (Fig. 10). Their densities had decreased substantially on all three substrate types and at all three sites in 2017.

Barnacles showed the opposite pattern: moderate to high densities at all three sites and on all three substrate types in 2015, but dramatic declines in 2016 and 2017.

Two colonial taxa present in high abundances in 2015 (an unidentified hydroid and the encrusting bryozoan *Membranipora* sp.) were present in 2016 and 2017 but not in high abundances. No potential causes (e.g., known predators) for their declines were evident, but wide variations in seasonal and year-to-year abundances of both taxa are typical (e.g., Gosner 1978; Saunders and Metaxas 2009).

The timing of larval settlement among the fouling community species could not be determined, but based on the ~100% cover of the barnacles and mussels in some areas it seems possible they could have inhibited oyster settlement. Moreover, and as noted in previous reports (Lodge et al. 2016, 2017), the relationships among potentially competing species in fouling communities is complex (Kochman et al. 2008; Barnes et al. 2010), and barnacles have been shown to inhibit oyster settlement and growth (Boudreaux et al. 2009). Although the present study was not designed to unravel the effects of various species interactions, monitoring of the major species that makeup the overall fouling community in future studies might yield relevant information for interpreting oyster reef development patterns.

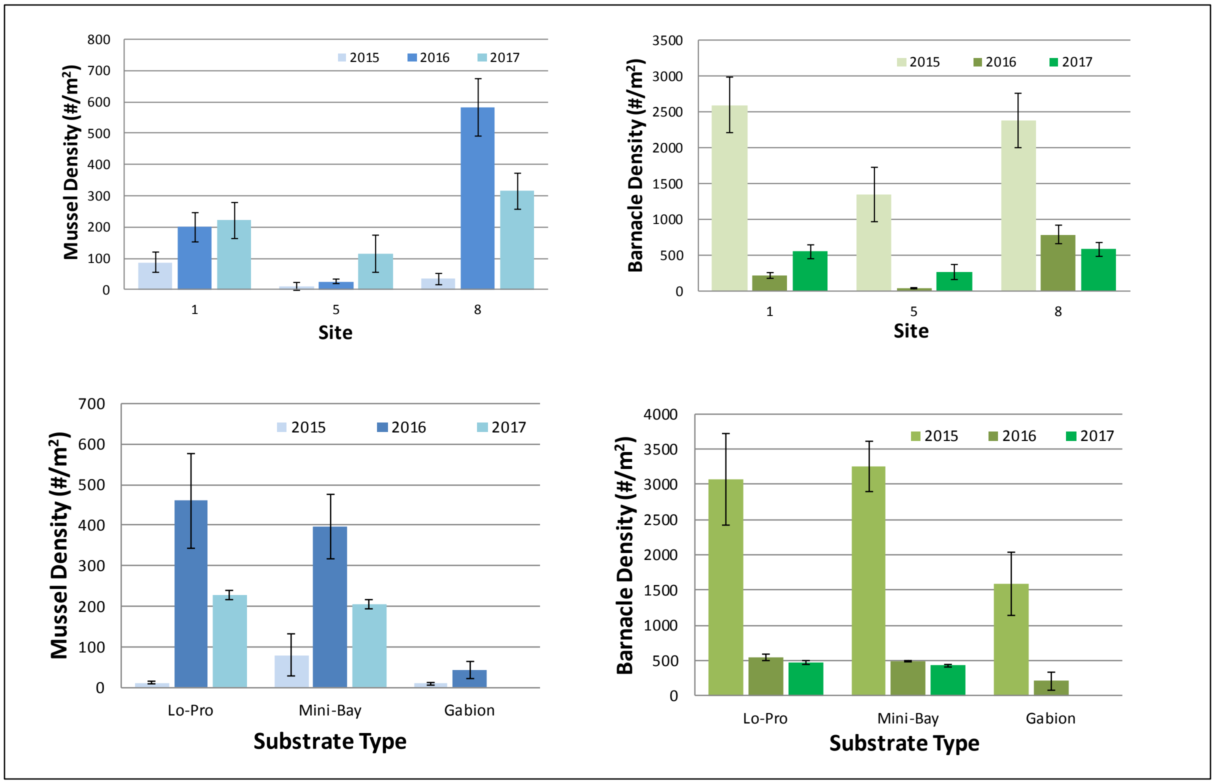


Fig. 10. Top row: mean (±1 SE) mussel density by site with all three substrates combined. Lower row: barnacle density by substrate type with all three sites combined.

Conclusions

The goal of the study was to inform the design of the Tappan Zee Bridge Oyster Restoration Project by providing information on the performance of three potential restoration substrates at three potential restoration sites. Although there were considerable variations in oyster performance metrics among the sites and test substrates, the monitoring data overall suggest that acceptable oyster recruitment, growth and survival can be expected at all three sites and on all three substrates.

One particularly surprising finding was the consistent recruitment and survival of oysters at Site 8, where salinity and dissolved oxygen were well below levels considered optimal for eastern oyster growth and survival for much of the monitoring period in 2015 and 2016 (Shumway 1996; also see discussion in AKRF 2016b). It may be that the oysters in this portion of the Hudson River are adapted to such conditions. In any case, data from the present study overall indicate Site 8 has good potential for full-scale restoration efforts.

Oyster growth (as inferred from changes over time in mean shell height) were very similar among the sites and substrates. In contrast, oyster density was consistently highest on the gabions compared to both types of Reef Balls. In large part, this probably was due to differences in structure, with the gabions providing a vertical dimension available for oyster recruitment. Live oysters of a wide range of sizes were found on shell cultch material deep within each gabion, whereas only the surfaces of the Reef Balls were available as potential substrate. Thus, although gabions provide a third dimension for reef development, the long-term survival of oysters deep within the gabions is unknown. Additionally, some of the gabions showed substantial damage in the second and third years of the study, mainly due to broken welds on the rebar frames. The gabions used in full-scale reef restoration should be constructed in a different manner than those used in the pilot study.

References

AKRF. 2016a. Tier 3 Progress report, Oyster research and restoration plan, New NY Bridge Project. AKRF, Inc., New York City. Submitted March 16, 2016

AKRF. 2016b. Tier 3 Progress report, Oyster research and restoration plan, New NY Bridge Project. AKRF, Inc., New York City. Submitted November 30, 2016.

Barnes, B.B., M.W. Luckenbach, and P.R. Kingsley-Smith. 2010. Oyster reef community interactions: the effect of resident fauna on oyster (*Crassostrea* spp.) larval recruitment. *Journal of Experimental Marine Biology and Ecology* 391:169-177.

Boudreaux, M.L., L.J. Walters, and D. Rittschof. 2009. Interactions between native barnacles, non-native barnacles, and the eastern oyster *Crassostrea virginica*. *Bulletin of Marine Science* 84:43-57.

Gosner, K.L. 1978. A field guide to the Atlantic seashore, from the Bay of Fundy to Cape Hatteras. Houghton Mifflin, Boston.

Grizzle, R., K. Ward, J. Lodge, D. Suszkowski, K. Mosher-Smith, K. Kalchmayr, and P. Malinowski. 2013. Oyster restoration research project (ORRP) final technical report. Submitted to: Hudson River Foundation, New York, NY. 26 pp. http://www.oyster-restoration.org/oyster-restoration-research-reports/; http://www.hudsonriver.org/?x=orrp

Grizzle, R.E., K.M. Ward, C.R. Peter, M. Cantwell, D. Katz, and J. Sullivan. 2016. Growth, morphometrics, and nutrient content of farmed eastern oysters, *Crassostrea virginica* (Gmelin), in New Hampshire, USA. *Aquaculture Research* 2016:1-13. Doi:10.1111/are.12988.

Kochman, J., C. Buschbaum, N. Volkenborn, and K. Reise. 2008. Shift from native mussels to alien oysters: differential effects of ecosystem engineers. *Journal of Experimental Marine Biology and Ecology* 364:1-10.

Levinton, J.S. and M. Doall, 2011. Guiding oyster restoration: growth, condition and spawning success of experimental populations of oysters throughout New York-New Jersey Harbor. Final Report to the Hudson River Foundation, New York, NY.

Levinton, J., M. Doall, and B. Allam, 2013. Growth and mortality patterns of the eastern oysters *Crassostrea virginica* in impacted waters in coastal waters in New York, USA. Journal of Shellfish Research 32:417-427.

Lodge, J., Grizzle, R., Coen, L., Mass Fitzgerald, A., Comi, M., and Malinowski, P., 2015. Community based restoration of oyster reef habitat in the Bronx River: assessing approaches and results in an urbanized setting. Final Report of the NOAA/WCS Regional Partnership Grant, New York, NY.

Lodge, J., R. Grizzle, K.M. Ward, and P. Malinowski. 2016. Progress Report #1, Tier 3 Tappan Zee Bridge oyster restoration pilot study. Submitted February 1, 2016.

Lodge, J., R. Grizzle, K.M. Ward, and P. Malinowski. 2017. Progress Report #2, Tier 3 Tappan Zee Bridge oyster restoration pilot study. Submitted January 9, 2017.

Saunders, M.I. and A. Metaxas. 2009. Population dynamics of a nonindigenous epiphytic bryozoan *Membranipora membranacea* in the western North Atlantic: effects of kelp substrate. *Marine Ecology Progress Series* 8:83-94.

Shumway, S. 1996. Environmental factors. pp. 467-514 In: The Eastern Oyster Crassostrea virginica. Eds. V.S. Kennedy, R.I.E. Newell, A.F. Eble. Maryland Sea Grant College, University of Maryland System, College Park.

APPENDIX E

OYSTER HABITAT RESTORATION
POST-CONSTRUCTION MONITORING PLAN

OYSTER HABITAT RESTORATION
POST-CONSTRUCTION MONITORING PLAN
6-19-2017
Revised 3-25-19

The mitigation requirement (New York State Department of Environmental Conservation Permit ID 3-9903-00043/00012) to establish shell/hard bottom oyster habitat was implemented during the summer of 2018. As part of the substrate placement phase of the project, water quality monitoring was conducted between June and November 2018 to characterize environmental conditions during the first oyster spat settlement event. Instruments were checked monthly and data downloaded. Sonde locations are depicted on Figures 1, 2, and 3. A post-construction monitoring effort was developed to help determine the effectiveness of the oyster habitat restoration program and consists of two major components, namely: monitoring oyster settling, survival, and growth on artificial substrates at the three locations, and monitoring water quality at those locations. A two year post-construction monitoring program (2019 and 2020) is the final element of the oyster habitat restoration effort that falls under the responsibility of the Thruway Authority (The Authority).

Artificial Substrates
The post-construction monitoring program will be conducted over two years and will provide insights into the success of the oyster habitat restoration program. Annual monitoring will take place in October 2019 and again in October 2020, and results will be used to determine extent of spat settling, oyster growth, and overwintering survival on introduced substrates at the three restoration sites (Sites 1, 8, and Site 0 (the Glove)). At Site 1, 414 reef balls ("Mini-bay Ball" style) and 193 gabions were distributed over 3.35 acres. At Site 8, 413 reef balls (Mini-bay Ball" style) and 193 gabions were distributed over 2.57 acres of river bottom (Figures 1 and 2). At Site 0, 54 reef balls and 36 gabions were distributed over a much smaller area of 0.07 acres (Figure 3).

At the start of each of the October monitoring events, divers will use tethered floats to mark the locations of *a priori* randomly selected gabions and reef balls at the three restoration sites. After substrates have been marked, a large buoy tender will be used to lift the selected gabions and reef balls, which each weigh about 300 pounds. Sixteen reef balls and eight gabions will be pulled to the surface for inspection from the arrays at Sites 1 and 8. At Site 0 four reef balls and three gabions will be pulled to the surface. The substrates will be returned to the river at approximately the same locations from which they were taken, to the extent practicable. It is estimated that this monitoring program will require f 10-11 days of field work during each of the two years.

Oyster size and density will be calculated from fixed size quadrats on the reef balls and the gabions, and converted to #s/m^2. Data will be analyzed both qualitatively and quantitatively using statistical methods. Conversion factors such as those described in the Hudson River Foundation's Oyster Restoration Pilot Study (Lodge et al. 2017) will be applied to facilitate qualitative comparisons of density estimates between the two substrate types. Size distribution and density will be graphically depicted and compared by location, by substrate, and combined across substrate and location. Parametric or non-parametric methods will be used to test each substrate type for statistically significant differences among locations for density and size distribution. Covariates such as salinity and/or dissolved oxygen measurements taken during the water quality monitoring described below may be included in the analysis of the oyster data, if considered appropriate. Any changes in sampling methodology form that described in the HRF Tier 3 final report will have to be approved by the Authority and the DEC.

Observations on the composition and abundance of the fouling community occurring at the three sites on the two substrate types will also be recorded, and a qualitative discussion on the dominant taxa (e.g., mussels, barnacles, bryozoans, hydroids) included in final reports. The methodology for monitoring and quantifying the fouling community will follow the same methodology used in the pilot study.

Draft reports will be submitted by the HRF on December 15, 2019 and 2020, and final reports will be submitted within 30 days of receipt of reviewer comments.

Water Quality:
Two sondes (HOBO U24-002-C, Onset, Bourne, MA) that measure conductivity and temperature, and two DO logger (Precision Measurement Engineering miniDOT, Vista, California) will be deployed at each of the three sites. The sondes and DO loggers will be elevated by buoys approximately 2 feet off of the river bottom and programmed to record at 15-minute intervals. They will be deployed in April of 2019 and 2020, retrieved monthly for downloading of data and probe maintenance, until mid-November, at which time the sondes and DO loggers will be removed from the river for the winter. Prior to the April deployments and upon each retrieval event, the sondes will be calibrated by taking a reading while submerged in a standard solution (5,000 µs/cm at 25° C); the readings are then used in the HOBOware Pro software to adjust the raw conductivity measurements from each sampling period. Every attempt will be made to deploy sondes and DO loggers in water depths that are comparable to those in proximity of the artificial substrates.

Past experience in 2015 or 2016 (Seewagen et al. 2016; 2018) has indicated that on a few occasions, a sonde could not be found during a given sampling event and the memory may have filled up before it was retrieved during the subsequent event, resulting in an incomplete time series. However, in 2016 none of the sondes were permanently lost and none of the DO loggers failed or were lost. All sondes were also recovered in 2018. The post-construction monitoring program has been designed with built in redundancy in gear deployment to ensure the procurement of a continuous time series of water quality data even if a sonde or DO logger is lost, or not properly functioning.

A draft report will be prepared within 60 days of completion of the collection of water quality data in fall of 2018, 2019, and 2020. Profiles of temperature, salinity and dissolved oxygen over time as well as frequency distributions of these parameters will be presented graphically. Ranges in salinity and dissolved oxygen (minimum, maximum, mean, 10th percentile and 90th percentile) will be presented in tabular format. Prolonged periods of low dissolved oxygen events or freshets will be identified and evaluated in terms of affecting restoration success. As indicated above, salinity and/or dissolved oxygen data may be included as part of the analysis assessing differences in oyster densities and survival among sites, if considered appropriate.

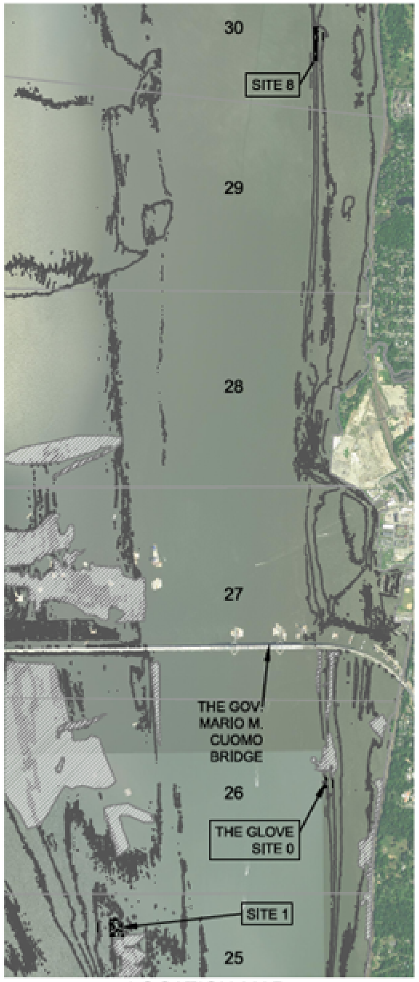
Both the Artificial Substrate and Water Quality Monitoring Reports will be distributed to the Oyster Work Group for comments following reviews by the Authority and DEC.

References

Lodge, J., R. Grizzle, K. Ward, P. Malinowski, and K. Mosher-Smith. 2017. Tappan Zee Bridge Oyster Restoration Pilot Study. Progress Report #2, 2016. Submitted to AKRF. January 2017. 10p.

Seewagen, C., F. Jacobs, and C. Stoll. 2016. Tier 3 Progress Report. Oyster Research and Restoration Plan, New NY Bridge Project. November 30, 2016.

Seewagen, C., F. Jacobs, and C. Stoll. 2018. Tier 3 Progress Report. Oyster Research and Restoration Plan, New NY Bridge Project. March 16, 2018



LOCATION MAP
N.T.S.

GPS POINT NUMBER	X VALUE (FT)	Y VALUE (FT)
1-1	658811.91	808137.92
1-2	658985.39	808136.93
1-3	659142.13	808034.44
1-4	659152.66	807691.07
1-5	658817.04	807674.13
1-6	658801.92	807806.13

STATION NUMBER	X VALUE (FT)	Y VALUE (FT)
1-1-Sonde-2018	658475.45	807808.08
1-2-Sonde-2018	658475.45	808008.48

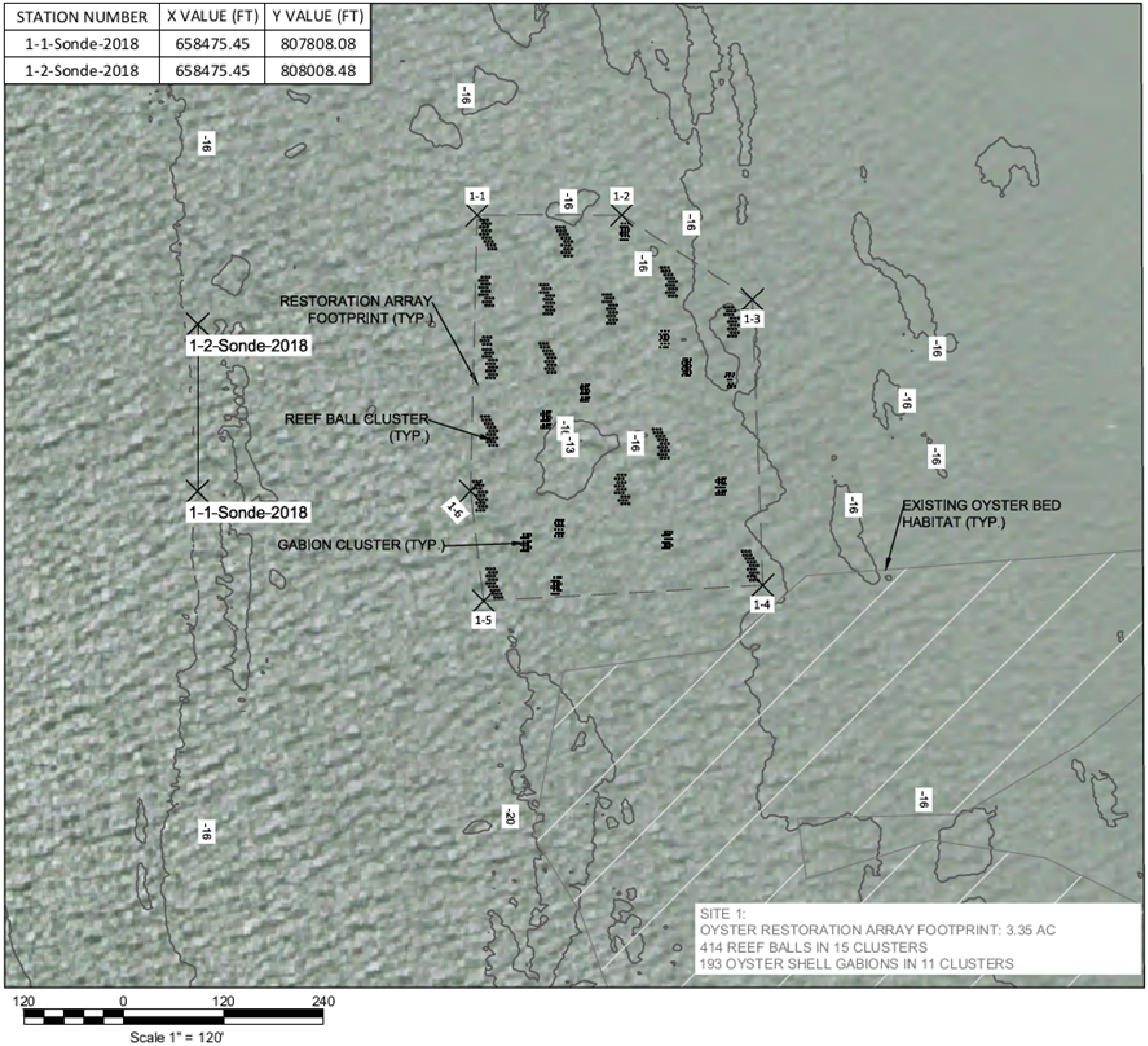
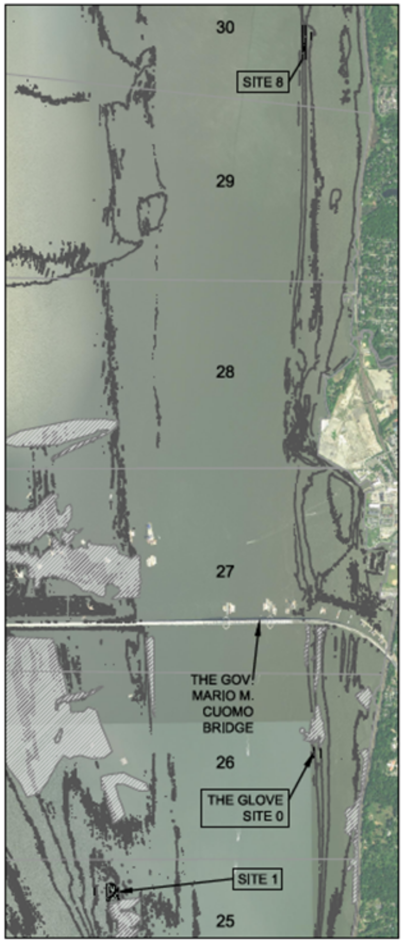
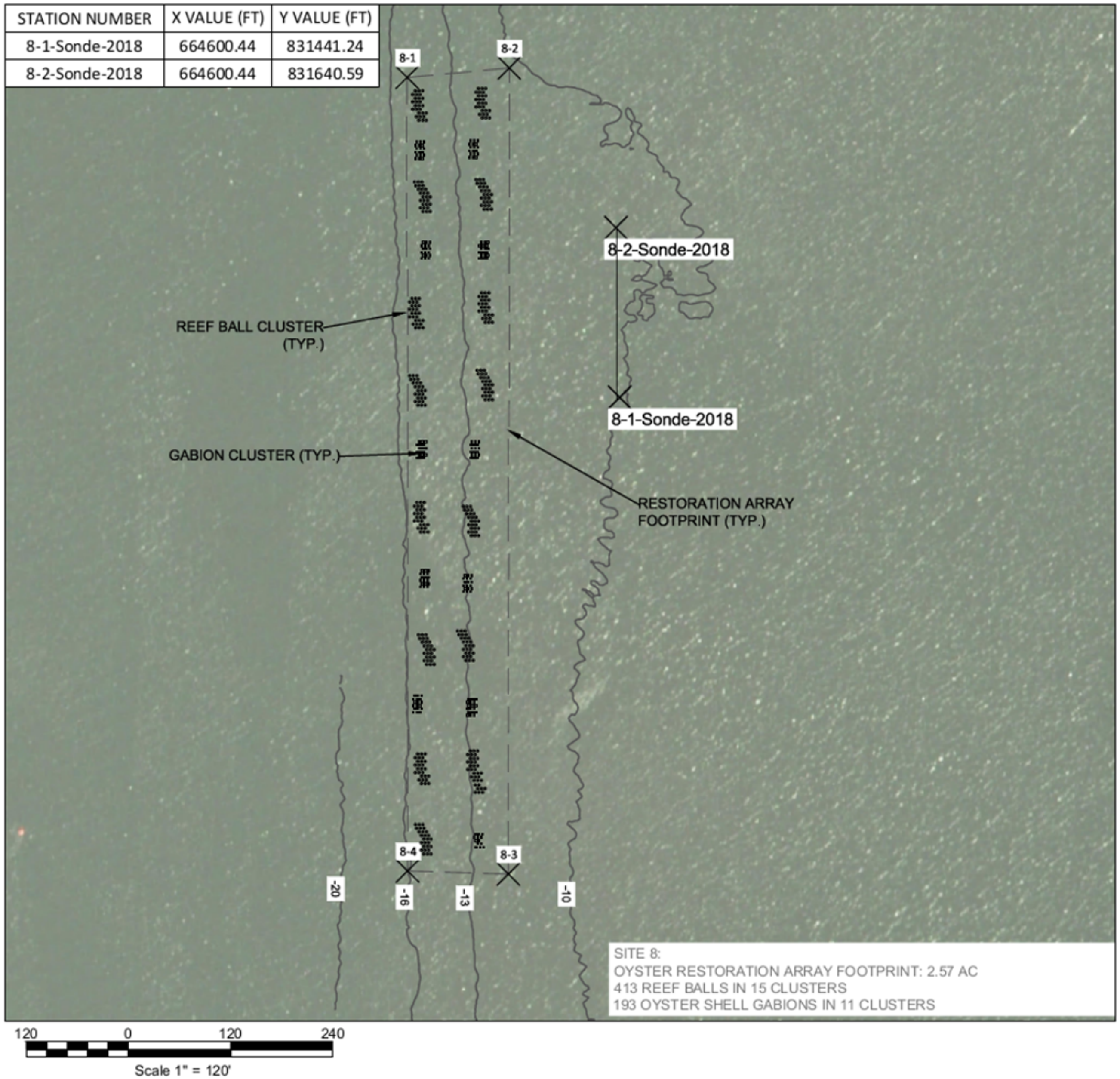


Figure 1. Locations for water quality sondes at Site 1 relative to the site boundaries and hypothetical placement of oyster substrates at the site.

STATION NUMBER	X VALUE (FT)	Y VALUE (FT)
8-1-Sonde-2018	664600.44	831441.24
8-2-Sonde-2018	664600.44	831640.59

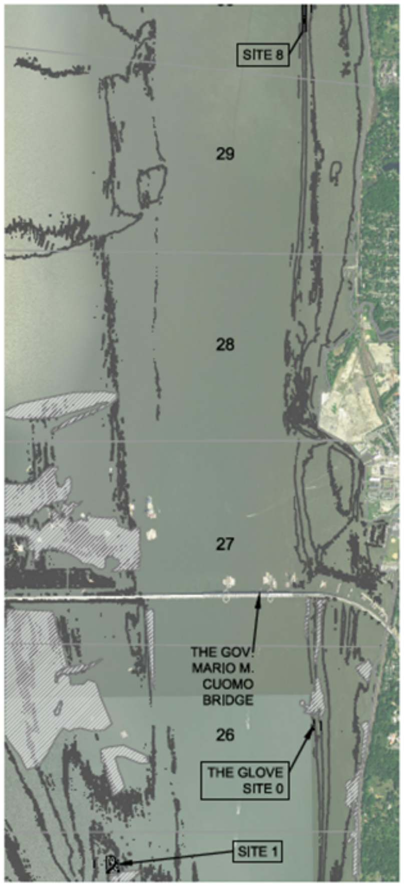


LOCATION MAP
N.T.S.



GPS POINT NUMBER	X VALUE (FT)	Y VALUE (FT)
8-1	664356.30	831818.70
8-2	664476.39	831829.12
8-3	664469.87	830881.66
8-4	664351.58	830886.06

Figure 2. Locations for water quality sondes at Site 8 relative to the site boundaries and hypothetical placement of oyster substrates at the site.



LOCATION MAP
N.T.S.

GPS POINT NUMBER	X VALUE (FT)	Y VALUE (FT)
0-1	664543.23	811893.10
0-2	664571.91	811892.82
0-3	664581.91	811766.84
0-4	664551.64	811768.37
0-5	664549.20	811668.87
0-6	664577.88	811668.59
0-7	664578.50	811571.83
0-8	664548.23	811573.36

STATION NUMBER	X VALUE (FT)	Y VALUE (FT)
0-1-Sonde-2018	664737.50	811605.90
0-2-Sonde-2018	664737.50	811807.29

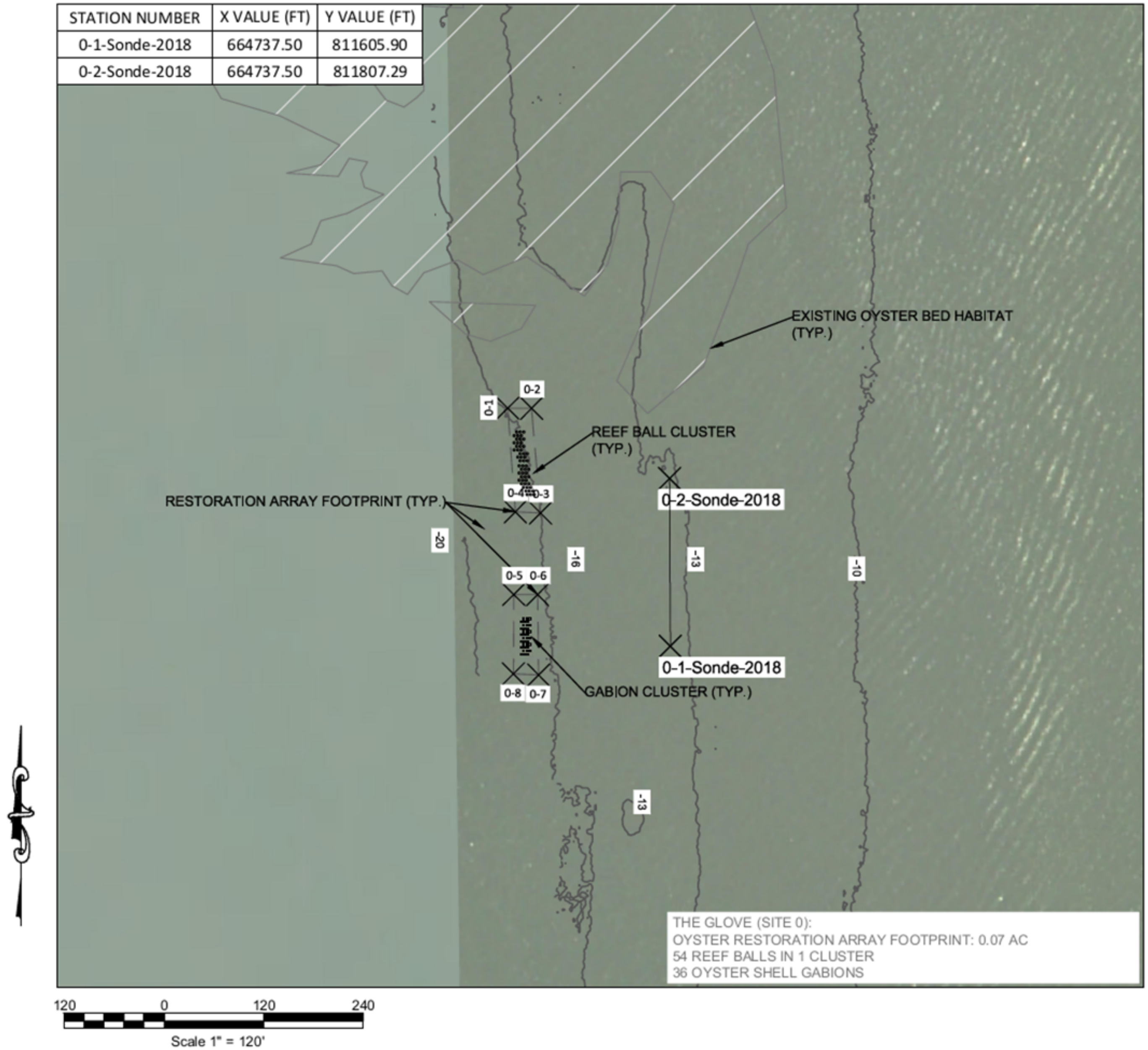


Figure 3. Locations for water quality sondes at Site 0 relative to the site boundaries and hypothetical placement of oyster substrates at the site.