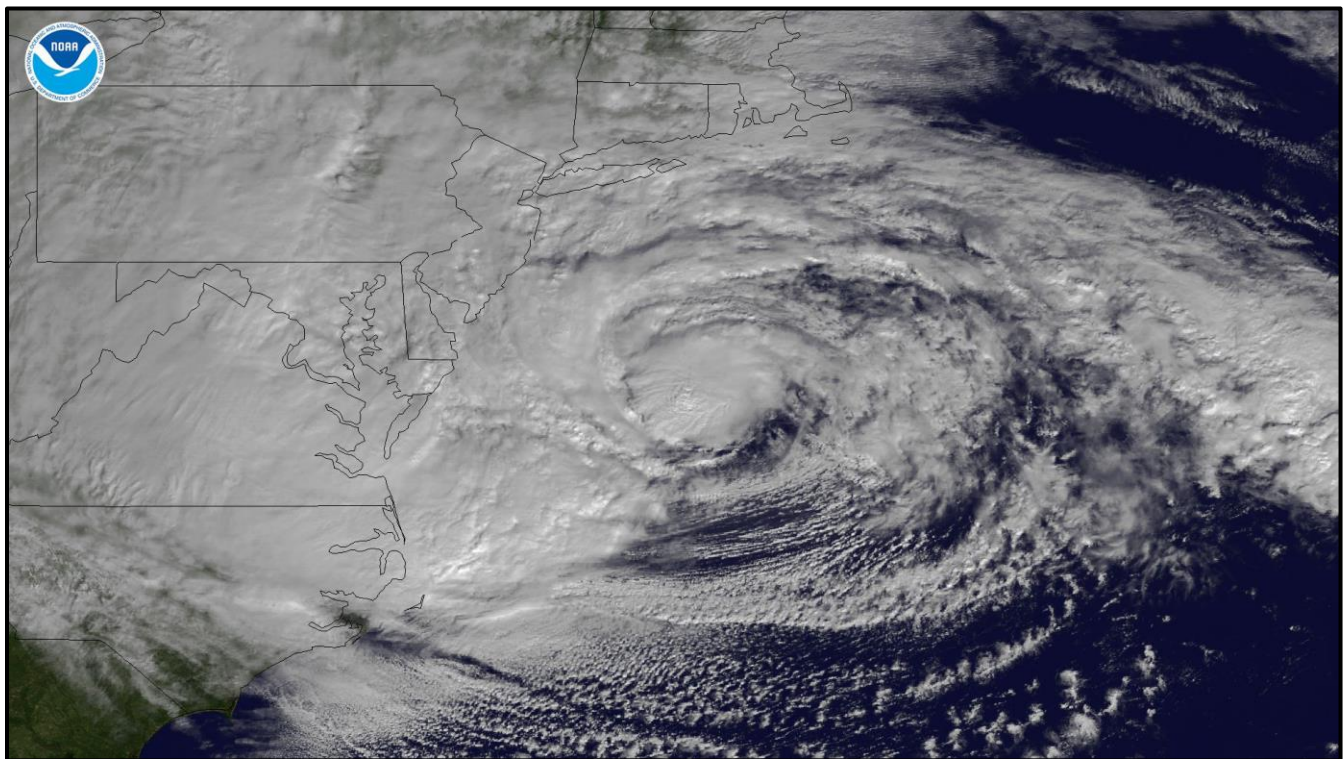




Assessing the Response of the Great South Bay Plankton Community to Hurricane Sandy

Natural Resource Report NPS/NCBN/NRR—2018/1781



ON THE COVER

Satellite photograph of Hurricane Sandy as the storm approached the northeastern U.S.
Photograph courtesy of the National Oceanographic and Atmospheric Administration

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Natural Resource Report NPS/NCBN/NRR—2018/1781

Christopher J. Gobler, Craig S. Young, Jennifer Goleski, Ryan B. Wallace, Florian Koch, Theresa K. Hattenrath-Lehmann, Mark W. Lusty, Jake D. Thickman, Kylie Langlois, Yuriy Litvinenko, Jackie L. Collier, Darcy J. Lonsdale

Stony Brook University,
School of Marine and Atmospheric Sciences,
Stony Brook, NY 11794

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Abstract

The south shore of Long Island is lined by barrier islands that have been breached by ocean waters dozens of times during the past 300 years. On October 29th, 2012, Hurricane Sandy created a new ocean inlet in eastern Great South Bay (GSB) that has had a strong effect on bay circulation and salinity. This provides a description of the changes in GSB and Moriches Bay (an adjacent bay to the east) water quality and plankton communities related to the creation of the New Inlet and the spatial and temporal extent of those changes. Time series sampling was performed at multiple locales within GSB and Moriches Bay from 2013 through 2015 and horizontal mapping of temperature, salinity, dissolved oxygen, and chlorophyll a was performed. Historical comparisons using past water quality monitoring data from academic and municipal sources was also made. The New Inlet provides asymmetrical ocean flushing, exchanging strongly with waters to the east significantly more than with waters to the west. Plankton communities displayed a bifurcated response to the New Inlet. In locales north (Bellport Bay) and east (Narrow Bay, Moriches Bay) of the New Inlet, water residence times within the bay, summer water temperatures, total and dissolved nitrogen, chlorophyll a, diatoms, cryptophytes, and dinoflagellates significantly decreased, while salinity, dissolved oxygen, and water clarity significantly increased. In contrast, waters west of the New Inlet within the center of GSB experienced little change in residence times, significantly increased chlorophyll a, pennate diatoms, cryptophytes, heterotrophic bacteria, and pico-phytoplankton, including harmful brown tides (*Aureococcus anophagefferens*), cyanobacteria, and chlorophytes, and significantly decreased in water clarity and summer dissolved oxygen levels. The formation of the New Inlet created beneficial conditions within the bay regions close to the breach in terms of temperatures, water clarity, and phytoplankton abundance and diversity, which are likely conducive to improved growth and performance of key estuarine resources such as vital resources including zooplankton, bivalves, and seagrasses. Conversely, more frequent occurrences of brown tides and other algal blooms in central GSB may have been due to the local effect of the breach or larger-scale changes in the ecosystem, and could have negative consequences for estuarine resource species. This information should be considered when determining the fate of current and future breaches along Long Island's south shore barrier islands.

Introduction

There are more than 2,200 coastal lagoons in the world (Pilkey, 2003), and in the United States lagoons are found along more than 75 percent of the East and Gulf coasts. Barrier island lagoon estuaries tidally exchange with ocean waters via inlets, a process that influences many estuarine properties including temperature, salinity, water clarity, and nutrient levels. Low rates of tidal exchange in many lagoonal estuaries allow them to accumulate nutrients from freshwater sources, and in turn, support highly productive food webs (Kjerfve and Magill, 1989).

The south shore of Long Island, NY, is composed of a series of bar-built lagoonal estuaries, formed nearly 10,000 years ago by glacial activity, that collectively stretch from the Nassau-Queens county line to the middle of Southampton, encompassing over 278 square kilometers, and designated as the South Shore Estuary Reserve (Bokuniewicz and Schubel, 1991; Sirkin, 1995). These estuaries are protected by long narrow stretches of land, which act as barriers between the enclosed bays and the coastal Atlantic Ocean. Fire Island is the longest continuous barrier (51 km) along Long Island's south shore and protects all of Great South Bay (GSB) and part of Moriches Bay. Due to the delicate and ephemeral nature of barrier islands, many lagoonal estuaries, including GSB and Moriches Bay, are prone to large-scale disturbance by tropical storms and hurricanes (Paerl et al., 2001; Bales, 2003; Peierls et al., 2003). Major storms often create breaches of protective barrier islands resulting in the formation of new inlets that enhance coastal ocean exchange. The effects of newly formed inlets can result in alterations of phytoplankton assemblages within the estuary, through changes in circulation and nutrient availability (Valiela et al., 1998; Gobler et al., 2005).

GSB is the largest of the barrier island estuaries on Long Island and is constantly changing. Between 1825 and 1953, the longshore transport of sand westward caused the Fire Island Inlet, the largest inlet in GSB, to migrate more than seven kilometers from its original position (Kana, 1995). Furthermore, over the last 300 years, it has been estimated that 28 inlets have temporarily been created as a result of Fire Island being breached by storms (Leatherman, 1985). On 29-October-2012, Hurricane Sandy created a barrier island breach within the eastern extent of GSB (Bellport Bay) in a location known as 'Old Inlet' named as such because there was an inlet present in this area during the early 1800s. This breach, called the "New Inlet," is likely to impact many physical, chemical, and biological aspects of this ecosystem.

In the 1970s and early 1980s, Great South Bay hosted the largest hard clam (Northern quahog; *Mercenaria mercenaria*) fishery in the U.S. (McHugh, 1991) but intense harvesting led to a sharp decline in the hard clam population through the late 1980's and 1990's (Kraeuter et al., 2005). Since 1985, GSB has experienced brown tides caused by the pelagophyte, *Aureococcus anophagefferens*, which have further contributed to the decline of resident hard clam populations (Bricelj et al., 2001; Greenfield and Lonsdale, 2002; Gobler et al., 2005). To date, there has yet to be a rebound of this commercially important fishery.

Plankton communities, including phytoplankton, zooplankton (e.g., microzooplankton such as ciliates and mesozooplankton, including copepods), and ichthyoplankton (e.g., larval fish) serve a critically important function at the base of the GSB trophic structure (Nutall et al., 2011). For

example, phytoplankton are a food source for shellfish; zooplankton graze on phytoplankton; larval and juvenile fish forage on zooplankton; seagrass distribution and productivity are controlled in large part by water column clarity which is influenced by phytoplankton abundance, especially brown tides (Nuttall et al., 2011). Historically, GSB has experienced shifts in phytoplankton community assemblages and multiple types of harmful algal blooms (HABs: Whipple, 1912; Ryther, 1954; Weaver and Hirshfield, 1976; Cassin, 1978; Kaufman et al., 1983; Lively et al., 1983; Gobler et al., 2002, 2004, 2005; Greenfield et al., 2005; Weiss et al., 2007; Harke et al., 2011). The most common HAB in GSB during the past 40 years has been brown tides caused by *A. anophagefferens* (Gobler et al., 2002, 2004, 2005; Harke et al., 2011) which, in addition to hard clams, can damage seagrasses, other bivalves, and zooplankton (Gobler and Sunda, 2012). A recent study of the diversity of phytoplankton, bacterioplankton, and microzooplankton communities in GSB revealed that interactions (competition, parasitism, predation) among the smallest phytoplankton and zooplankton in GSB differ between years with and without a brown tide (Liu, 2012). Given the small size of brown tide cells ($\sim 2 \mu\text{m}$), one plausible food web outcome of brown tides may be a reduction in ecosystem productivity (Chasar et al., 2005).

The goal of this study was to characterize the response of the GSB plankton community to the New Inlet that was formed by Hurricane Sandy in October 2010. The plankton community after the breach occurred (2013-2015) was compared to conditions prior to the formation of the breach. Ancillary data (e.g., salinity, nutrients, water clarity, oxygen, pH, temperature) was collected to assess factors that may have influenced changes in plankton community species composition, abundance, and distribution across GSB.

Methods

Historical comparisons and analyses

A 38-year (1976-2014) data set compiled by the Suffolk County Department of Health Services (SCDHS) water quality monitoring program was analyzed to compare conditions before and after the formation of the New Inlet in GSB (Figure 1). Neither the County of Suffolk nor the Department of Health Services makes any warranty, either expressed or implied, as to the accuracy, completeness, reliability, quality or usability of the information. To supplement the historic record we collected additional water quality data (temperature, salinity, turbidity) and nutrients by standard methods (Parsons et al., 1984) using a small boat. Chlorophyll a was measured fluorometrically (Parsons et al., 1984). Long term averages for all parameters and seasons were generated for all SCDHS stations in Moriches Bay and GSB from 2000 – 2012 and compared to 2013-2015 (Figure 1). To account for seasonality in water temperature and dissolved oxygen levels, analyses were carried out only on data collected during summer months, defined here as June 21 – September 20. Analyses were then performed comparing mean pre-breach and post-breach water quality conditions, utilizing GIS to visualize spatial changes in water quality conditions following the breach across all stations examined. Data are presented as an anomaly model, i.e. the difference between mean water quality conditions before and after breach formation. Values between sampling stations in GIS Figures were interpolated through inverse-distance weighting using ESRI® ArcGIS® 10 with the Geostatistical Analyst extension.

Comparisons were also made to a study of phytoplankton communities in GSB and Moriches Bay conducted during 2004 and 2005 (Curran, 2006). During that study, three sites in GSB and one site in Moriches Bay (western GSB; Latitude 40.626400, Longitude -73.259461), central GSB (40.690790, -73.078770), Bellport Bay (40.743591, -72.909198), and eastern Moriches Bay (40.773887, -72.794185; Figure 1) were sampled approximately biweekly from spring through fall. During that study, measurements were made for size fractionated chlorophyll a (0.2, <2, 2-5, and 5 μm), microscopic quantification of plankton > 10 μm , flow cytometric quantification of picocyanobacteria and eukaryotic algae, and HPLC algal pigment analysis as described below. For this study, these measurements were made in the same way at the same locations, and same time of year in order to facilitate comparisons of the sites before and after the New Inlet. The sites western GSB, central GSB, Bellport Bay, and eastern Moriches Bay from Curran (2006) were directly compared to the present study sites Fire Island Inlet, Mid-Bay, New Inlet, and Moriches Bay, respectively. Patchogue Bay was not sampled by Curran (2006), so no comparison could be made to our present Patchogue Bay dataset.

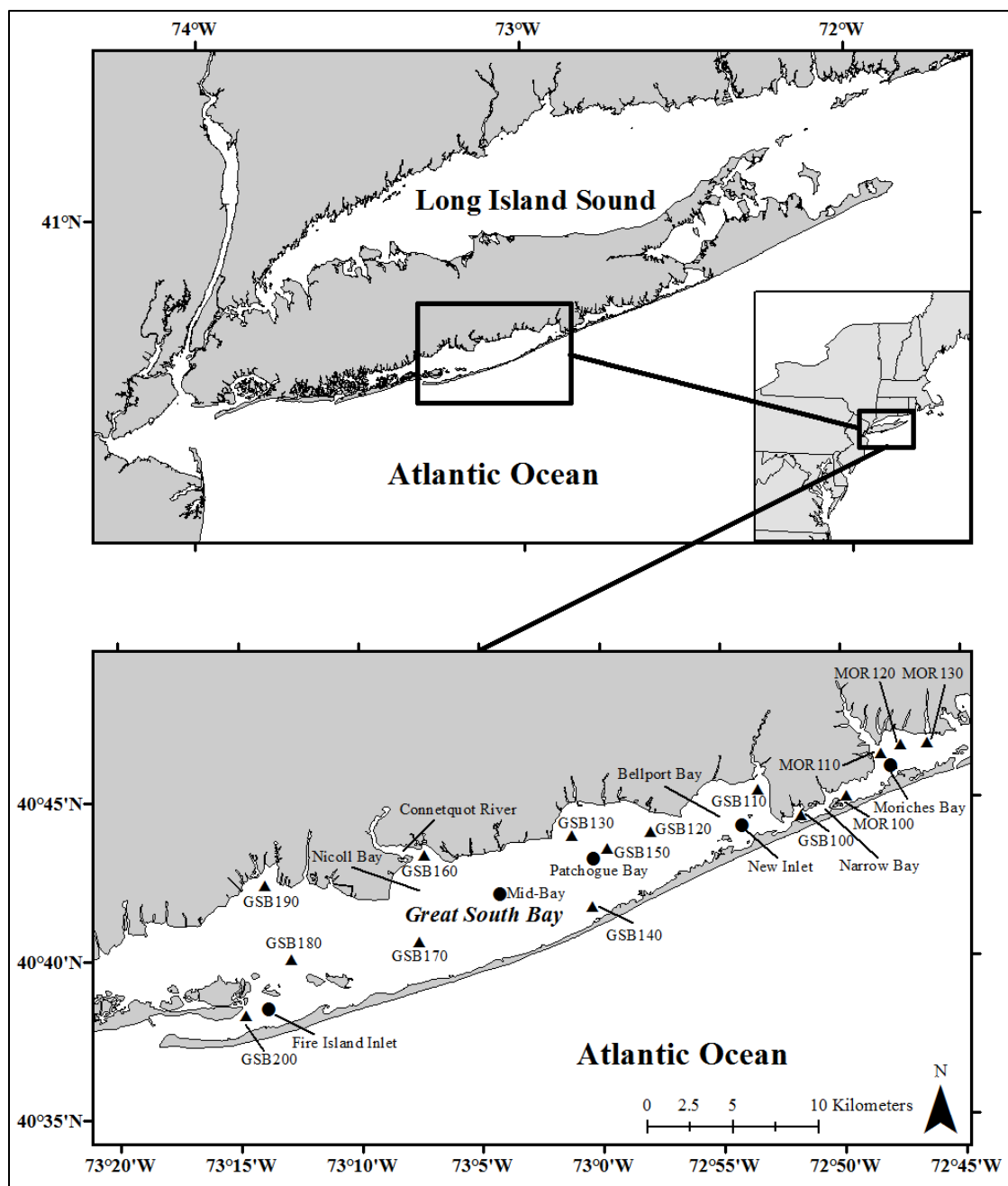


Figure 1. Post Hurricane Sandy sampling stations in Great South Bay and Moriches Bay, Long Island, NY. Triangles represent Suffolk County monitoring sites and circles represent sampling sites used for the study.

Horizontal mapping of plankton communities and water quality

Surface seawater conditions across GSB and Moriches Bay were mapped using new, small boat surveys. A YSI EXO2 sonde with probes to measure temperature, salinity, dissolved oxygen, and in vivo chlorophyll a fluorescence was affixed to a small boat along with a data logging GPS unit and horizontal transects were made from the Fire Island Inlet to the Shinnecock Inlet with enough north-south longitudinal coverage to provide high resolution in Bellport Bay and within vicinity of the New

Inlet. The depth at which data were collected was 0.25 m. Mapping cruises were performed at least monthly from 2013 through 2015. Tens of thousands of GPS-grounded data points per cruise were used to produce horizontal distribution maps of dissolved oxygen, temperature, salinity, chlorophyll *a*, and pH using ESRI® ArcGIS® 10 with the Geostatistical Analyst extension and an ordinary kriging algorithm to interpolate between random point data. Discrete water samples were obtained to ground truth continuous measurements via dissolved oxygen (Grasshoff et al., 1983) and chlorophyll *a* (Parsons et al., 1984).

Discrete field sampling

New, discrete water samples were collected via small boats at least biweekly from April through October and monthly November through March from stations in western GSB (Latitude 40.626400, Longitude -73.259461), central GSB (40.690790, -73.078770), Patchogue Bay (40.726681, -72.994170), Bellport Bay (40.743591, -72.909198), and eastern Moriches Bay (40.773887, -72.794185; Figure 1). Once on station, surface temperature, salinity, and dissolved oxygen were measured at the surface and near the bottom using a YSI® 556 sonde to confirm that the water column, which was typically 2 m deep, was well-mixed as expected (Wilson et al., 1991). Secchi depths were also recorded. Water samples were collected in 20-L carboys at each station for laboratory analyses. During each survey, plankton net tows (*n* = 4) using 64- μ m mesh nets fitted with flowmeters were performed off the back of a small boat, but only at the stations at Fire Island Inlet, central GSB (Mid-Bay), and the New Inlet. Volumes of water passed through nets were recorded. For two net tows, the biovolume of ctenophores was measured with a graduated cylinder. Net tow contents were washed in the net cod end and were then poured into a glass jar and preserved in 10% buffered formalin (final concentration 5%).

Plankton sample processing and analysis

Size fractionated chlorophyll *a* samples were collected on polycarbonate filters (0.2, 2, 5 μ m) in triplicate, frozen, and analyzed by standard fluorometric methods (Parsons et al., 1984). Duplicate plankton samples were collected and preserved with Lugol's iodine for settling chamber analysis using an inverted light microscope (Hasle, 1978). Plankton > 10 μ m were grouped as pennate diatoms, centric diatoms, dinoflagellates, and ciliates and identified to the most specific taxonomic level possible. Densities of the brown tide alga, *Aureococcus anophagefferens*, were quantified on a flow cytometer using a species-specific immuno-assay (Stauffer et al., 2008). Triplicate samples for flow cytometry were preserved with 0.5% paraformaldehyde, flash frozen in liquid nitrogen, and stored at -80°C until analysis on a Becton Dickinson FACScan flow cytometer. Analysis of flow cytometric fluorescence and light scatter patterns provided abundance, size (estimated from forward light scatter), and cell fluorescence for all identifiable cell populations <20 μ m (Olson, 1991; Collier et al., 1999) including phycoerythrin-containing (PE) cyanobacteria (presumed to be *Synechococcus* spp.), phycocyanin-containing (PC) cyanobacteria, picoeukaryotes, and larger eukaryotes. Samples for HPLC algal pigment analysis were collected on GF/F glass fiber filters, flash frozen in liquid nitrogen, and stored frozen at -80°C. Samples were analyzed via a C8 HPLC column using a methanol-based reversed-phase gradient solvent system, a simple linear gradient, and a column temperature of 60°C (Wright et al., 1991). Five phyto-pigments found exclusively in single classes of phytoplankton were quantified to represent five algal groups. Peridinin was used as an indicator of

dinoflagellates, alloxanthin was analyzed as a proxy for cryptophytes, lutein to indicate chlorophytes, zeaxanthin to represent cyanobacteria, and fucoxanthin for diatoms and some chrysophytes (Gieskes and Kraay, 1983; Wright et al., 1991; Descy et al., 2000; Glibert et al., 2004). Pigment concentrations were also normalized to biomass by calculating photopigment to chlorophyll *a* ratios (Gieskes and Kraay, 1983; Descy et al., 2000; Glibert et al., 2004).

The mesozooplankton and ichthyoplankton community concentrated by 64 μm net tows was characterized and quantified using light microscopy on formalin-preserved organisms. Organisms were identified and enumerated to the most specific taxonomic level possible for nauplii, copepods, non-copepod mesozooplankton, invertebrate larvae, and ichthyoplankton using an Olympus SZX12 dissecting microscope.

Samples for nutrient analyses were filtered through precombusted (2 h @ 450°C) glass fiber filters (GF/F pore size) into acid washed high density polyethylene bottles. This filtrate was analyzed spectrophotometrically for total dissolved nitrogen and phosphorus and inorganic (nitrate, nitrite, ammonium, orthophosphate, silicate) nutrient concentrations (Valderrama, 1981; Jones, 1984; Parsons et al., 1984). Dissolved organic nitrogen and phosphorus were determined by difference.

The plankton community in the size range of 2 to 100 microns was also characterized using a FlowCAM (Fluid Imaging Technologies; Scarborough, Maine, USA) at 4x magnification in the FlowCAM's AutoImage mode with a 300 micron (depth) flow cell at a flow rate of 0.53 mL min⁻¹ (standard deviation = 0.0065). Samples were stored on ice until analysis, and the suspended particulate matter (SPM or seston) in each sample was imaged on the day of collection. The raw FlowCAM image files were opened in Visual Spreadsheet and a classification was created for each sample as follows. Particles smaller than 25 microns could not generally be identified, so they were grouped into four bins based on equivalent spherical diameter (ESD): 2 to 3 microns, 3 to 7 microns, 7 to 12 microns, and 12 to 25 microns. The remaining particles, greater than 25 microns ESD, were classified in more detail. These particles were placed in one of 9 top-level categories: diatoms, dinoflagellates, ciliates, rotifers, bivalves, polychaetes, copepods, detritus, or plankton. Nested within each top-level category were classifications based on the family or genus name where possible and otherwise on visible attributes of the particles. 'Plankton' as a top-level category was used for unidentified living plankton that were prevalent enough to warrant their own classification. A tenth top-level category, 'Unknowns', was created for unidentified particles that were not found in great enough numbers to warrant their own classification and those that were poorly photographed (e.g., too far out of the focal plane). The 'detritus' classification comprised particles that were not identifiable as living plankton or were aggregates of plankton. The detritus that could be identified as the dead form of classified plankton was categorized in greater detail, e.g., "detritus_diatoms_thalassionema".

For each sample, the number of particles in each category per mL seawater was calculated by dividing the number imaged by the volume imaged (calculated by the FlowCAM based on magnification, flow cell depth and other context settings). For each category, mean particle biovolume was estimated using mean values of various parameters measured by the FlowCAM along with the geometric formula for the most similar simple shape (sphere, ellipsoid, cylinder), and

multiplied by the number of particles per mL seawater to yield total biovolume for each category in cubic microns per mL seawater. The parameters used in these calculations were mean area-based diameter (ABD) volume for ‘spherical’ particles, and length mean and width mean for ‘ellipsoid’ and ‘cylindrical’ particles. Then, the biomass as nanograms of carbon (C) per mL seawater was calculated for each category using the total biovolume and the appropriate regression from Menden-Deuer and Lessard (2000). As a quality control measure, total seston particulate organic carbon (POC) estimated from the FlowCAM data, when corrected for the smallest plankton (heterotrophic bacteria, picocyanobacteria) undetectable by the FlowCAM, was statistically indistinguishable from historical measurements of POC made in Great South Bay by SCDHS (not shown).

Because many important planktonic organisms are too small and morphologically similar to be distinguished by microscopy-based methods, we also used high-throughput sequencing of both 16S and 18S ribosomal RNA (rRNA) genes to characterize the plankton communities found in Great South Bay both before and after the formation of New Inlet. The “pre-breach” samples were collected at SCDHS stations 150 (in central GSB) and 110 (in Bellport Bay) during 2008-09 (Figure 1).

Particles from 20-25 mL of surface seawater from each site were collected onto 47 mm diameter, 0.2 μ m pore-size polycarbonate filters in either duplicate or triplicate, and filters were stored at -80°C until extraction by the CTAB method (Dempster et al., 1999). Regions of the genes encoding 16S and 18S rRNA were amplified from each sample and sequenced using Illumina MiSeq, performed by MR DNA (www.mrdnalab.com, Shallowater, TX, USA). After pre-processing of raw sequence data, operational taxonomic units (OTUs) were defined by clustering at 3% divergence (97% identity) followed by removal of singleton sequences and chimeras (Dowd et al., 2008a; Dowd et al., 2008b; Edgar, 2010; Capone et al., 2011; Eren et al., 2011; Swanson et al., 2011). Final OTUs were taxonomically classified using BLASTn against a curated database derived from GreenGenes, RDP II and NCBI (www.ncbi.nlm.nih.gov, DeSantis et al., 2006, <http://rdp.cme.msu.edu>).

Microbial community analyses were carried out using the QIIME (v.1.9.1-amd64.vdi) pipeline (Caporaso et al., 2010), run through a 64-bit Virtual Box (VB) (v.5.0. 14 r 105127) (<https://www.virtualbox.org/wiki/VirtualBox>). While high throughput amplicon sequencing does not provide absolute abundance (Pinto and Raskin, 2012), changes in sequence proportion can provide an accurate description of changes in the composition of the microbial community through time (Ibarbalz et al., 2014). Changes in the relative abundance of the most abundant genera at each location were visualized by generating barplots in R. Non-metric multidimensional scaling (NMS) analysis was carried out in PC-Ord (v. 5.10; <https://www.pcord.com/>) (McCune and Mefford, 2006) using Sørensen (Bray-Curtis) distance to calculate the distance matrix (Kruskal, 1964; Mather, 1976). The main matrix was the normalized 16S or rarefied 18S OTU table relativized by a relative Euclidean distance (RED) measure. The second matrix contained metadata related to each sample. In order to test if pre- and post-breach sample sets were statistically different, an MRPP analysis (Multiple Response Permutation Procedure) was conducted in PC-Ord (Mielke et al., 1976; Mielke, 1984), using the Sørensen (Bray-Curtis) distance measure to calculate any significant difference between stations with the post-breach era.

Analysis of water residence times

Water residence times of regions of GSB and Moriches Bay were determined using a salt balance approach that assessed the volumes of the bays, rates of freshwater flow, and the distribution of salinity across the estuarine region (Pickard and Emery, 1990; Fischer et al., 2013). The following two equations were used to determine residence time in days: $t_F = (f \times V) / R$ and $f = (SO - S) / SO$, where V equals the volume of the estuary (or section thereof), R equals the freshwater input, SO equals the salinity of the ocean water and S equals the salinity of the section of estuary (Fischer et al., 2013). It was assumed that water parcels were flushed to the ocean inlet they were nearest to, with the exception of regions of central GSB following the formation of the New Inlet given that the distribution of temperature and salinity suggested these regions were exchanging with the Fire Island Inlet.

Statistical analyses of water quality measurements

The extent to which changes in water quality data were correlated with each other was evaluated via a Spearman's rank order correlation matrix. Differences in water quality parameters measured across sites were assessed via a One-Way ANOVA and post-hoc tests. Differences in water quality parameters measured before and after the formation of the New Inlet were assessed via T-tests. The extent to which changes in water quality data were correlated with residence times was evaluated via a Spearman's rank order correlation matrix. A G-test of independence was used to assess differences in the frequency of events before and after the formation of the New Inlet. All analyses were performed using SigmaStat within SigmaPlot 11.0.

Results

Historic pre/post breach assessment, Suffolk County data

An increase in salinity was seen across all sites examined following formation of the breach (Figure 2). The largest changes in salinity were seen just to the east of the site of the breach in the eastern portions of Bellport Bay and Narrow Bay (Figure 2). At these sites salinity increased by as much as 20% from a mean of 24 to 28 in Bellport Bay (Figure 2). Sites further from the site of the breach also showed increased salinity, but the strength of the trend decreased gradually as distance from the breach increased, with only 3% - 5% increases seen at the easternmost and westernmost sites examined.

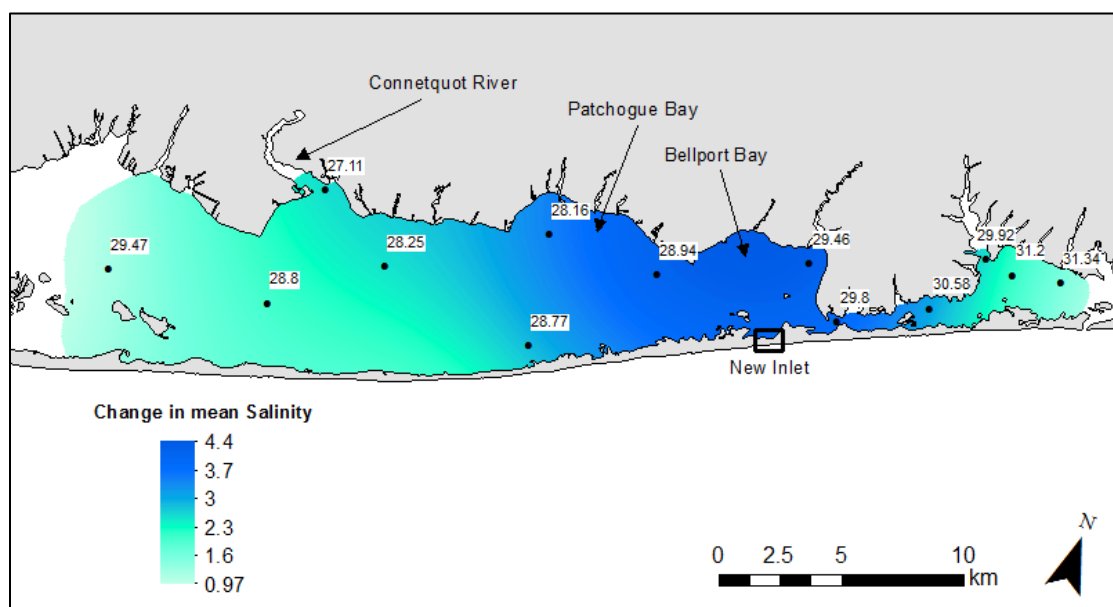


Figure 2. Changes in mean salinity from pre (Jan 2000 – Oct 2012) to post (Nov 2012 – Dec 2015) breach formation, Long Island, NY. Black dots represent surface sampling locations. Mean post breach salinity indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

Changes in summer water temperatures following breach formation were spatially limited (Figure 3). The strongest trends were seen at sites just east of where the breach was formed. At these sites temperatures were, on average, 2°C lower in summer, the equivalent to approximately an 8% decrease (Figure 3). Trends were limited elsewhere, with only minor variations in temperature seen in Patchogue Bay and Moriches Bay, while other sites showed virtually no change (Figure 3).

Changes in summer dissolved oxygen levels varied across Great South Bay following breach formation. Declines in dissolved oxygen were observed at a majority of sampling sites, with the notable exception of sites located in close proximity to the breach that showed increases in dissolved oxygen approaching 10% and ~ 0.5 mg L⁻¹ (Figure 4). This spatial trend reversed abruptly at the majority of sampling sites further west and east (Figure 4).

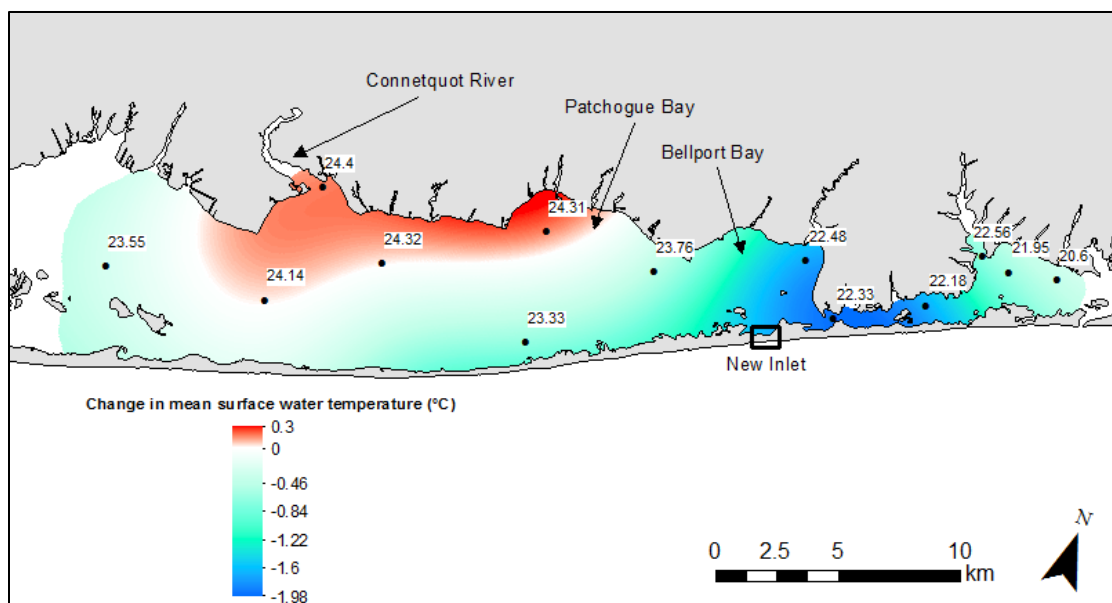


Figure 3. Changes in mean summer (Jun 21 – Sep 20) surface water temperature (°C) from pre (2000 – 2012) to post (2013 – 2015) breach formation, Long Island, NY. Mean post breach surface water temperatures are indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

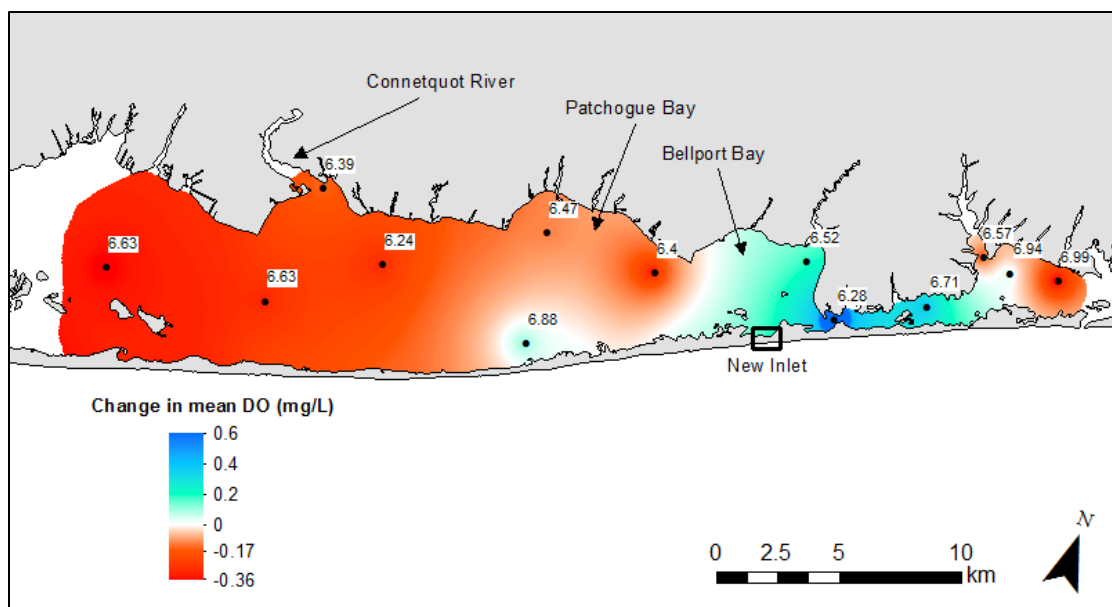


Figure 4. Changes in mean summer (Jun 21 – Sep 20) dissolved oxygen concentration (mg L^{-1}) from pre (2000 – 2012) to post (2013 – 2015) breach formation, Long Island, NY. Mean post breach DO concentrations indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

Changes in turbidity as measured via secchi disk depth displayed a spatial distribution similar to dissolved oxygen (Figure 5). Sites located in close proximity to the breach had secchi disk depth readings close to a foot and 25% higher, representing a substantial increase in water clarity (Figure 5). In contrast, there were declines in secchi disk depth at the far eastern and western sampling sites examined, and minimal change in areas located slightly further from the breach (Figure 5).

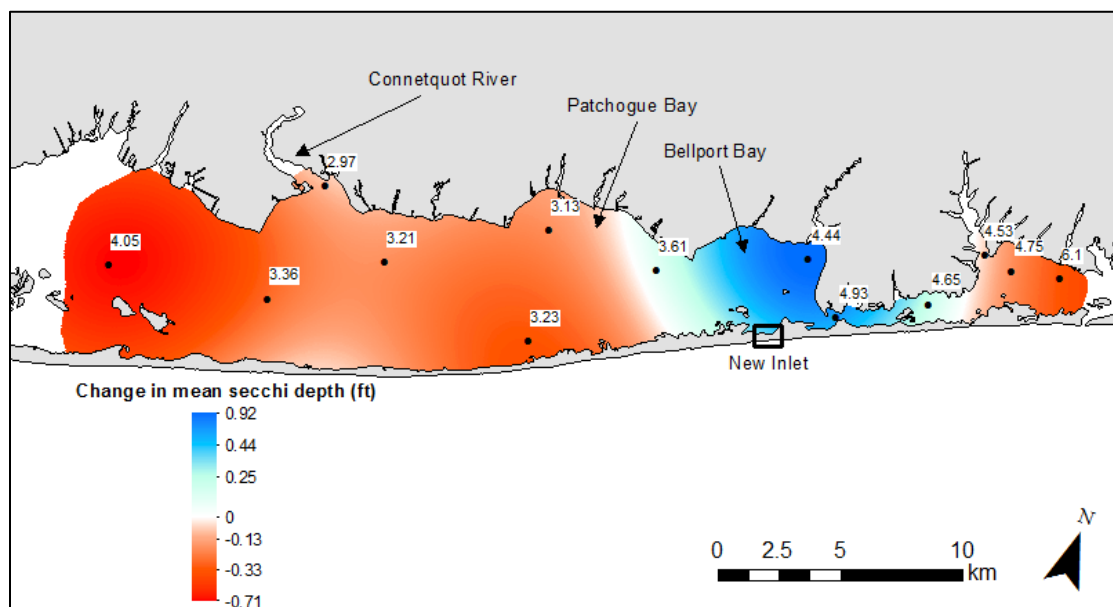


Figure 5. Changes in mean secchi depth (ft) from pre (Jan 2000 – Oct 2012) to post (Nov 2012 – Dec 2015) breach formation, Long Island, NY. Black dots represent surface sampling locations. Mean post breach secchi depth measurements are indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

Changes in summer chlorophyll a levels following breach formation differed between the eastern and western portions of Great South Bay (Figure 6). The western portion of the bay displayed increased chlorophyll a with some variation between sites while the trend reversed to the east with lower chlorophyll a in eastern Patchogue Bay and sites extending through Moriches Bay, with the strongest change observed at sites in close proximity to the breach (Figure 6). At sites surrounding the breach chlorophyll a declined by as much as $5 \mu\text{g L}^{-1}$ or 40%, and this trend was less spatially isolated as compared to increases in oxygen and water clarity (Figure 6).

Changes in total nitrogen following the formation of the breach were similar to changes in chlorophyll a (Figure 7). Sampling sites in the western portions of Great South Bay displayed a slight increase in total nitrogen following the breach, while sites in the eastern portion of Great South Bay and Moriches Bay showed a decrease in total nitrogen (Figure 7). The strongest trends were again observed within close proximity to the breach, where total nitrogen declined by as much as 0.14 mg L^{-1} or 30% following breach formation (Figure 7).

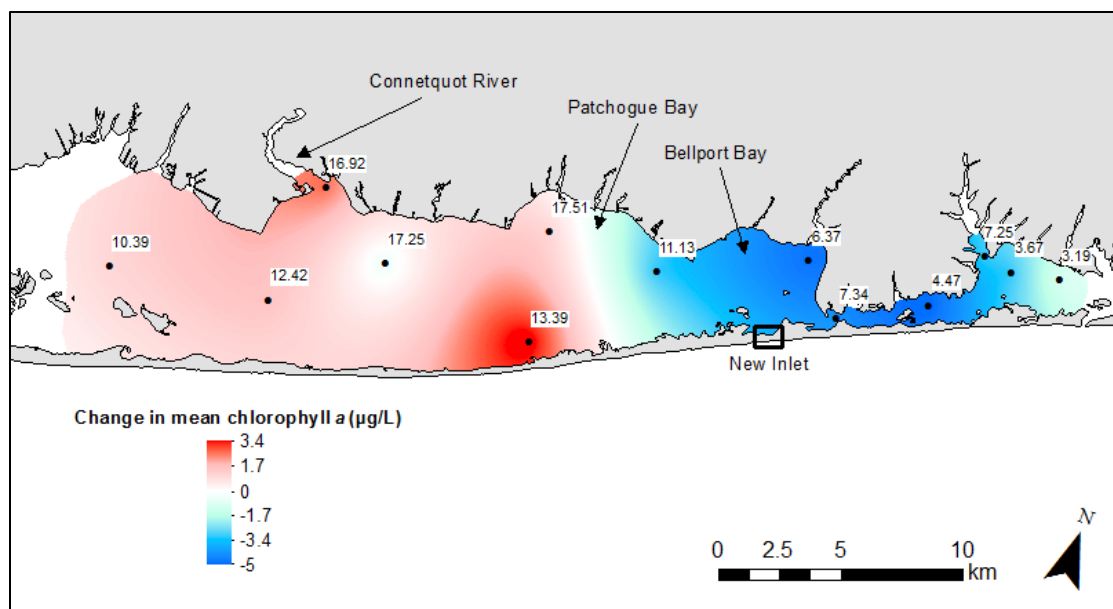


Figure 6. Changes in mean chlorophyll a ($\mu\text{g L}^{-1}$) from pre (Jan 2000 – Oct 2012) to post (Nov 2012 – Dec 2015) breach formation, Long Island, NY. Black dots represent surface sampling locations. Mean post breach chlorophyll a concentrations are indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

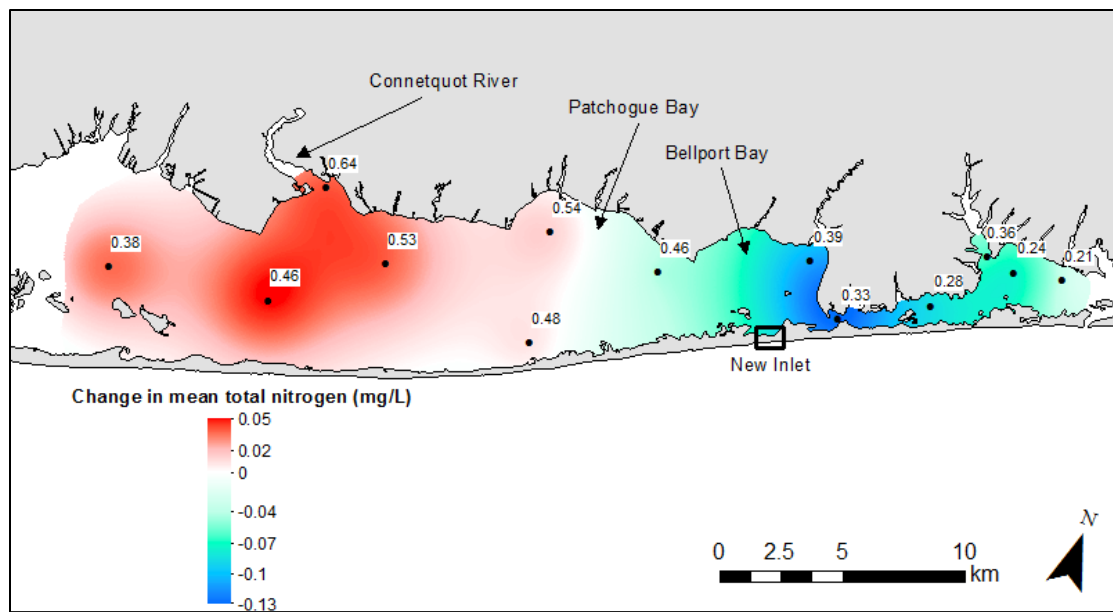


Figure 7. Changes in mean total nitrogen (mg L^{-1}) from pre (Jan 2000 – Oct 2012) to post (Nov 2012 – Dec 2015) breach formation, Long Island, NY. Black dots represent surface sampling locations. Mean post breach total nitrogen concentrations are indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

Declines in dissolved nitrogen following breach formation extended further into the western portions of GSB than total nitrogen (Figure 8). Sites in the far western portion of the bay saw little to no change, save for a slight increase at the mouth of the Connetquot River (Figure 8). In contrast, sites in the eastern portion of Great South Bay and Moriches Bay showed declines in dissolved nitrogen, decreasing by as much as 0.09 mg L⁻¹ (25%) at sites in close proximity to the breach (Figure 8).

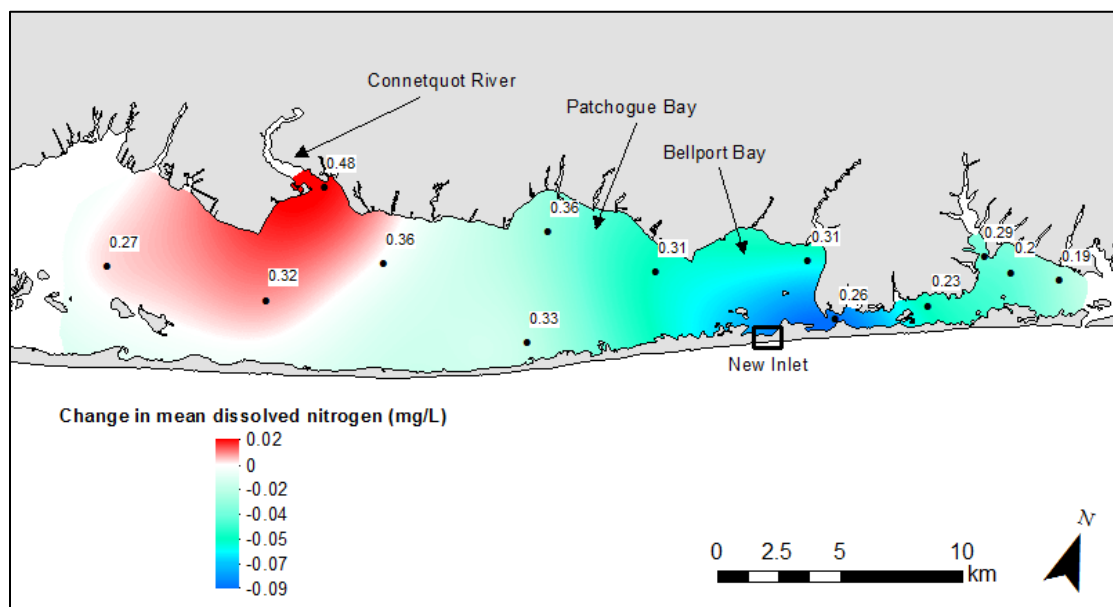


Figure 8. Changes in mean dissolved nitrogen (mg L⁻¹) from pre (Jan 2000 – Oct 2012) to post (Nov 2012 – Dec 2015) breach formation, Long Island, NY. Black dots represent surface sampling locations. Mean post breach dissolved nitrogen concentrations are indicated by values adjacent to sampling locations. Breach location indicated by black box labeled 'New Inlet'.

Post-breach, August 2013 continuous monitoring cruise

During a continuous monitoring cruise across the south shore of Long Island in August of 2013, salinity was highest in proximity to ocean inlets. In Great South Bay, salinity was greater than 30 at the Fire Island Inlet and the New Inlet site, and generally lower than 28 in the middle of the bay (Figure 9). Salinity was greater than 29 through much of Moriches and Shinnecock Bay with the exception of the region between eastern Moriches Bay and western Shinnecock Bay (Figure 9). Bay temperatures within close proximity to ocean inlets were < 21°C, whereas back bay regions had temperatures in excess of 23.5°C (Figure 10).

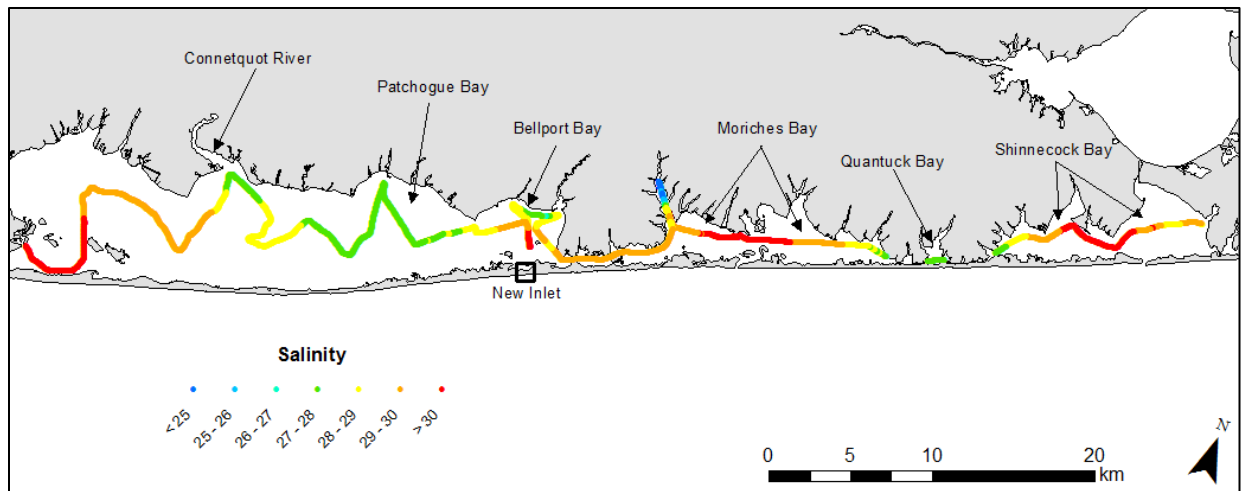


Figure 9. Salinity across Shinnecock Bay, Moriches Bay, and Great South Bay during August 2013, Long Island, NY. Breach location indicated by black box labeled 'New Inlet'.

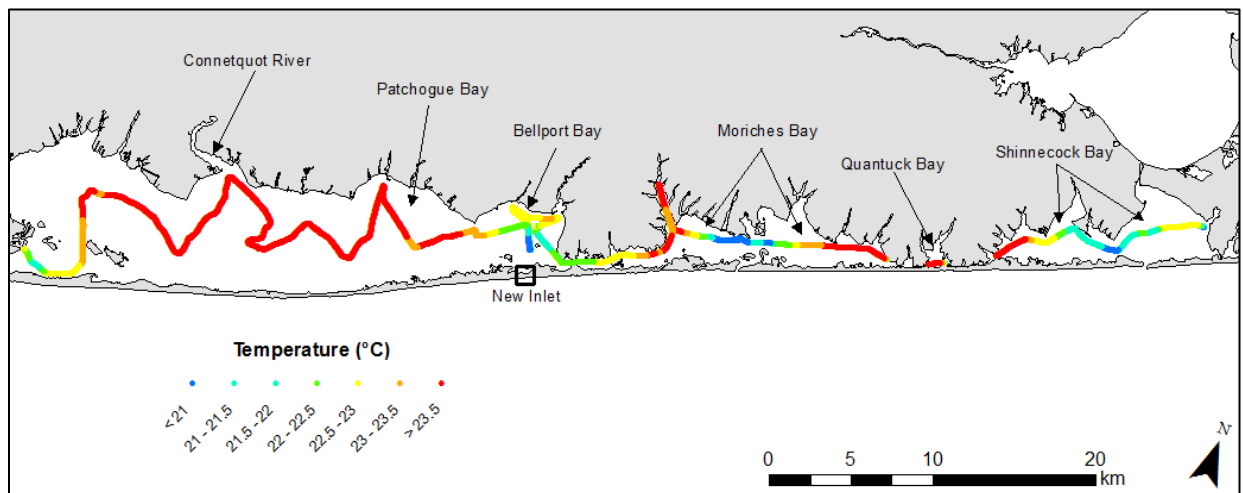


Figure 10. Water temperature across Shinnecock Bay, Moriches Bay, and Great South Bay during August 2013, Long Island, NY. Breach location indicated by black box labeled 'New Inlet'.

Dissolved oxygen was below 7 mg L^{-1} throughout most of Moriches Bay and Great South Bay during August 2013, but around the New Inlet site and near the Shinnecock Inlet, dissolved oxygen levels were higher than 7.3 mg L^{-1} (Figure 11). Chlorophyll *a* concentrations across the south shore during August 2013 were lower in close proximity to all of the ocean inlet sites ($< 10 \mu\text{g L}^{-1}$) and highest concentrations occurred in the middle sections of bays ($> 60 \mu\text{g L}^{-1}$; Figure 12).

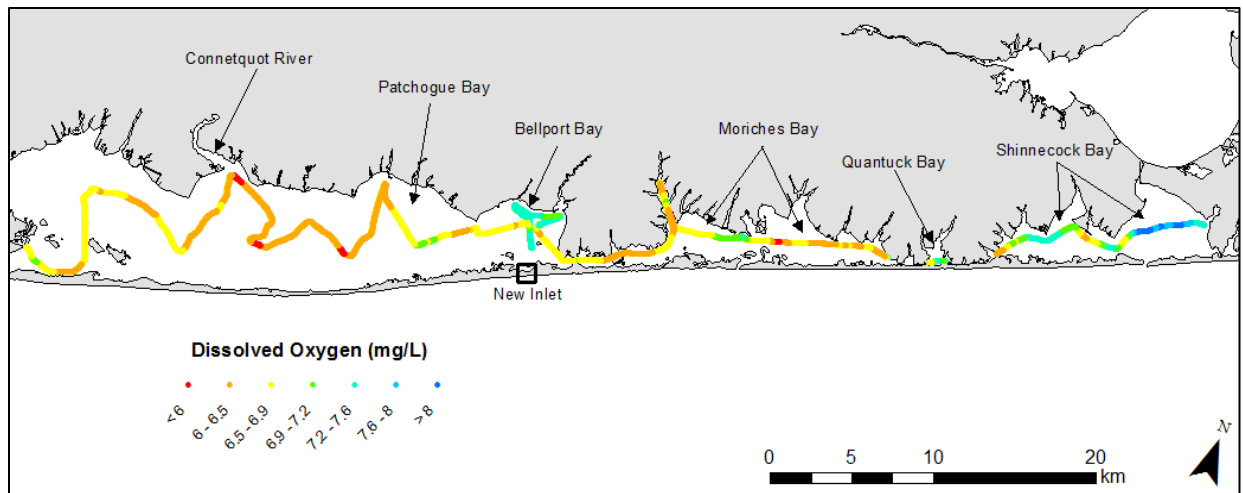


Figure 11. Dissolved oxygen across Shinnecock Bay, Moriches Bay, and Great South Bay during August 2013, Long Island, NY. Breach location indicated by black box labeled 'New Inlet'.

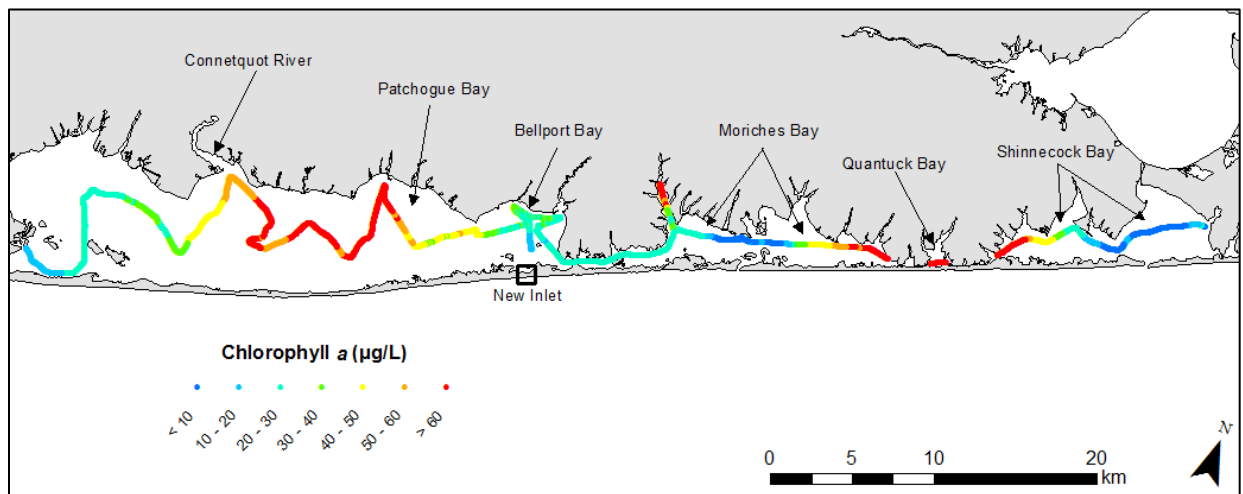


Figure 12. Chlorophyll a concentrations across Shinnecock Bay, Moriches Bay, and Great South Bay during August 2013, Long Island, NY. Breach location indicated by black box labeled 'New Inlet'.

Seasonal variation in physical, and chemical parameters

Across all sites, the average water temperature was low in winter (2-5° C), increased through August (20-25°C), and then decreased (Figure 13). Temperatures at the Mid-Bay and Patchogue Bay sites were lower during the winter months and higher during summer (Figure 13).

Salinity did not display clear temporal trends but the Mid-Bay and Patchogue Bay sites had consistently and significantly lower salinity than the other sites (Tukey test; $p < 0.05$; Figure 14). In general, salinity at the Fire Island Inlet and New Inlet sites was consistently and significantly higher than other sites, usually remaining above 30, and never decreasing below 28 (Tukey test; $p < 0.05$; Figure 14).

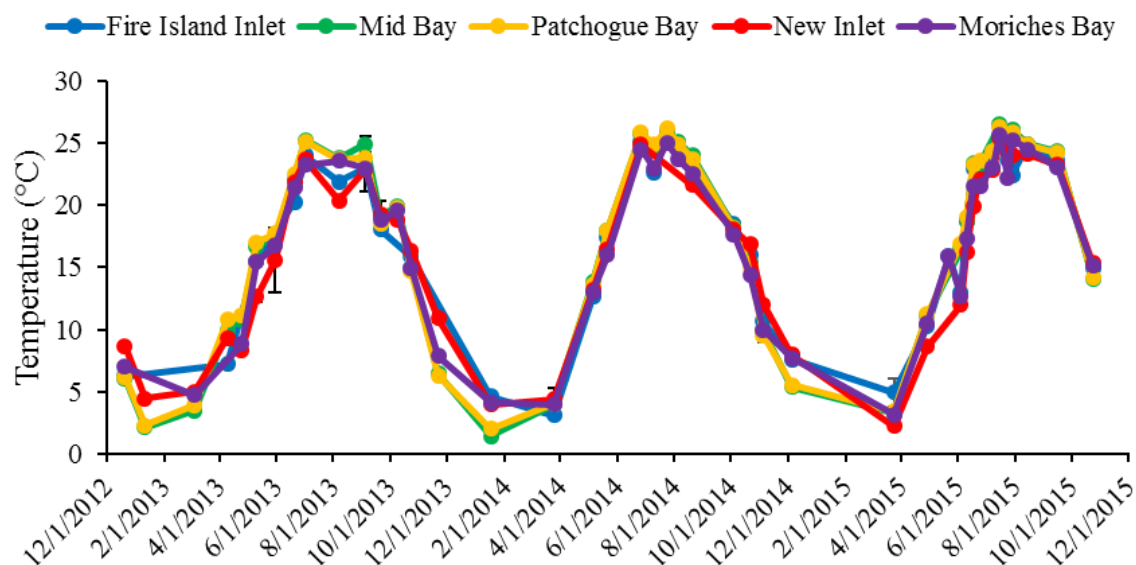


Figure 13. Post-breach temperature values for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

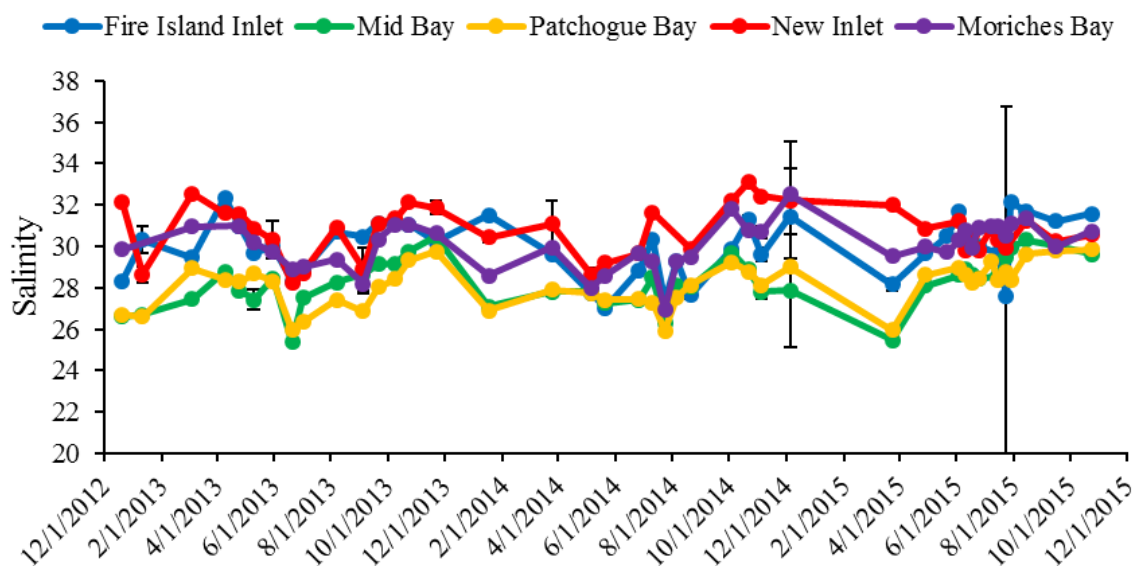


Figure 14. Post-breach salinity values for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Dissolved oxygen followed a seasonal pattern of high levels ($>10 \text{ mg L}^{-1}$) during the winter months and decreasing to $\sim 6 \text{ mg L}^{-1}$ during the summer months with no significant difference in dissolved oxygen among the sites (Tukey test; $p>0.05$; Figure 15).

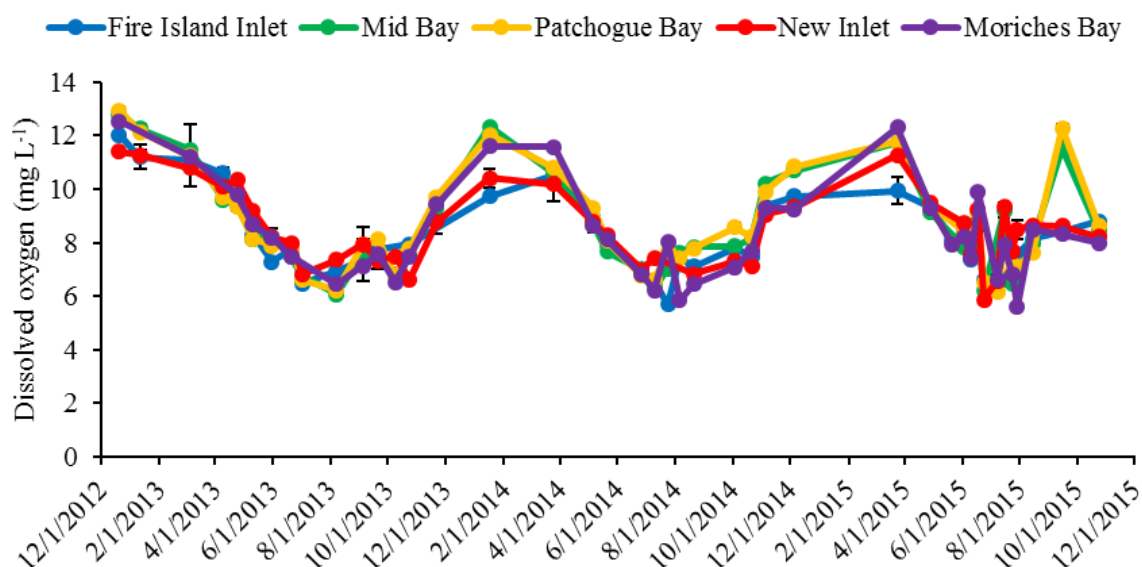


Figure 15. Post-breach dissolved oxygen values for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Based on discrete sampling, there were no discernable seasonal trends in nitrate concentrations and no significant differences among sites (Figure 16; Tukey test; $p > 0.05$). Nitrate concentrations were never above 5 μM for any of the sites with the exception of the New Inlet during the first half of 2013, where concentrations were approximately $> 15 \mu\text{M}$ for 5-March-2013 and 10-May-2013.

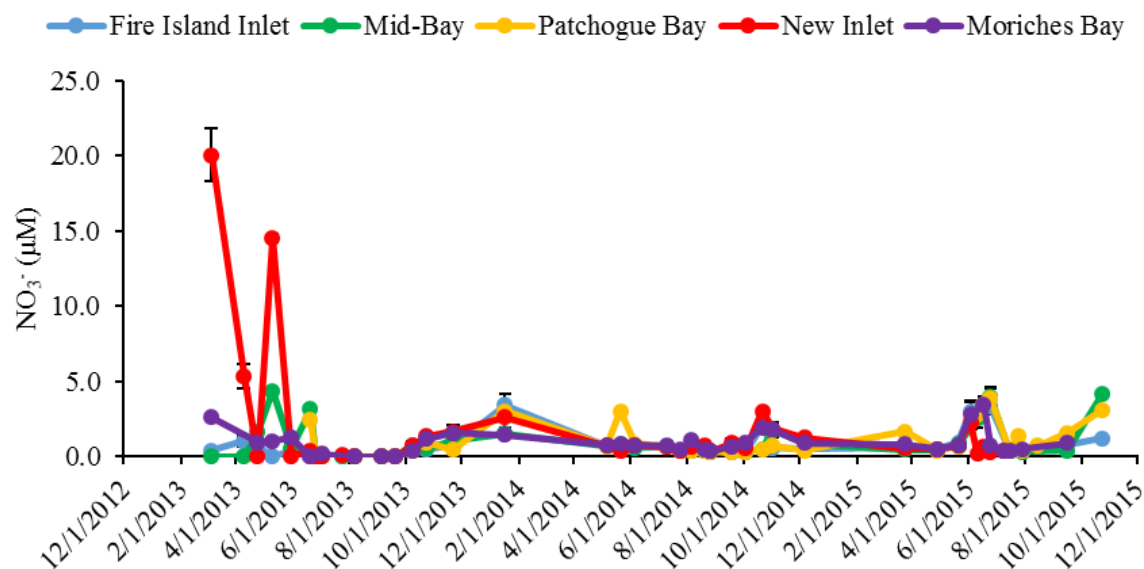


Figure 16. Post-breach nitrate concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

There were no noticeable seasonal trends in phosphate concentration for 2013 (Figure 17). However, in 2014 and 2015, phosphate concentrations increased in late summer, before decreasing into the fall and winter with the 2014 increase exceeding 2015. On average, phosphate concentrations were lower

at the Mid-Bay and Patchogue Bay sites than the other three sites. There were no significant differences in concentrations among the other sites (Figure 17; Tukey test; $p>0.05$) nor obvious seasonal trends (Figure 17).

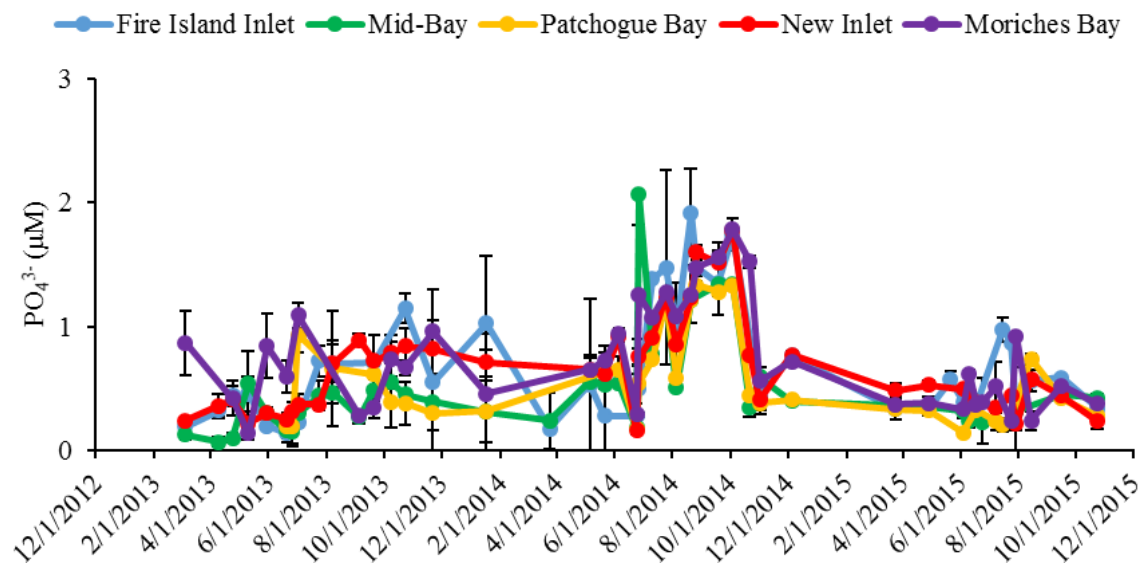


Figure 17. Post-breach phosphate concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Ammonium concentrations did not vary seasonally and there were no significant differences amongst any sites (Figure 18; Tukey test; $p>0.05$).

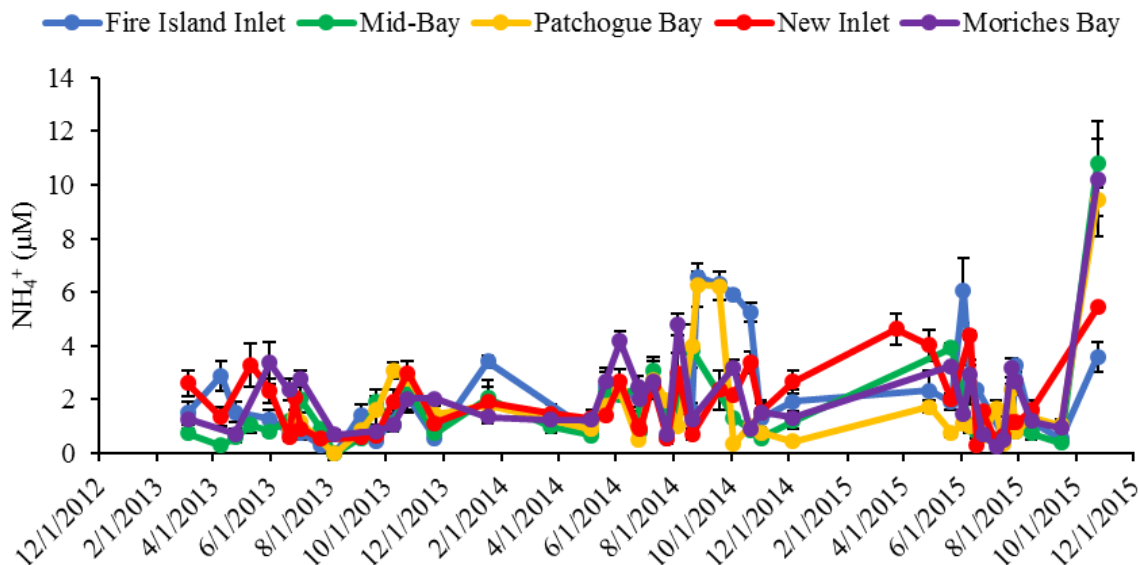


Figure 18. Post-breach ammonium concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

There was a seasonal trend in dissolved organic nitrogen (DON) concentrations with levels being low throughout the winter months, before increasing throughout the summer (Figure 19). DON concentrations were significantly higher at Mid-Bay and Patchogue Bay than the other sites (Tukey test; $p < 0.05$; Figure 19).

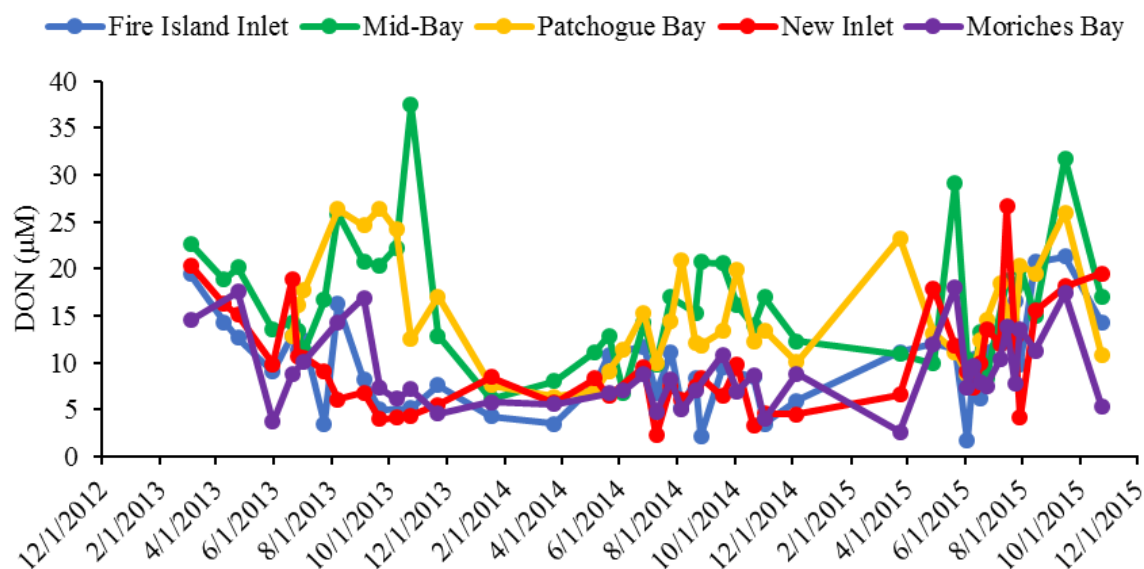


Figure 19. Post-breach dissolved organic nitrogen concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

On average, silicate concentrations were lowest ($< 10 \mu\text{M}$) during the winter, before increasing with the onset of summer (Figure 20). Concentrations of silicate were significantly higher at Patchogue Bay than all sites except Mid-Bay (Tukey test; $p < 0.05$). There was no significant difference in concentrations among the other sites (Tukey test; $p > 0.05$).

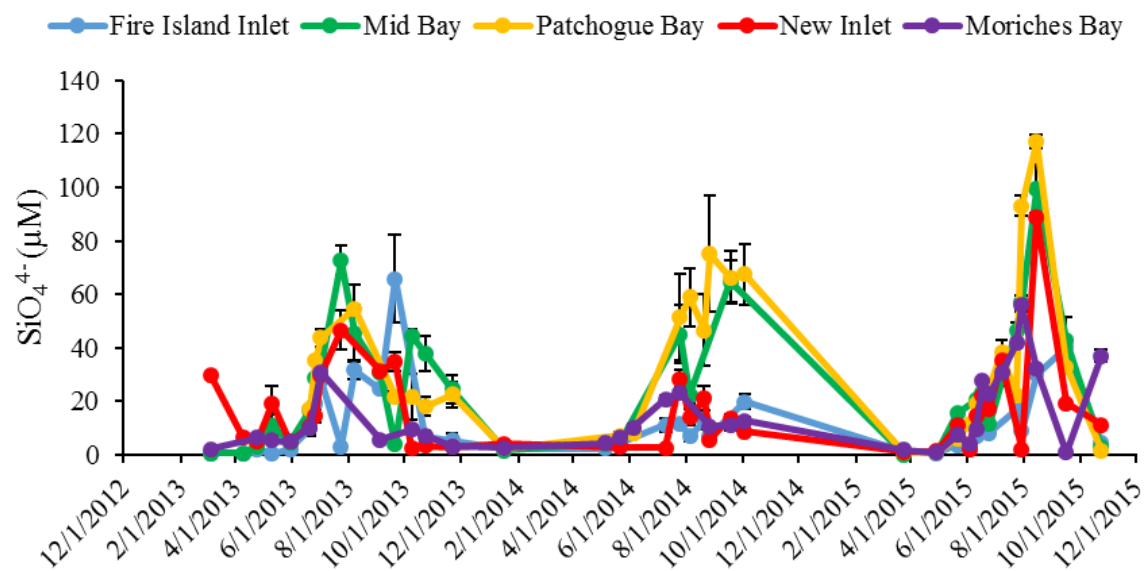


Figure 20. Post-breach silicate concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Phytoplankton communities

Total concentrations of chlorophyll *a*, across all sites, were consistently low ($<10 \mu\text{g L}^{-1}$) during the winter and spring months but were higher in summer and fall (Figure 21). In 2013 and 2015, chlorophyll *a* peaked in August and June, respectively, whereas in 2014, chlorophyll *a* peaked in early December, and did not decrease until April 2015. The concentrations of chlorophyll *a* at the Mid-Bay and Patchogue Bay sites were significantly higher than other sites (Figure 21; Tukey test; $p<0.05$).

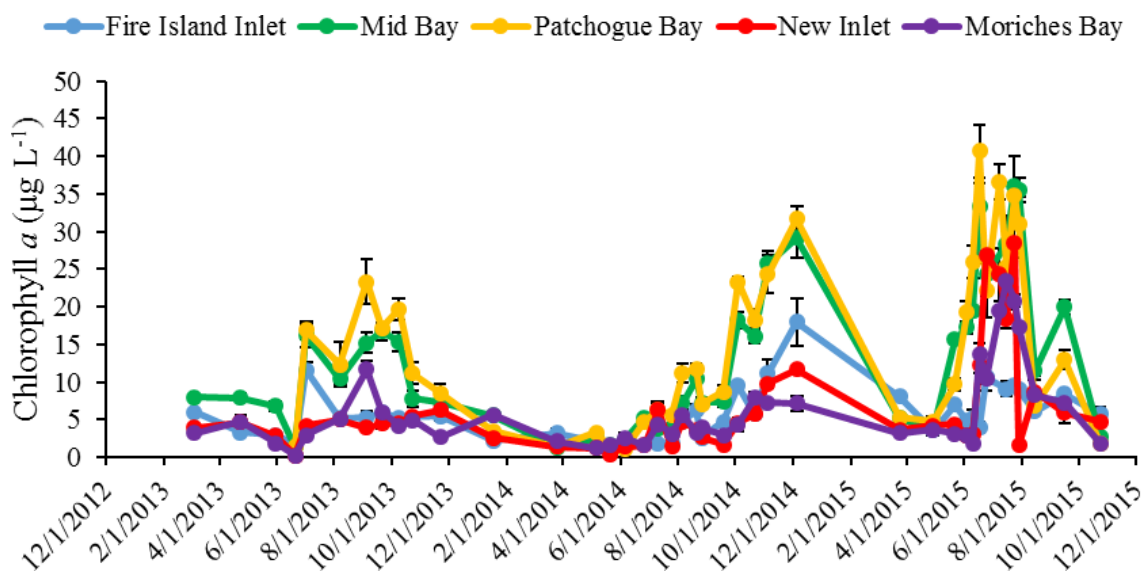


Figure 21. Post-breach whole chlorophyll *a* concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Like total chlorophyll, $<2\mu\text{m}$ chlorophyll *a* concentrations were low ($0-10 \mu\text{g L}^{-1}$) during the winter and spring months and higher in summer and fall, and represented 52% of total chlorophyll *a* (Figure 22).

Concentrations of $<2\mu\text{m}$ chlorophyll *a* at Mid-Bay and Patchogue Bay were significantly higher than other sites (Tukey test; $p<0.05$). Chlorophyll *a* in the $2-5\mu\text{m}$ size fraction was 26% of total chlorophyll *a* with a temporal pattern similar to other chlorophyll fractions (Figure 23). While the greatest peaks in the $2-5\mu\text{m}$ size fraction chlorophyll *a* occurred in Mid-Bay and Patchogue Bay, there were no significant differences among the sites (Tukey test; $p>0.05$; Figure 23).

There were no clear temporal or spatial trends for $>5\mu\text{m}$ chlorophyll *a* concentrations, which represented 23% of total chlorophyll *a* (Figure 24).

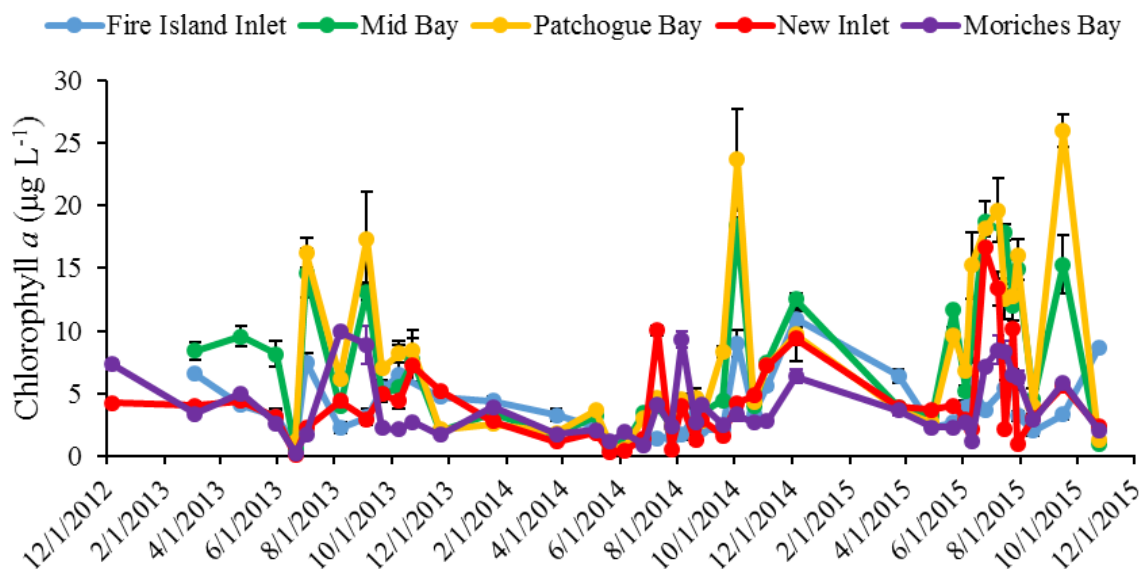


Figure 22. Post-breach <2µm chlorophyll *a* concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

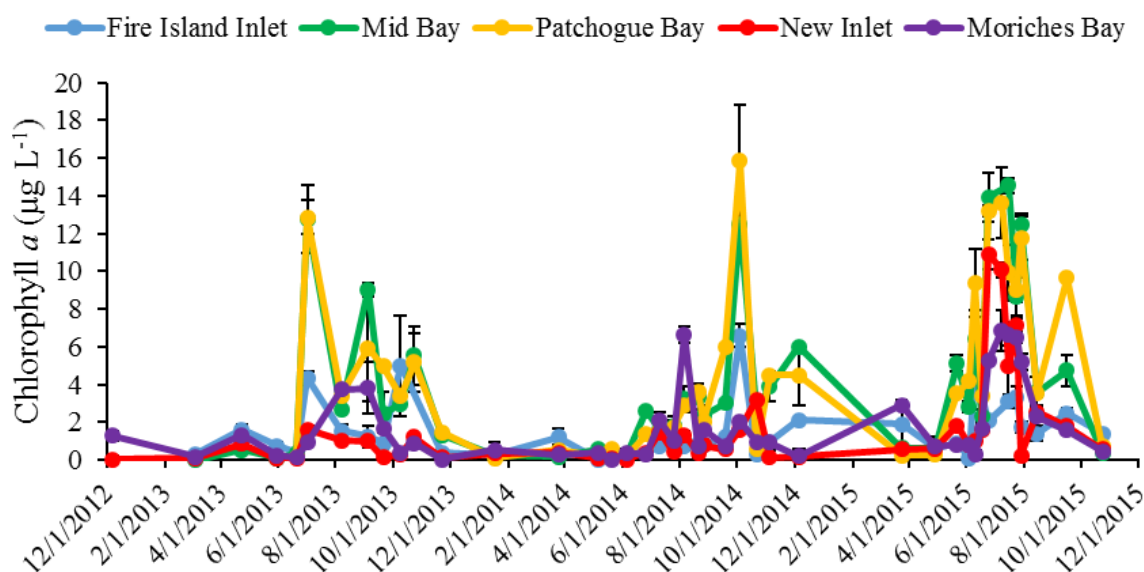


Figure 23. Post-breach 2-5µm chlorophyll *a* concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

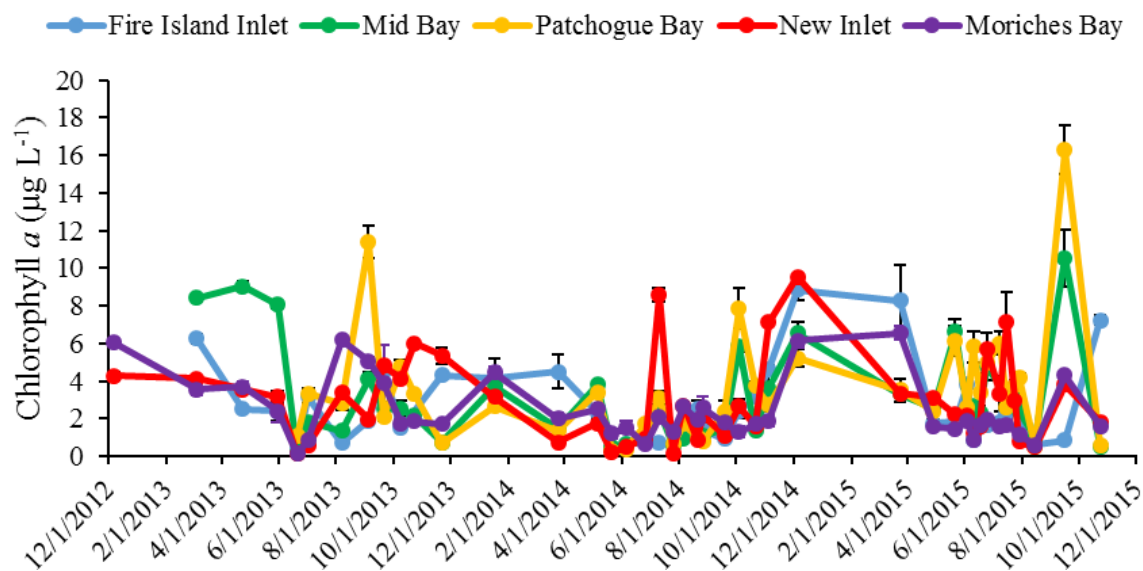


Figure 24. Post-breach >5µm chlorophyll a concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Four distinct brown tides caused by the pelagophyte *A. anophagefferens* occurred during this study. The first occurred during the summer of 2013 when concentrations exceeding 4×10^5 cells mL⁻¹ occurred within the Fire Island Inlet, Mid-Bay, and Patchogue Bay with peak densities exceeding 10^6 cells mL⁻¹ occurring in Mid-Bay in July (Figure 25). For perspective, densities exceeding 4×10^4 cells mL⁻¹ can be harmful to marine life (Gobler et al., 2005). While the bloom collapsed in August, it returned to Mid-Bay and Patchogue Bay only during September and October of 2013 peaking at around 9×10^5 cells mL⁻¹ (Figure 25). While there was not a brown tide during the summer of 2014, it returned again in the fall of 2014, persisting at $> 5 \times 10^5$ cells mL⁻¹ from early October through December within the Mid-Bay and Patchogue Bay sites and achieving lower levels for a shorter period of time at the Fire Island Inlet site ($< 2 \times 10^5$ cells mL⁻¹ during November and December; Figure 25). The final brown tide of this study occurred during June and July of 2015 when a bloom initiated at Mid-Bay and Patchogue Bay (peak cell densities around 8×10^5 cells mL⁻¹) and then spread to other locations where cell densities were lower ($< 3 \times 10^5$ cells mL⁻¹). Over the entire study, brown tide concentrations at Mid-Bay and Patchogue Bay were significantly higher than New Inlet and Moriches Bay (Figure 25; Tukey test; $p < 0.05$).

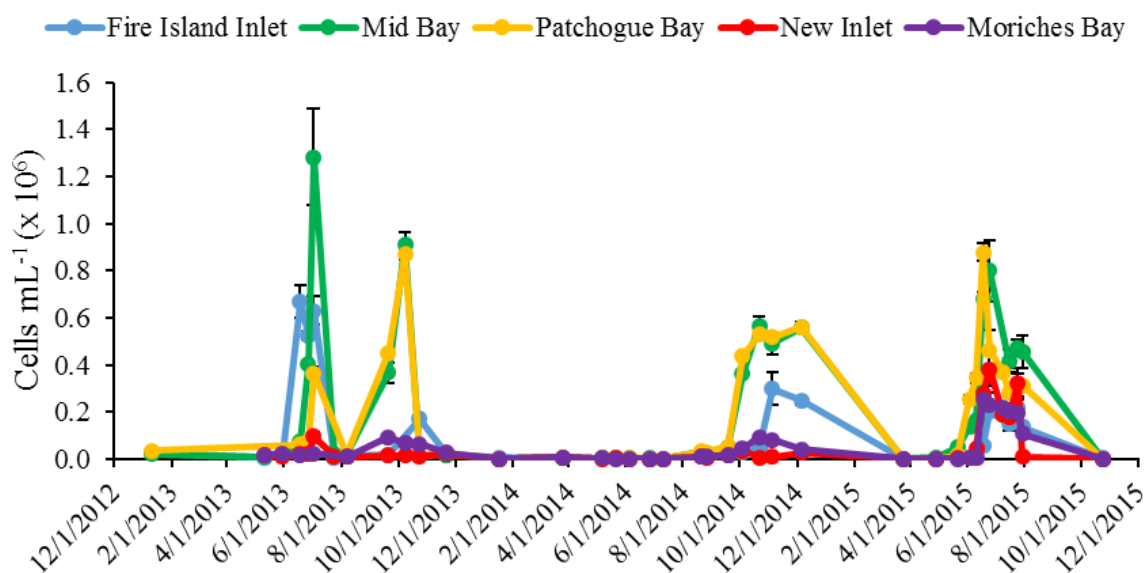


Figure 25. Post-breach *Aureococcus anophagefferens* concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Concentrations of pico-cyanobacteria followed a seasonal trend of low concentrations during the winter and spring months and significantly increasing throughout summer (Figure 26).

Concentrations of cyanobacteria were found to be significantly higher at Mid-Bay and Patchogue Bay than the other three sites (Tukey test; $p < 0.05$), with no statistical difference occurring among the latter three although the lowest concentrations were consistently observed at the New Inlet site (Figure 26).

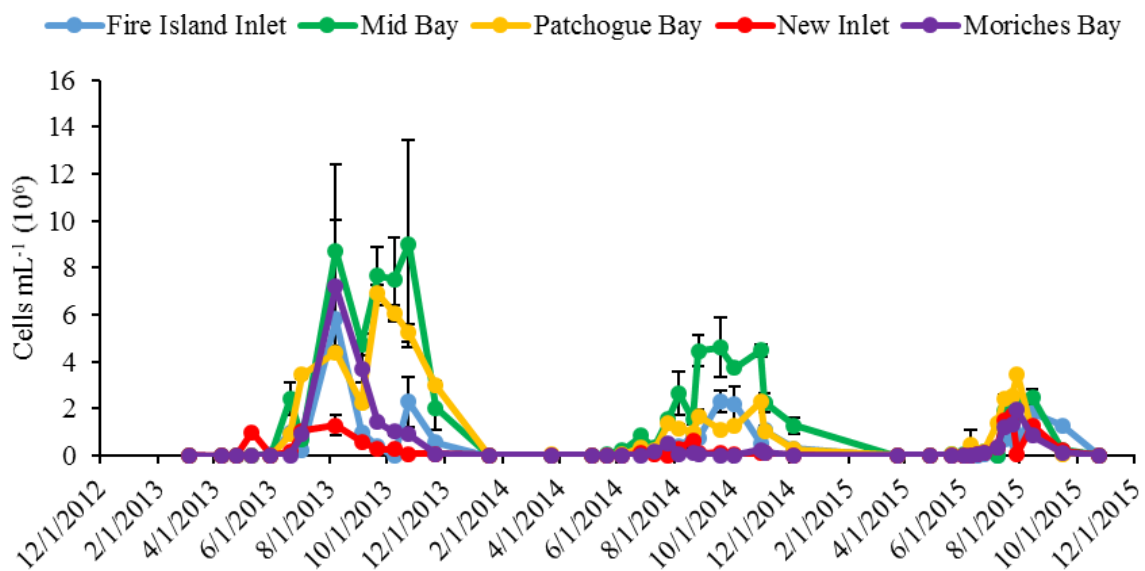


Figure 26. Post-breach cyanobacteria concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Concentrations of autotrophic eukaryotes (quantified via flow cytometry) followed a seasonal trend similar to other autotrophs being low during the winter and spring months but high in summer and fall (Figure 27). While there were generally similar peak concentrations among sites through the study, during summer 2014 the Mid-Bay site had an average concentration of approximately 1.2×10^6 cells mL^{-1} which was significantly greater than all other sites during this season (Figure 27; Tukey test; $p < 0.05$). There was no significant difference among sites throughout the study or during a particular season (Figure 27; Tukey test; $p > 0.05$).

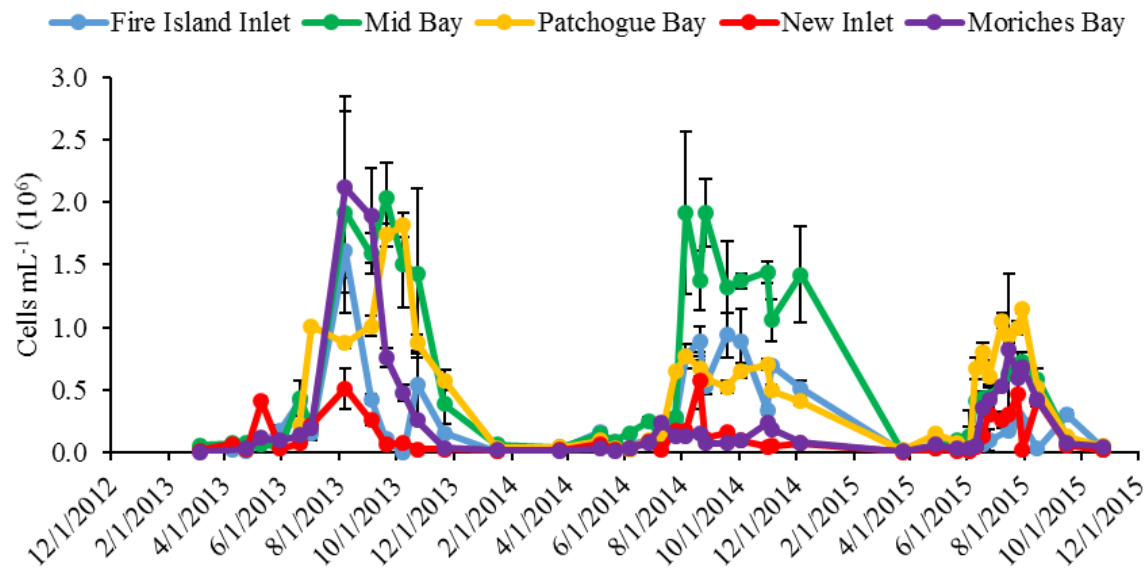


Figure 27. Post-breach total autotrophic eukaryote concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Autotrophic eukaryotes consisted of approximately 75% of pico-eukaryotes ($< 2 \mu\text{m}$; Figure 28) and 25% nano-eukaryotes ($> 2 \mu\text{m}$; Figure 29). There were significantly higher concentrations of pico- and nano-eukaryotes at Mid-Bay and Patchogue Bay than other sites (Tukey test; $p < 0.05$).

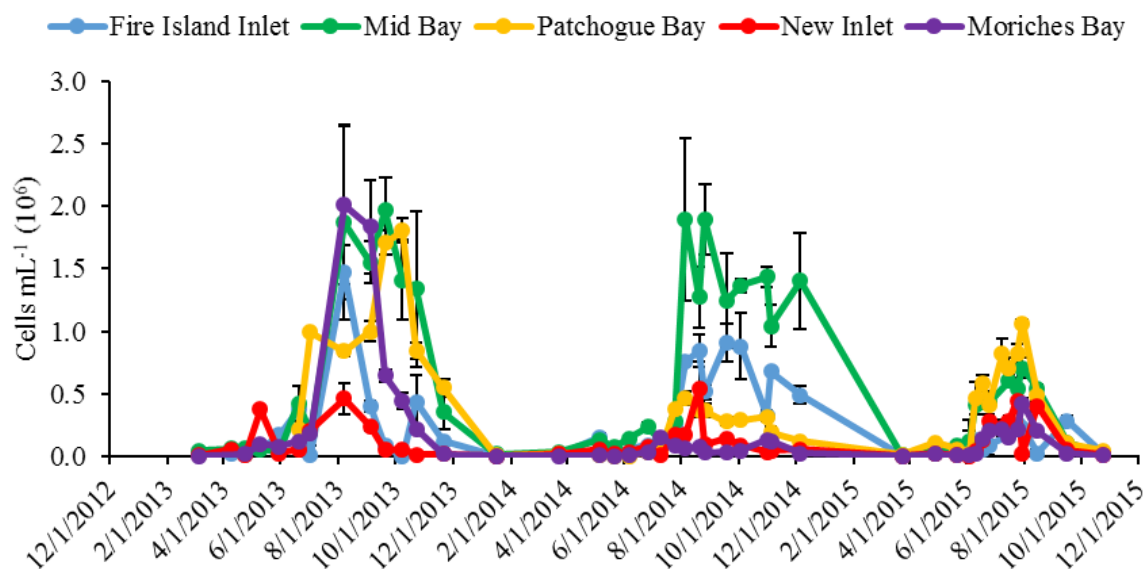


Figure 28. Post-breach autotrophic pico-eukaryote concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

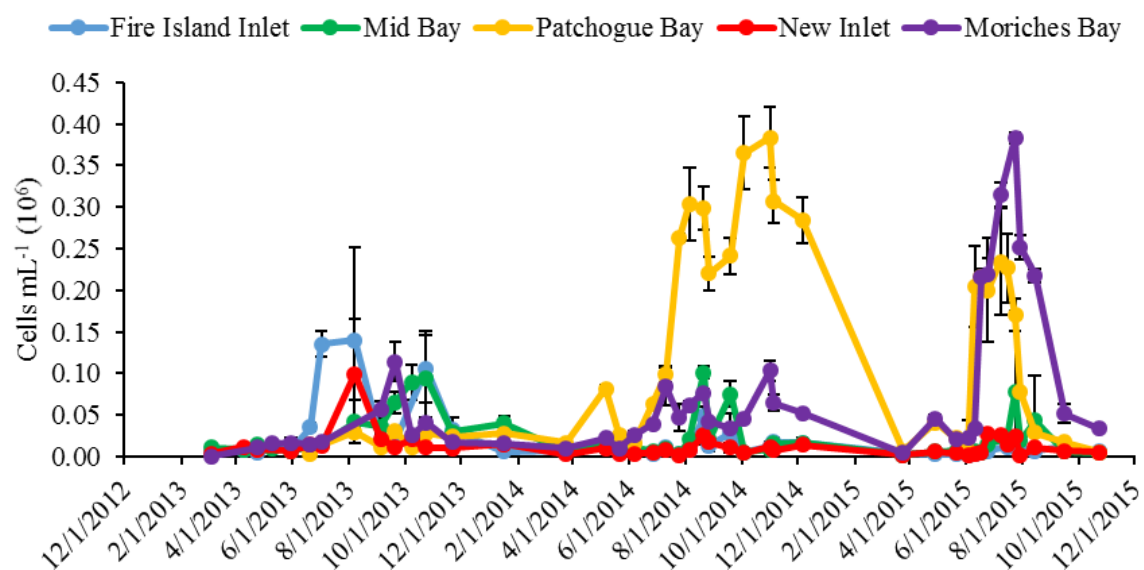


Figure 29. Post-breach autotrophic nano-eukaryote concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Heterotrophic bacteria displayed peak summer concentrations with the location of the highest densities differing by year. In 2013, there were relatively low levels of heterotrophic bacteria ($<10 \times 10^6$ cells mL^{-1}) for all sites except Patchogue Bay, where concentrations reached approximately $2.0\text{--}5.4 \times 10^7$ cells mL^{-1} during the summer (Figure 30). In 2014, similarly high heterotrophic bacteria were observed at Mid-Bay whereas lower levels were observed elsewhere. In 2015, the highest heterotrophic bacteria concentrations occurred again at Patchogue Bay in summer (Figure 30). Concentrations of heterotrophic bacteria were significantly higher at Mid-Bay and Patchogue Bay

than the other three sites (Tukey test; $p < 0.05$), with no statistical difference in concentrations among the latter three sites ($p > 0.05$).

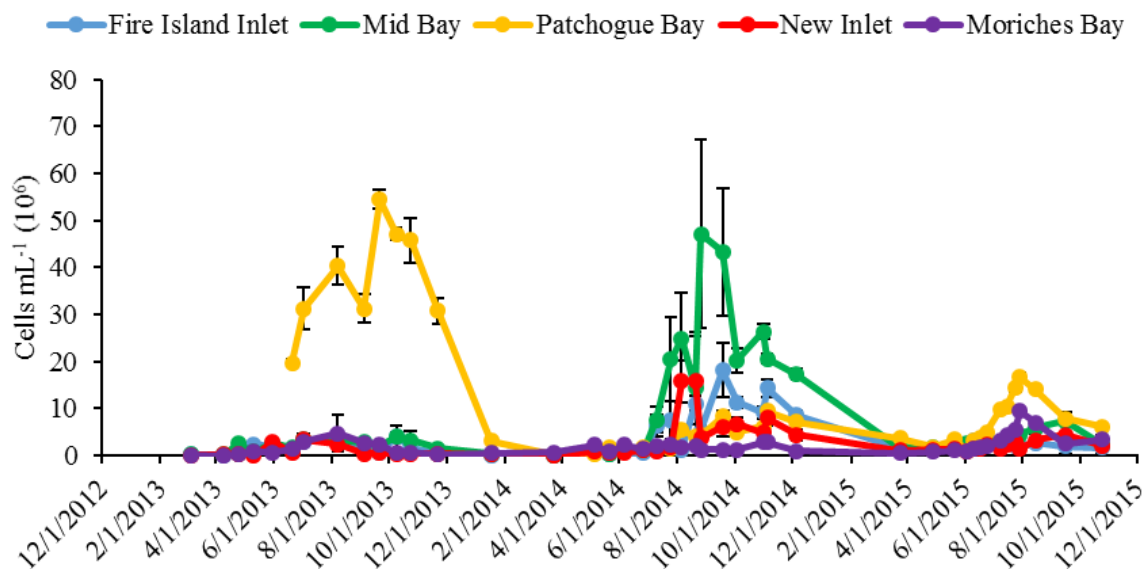


Figure 30. Post-breach heterotrophic bacteria concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

During 2013, densities of diatoms, dinoflagellates, and autotrophic nanoplankton were consistently low with the exception of a pennate diatom bloom that occurred within Mid-Bay and near the Fire Island Inlet during April and May of that year (Figures 31-34). In 2014, diatoms, dinoflagellates, and autotrophic nanoplankton were more dynamic and displayed temporal patterns that were nearly the opposite of other phytoplankton groups quantified during this study, being elevated in winter and spring, low in summer, but higher again in later summer and fall (Figures 31-34). On average, the Mid-Bay stations had significantly higher concentrations of centric diatoms than the New Inlet ($p < 0.05$). Autotrophic nanoflagellate concentrations were significantly higher at Mid-Bay and Patchogue Bay than the other sites (Tukey test; $p < 0.05$), with the exception of Fire Island Inlet.

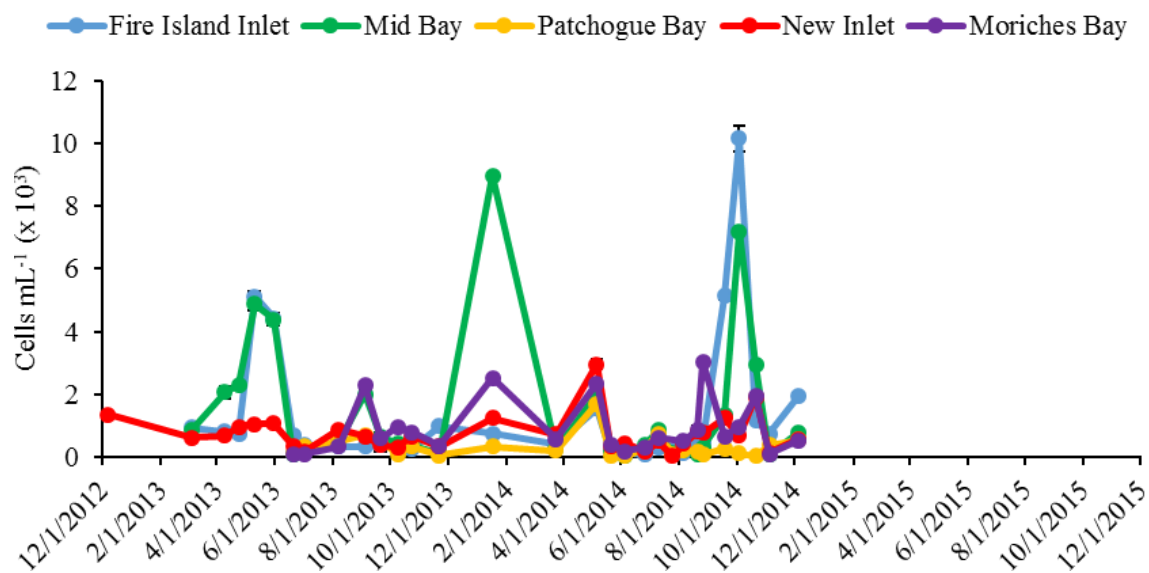


Figure 31. Post-breach pennate diatom concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Error bars represent standard deviation.

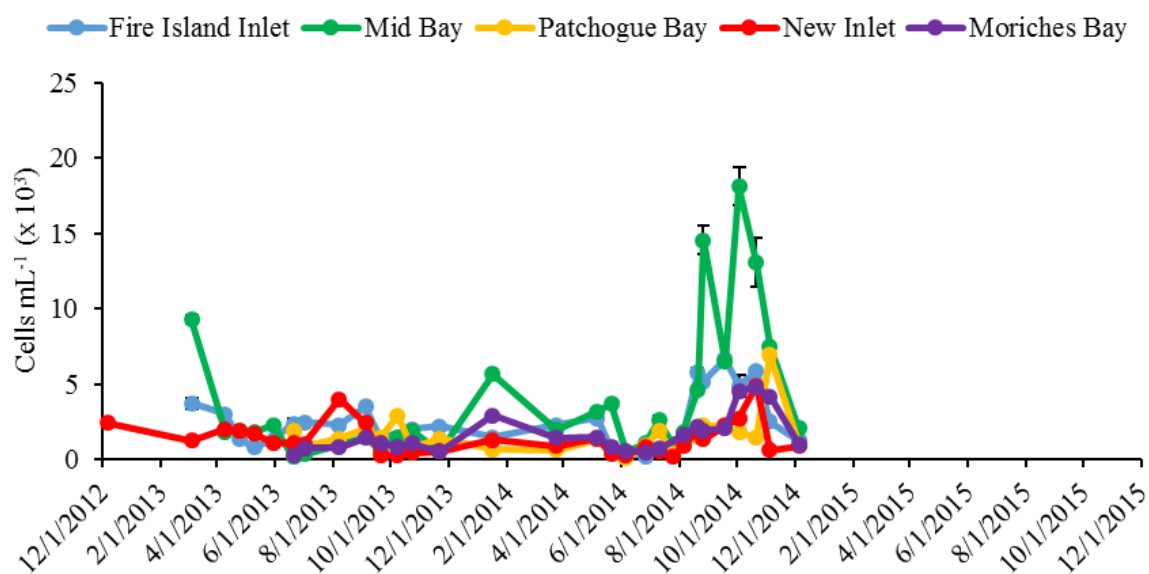


Figure 32. Post-breach centric diatom concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

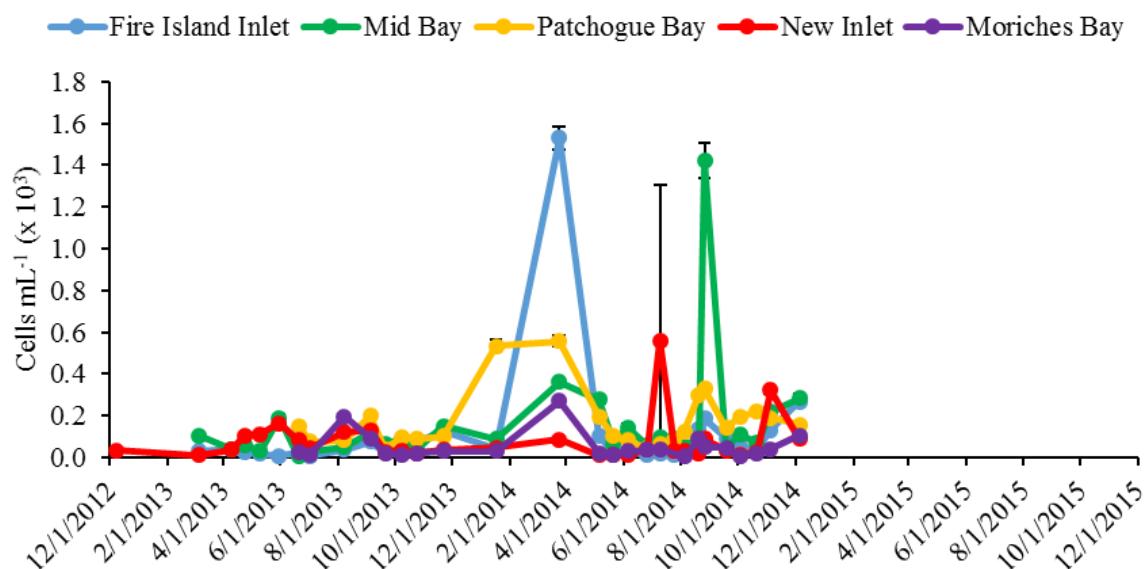


Figure 33. Post-breach dinoflagellate concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

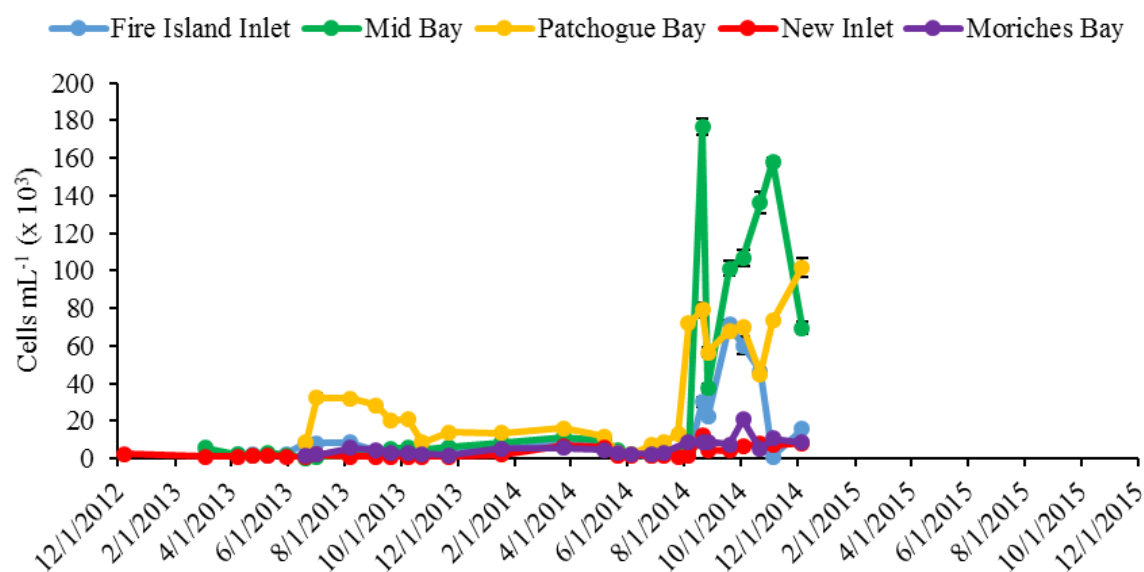


Figure 34. Post-breach autotrophic nanoflagellate concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Flow Cam analysis of plankton communities

During fall 2013, the plankton community near the New Inlet was consistently different from the interior Great South Bay sites (Mid-Bay and Patchogue Bay) and most similar to the community near Fire Island Inlet. For example, from September through November 2013, the proportion of total plankton biomass smaller than 5 μm was less, and the proportion greater than 25 μm was more, at the Fire Island Inlet and New Inlet than at Mid-Bay and Patchogue Bay (Figures 35-36).

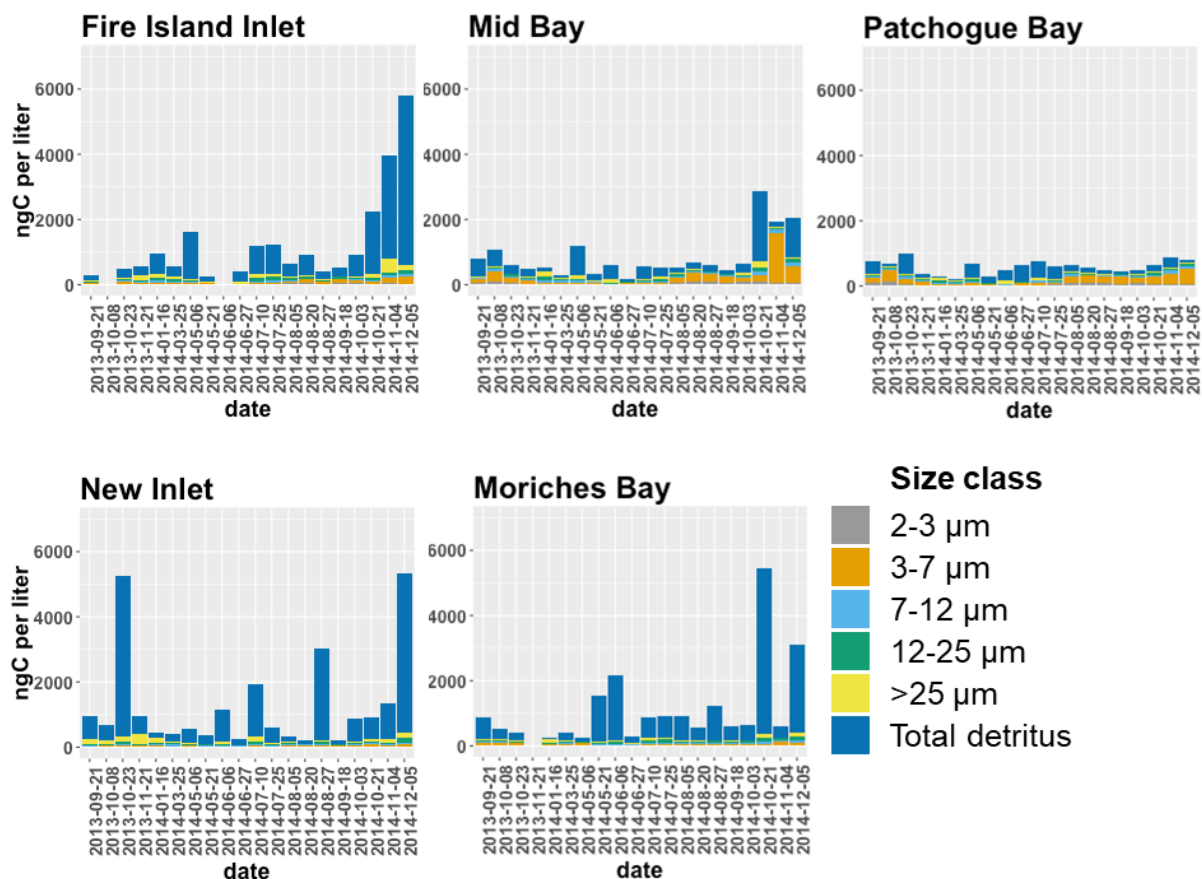


Figure 35. Absolute biomass (micrograms organic carbon per liter seawater) in various size classes (equivalent spherical diameter, ESD, in micrometers) plus large (>25 micrometers) detritus for plankton samples from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay), Moriches Bay, Long Island, NY.

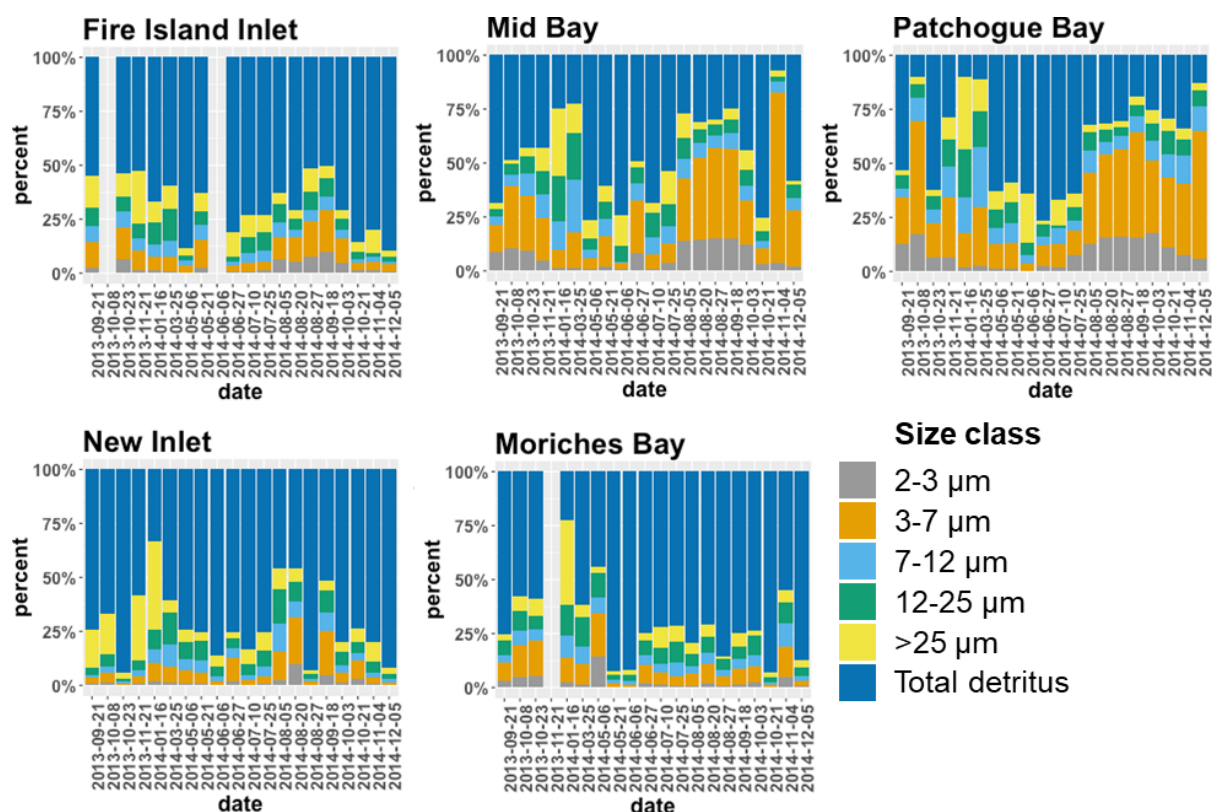


Figure 36. Normalized biomass (micrograms organic carbon per liter seawater) in various size classes (equivalent spherical diameter, ESD, in micrometers) plus large (>25 micrometers) detritus for plankton samples from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay), Moriches Bay, Long Island, NY.

These differences largely reflected the presence of more abundant and diverse large, chain-forming centric diatoms at the two stations nearest the inlets compared to the interior sites (Figures 37-38). *Thalassiosira*, *Eucampia*, *Chaetoceros* and *Rhizosolenia* were particularly more abundant near the inlets. In contrast, ciliates were more prominent community members in Mid-Bay and Patchogue Bay, and a brown tide contributed substantially to the biomass in the smallest size class at Mid-Bay and Patchogue Bay (Figure 25).

Cluster analysis confirmed the difference between the near-inlet and interior bay sites: the deepest split in the dendrogram separates almost all of the fall samples from the Fire Island Inlet and New Inlet from all of the fall samples from Mid-Bay and Patchogue Bay (Figure 39).

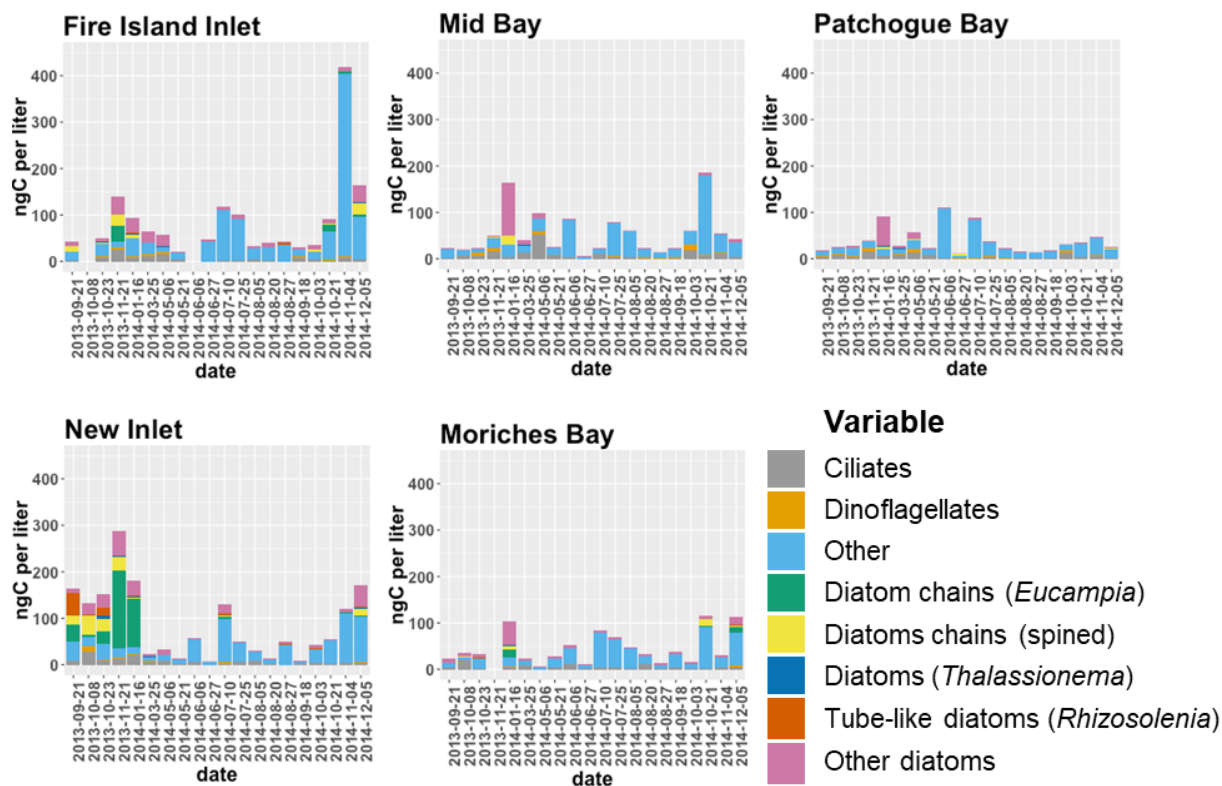


Figure 37. Absolute biomass (micrograms organic carbon per liter seawater) of various major groups of large (greater than 25 micrometer equivalent spherical diameter, ESD), live plankton in samples from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay), Moriches Bay, Long Island, NY.

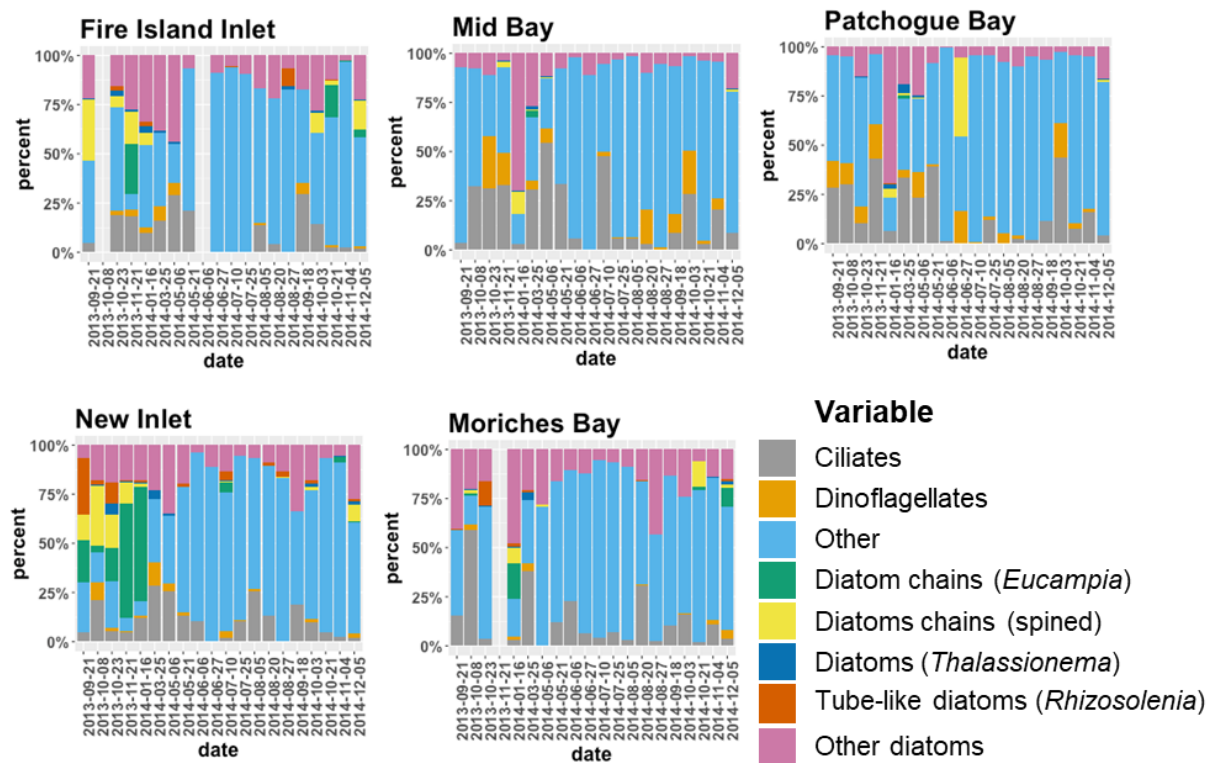


Figure 38. Normalized biomass (micrograms organic carbon per liter seawater) of various major groups of large (greater than 25 micrometer equivalent spherical diameter, ESD), live plankton in samples from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay), Moriches Bay, Long Island, NY.

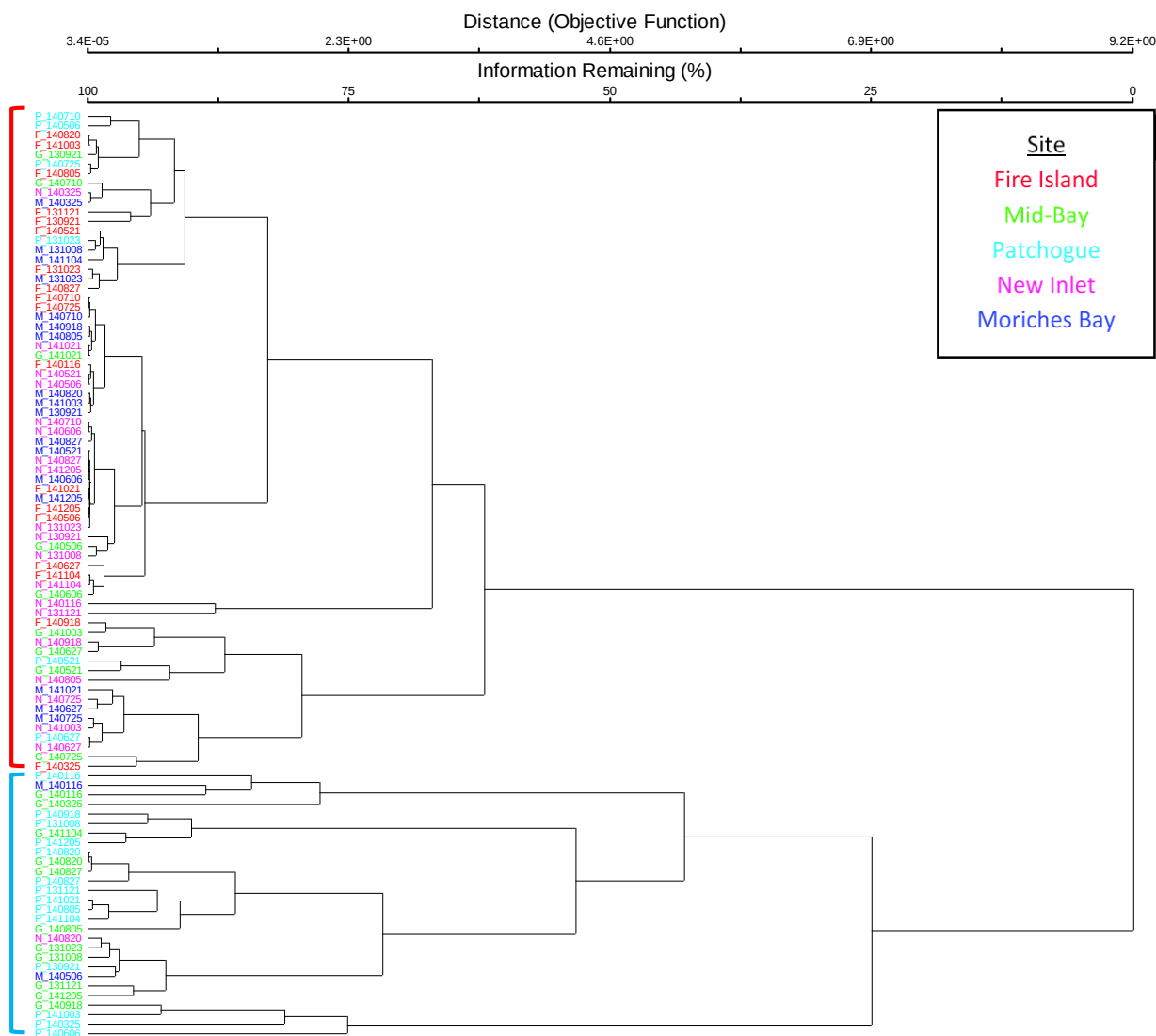


Figure 39. Cluster analysis of all live plankton categories in all samples analyzed by FlowCAM. Each sample is named with a letter indicating the station (F, G, P, N, and M for Fire Island Inlet, Mid-Bay, Patchogue Bay, New Inlet, and Moriches Bay, respectively) and the date as yymmdd, Long Island, NY. The deepest division separates two clusters, the lower containing mainly the Mid Bay and Patchogue Bay samples, and the upper containing mainly the Fire Island Inlet, New Inlet, and Moriches Bay samples.

In January 2014, Mid-Bay and Patchogue Bay experienced an increase in biomass of large phytoplankton due mainly to a widespread bloom of the colony-forming diatom *Thalassiosira* (Figures 35-38). This change in size structure persisted for the rest of the spring and summer. The January and March 2014 samples still clustered into the same two large groups as the fall samples (near-inlet vs interior; Figure 39), although the January and March interior samples fell onto a different branch than the fall interior samples. A clear difference between near-inlet and interior sites was no longer evident during the spring and early summer (May through early June) of 2014 (Figures 35-39).

The Moriches Bay samples did not group consistently with either the near-inlet or the interior Great South Bay samples (Figure 39). This may reflect that this site was affected by a variety of additional processes. The Moriches Bay station also differed from the Great South Bay stations in being more commonly dominated by the diatom *Leptocylindrus*, which was included in the ‘other diatoms’ category to ease visualization of patterns among the Great South Bay stations (Figures 37-38).

Like bulk chlorophyll, which showed very similar temporal patterns at the two interior stations as well as at the New Inlet and Moriches Bay stations, the size structure of the plankton communities at Mid Bay and Patchogue Bay showed similar temporal patterns, as did those at New Inlet and Fire Island Inlet, especially for the smallest size fractions (Figures 40-43). During fall 2014, the difference in size structure between the near-inlet and interior sites returned with the onset of another brown tide event (greater proportion of larger plankton near the inlets; (Figures 25, 40-43). Even the Fire Island Inlet station had a greater proportion of biomass in the smallest size fractions, suggesting relatively faster exchange with the open ocean through Fire Island Inlet than was occurring via the New Inlet and Moriches Inlet. Detritus was often more abundant at the Fire Island Inlet and New Inlet stations than the interior GSB stations (Figures 40-41), perhaps reflecting differences in tidal currents and turbulence capable of resuspending sediments. Diatoms were also generally more abundant at the inlet stations (Figures 42-43).

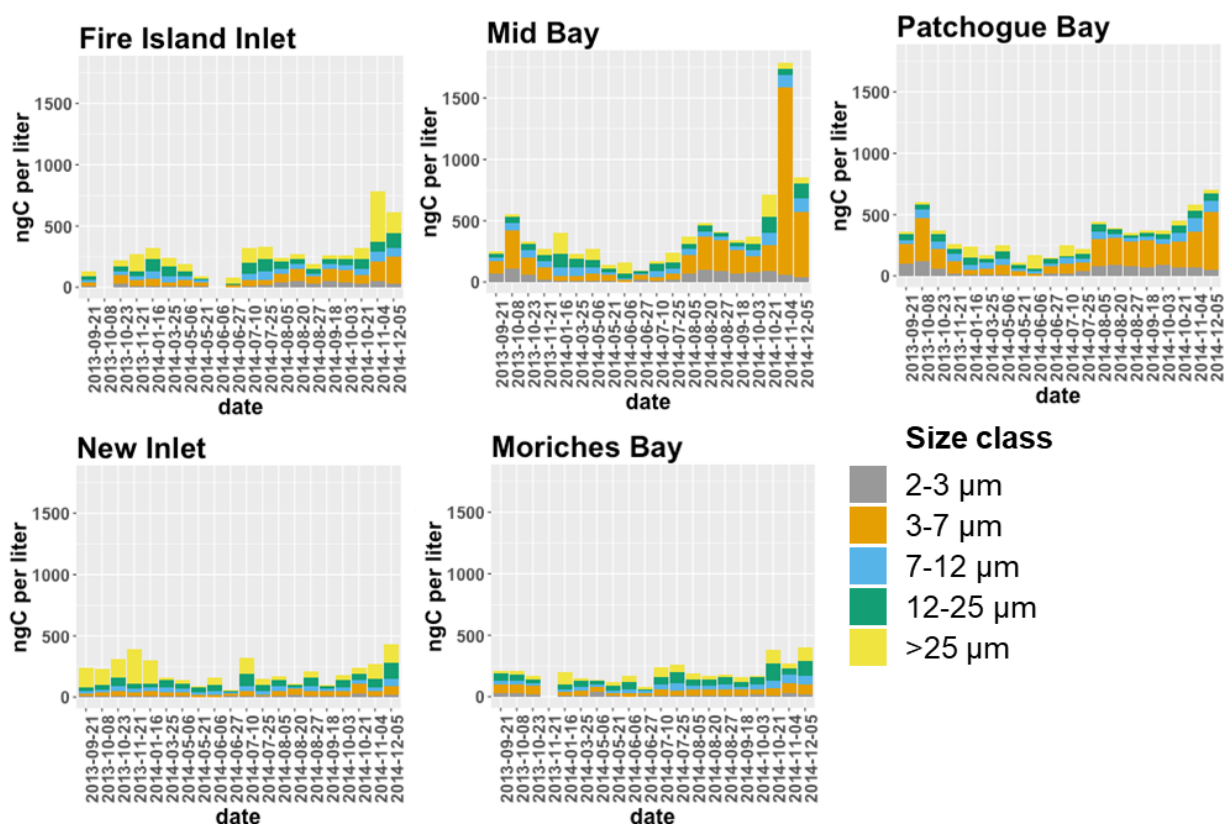


Figure 40. Absolute biomass (micrograms organic carbon per liter seawater) of live plankton in various size classes (equivalent spherical diameter, ESD, in micrometers) from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay) and Moriches Bay, Long Island, NY.

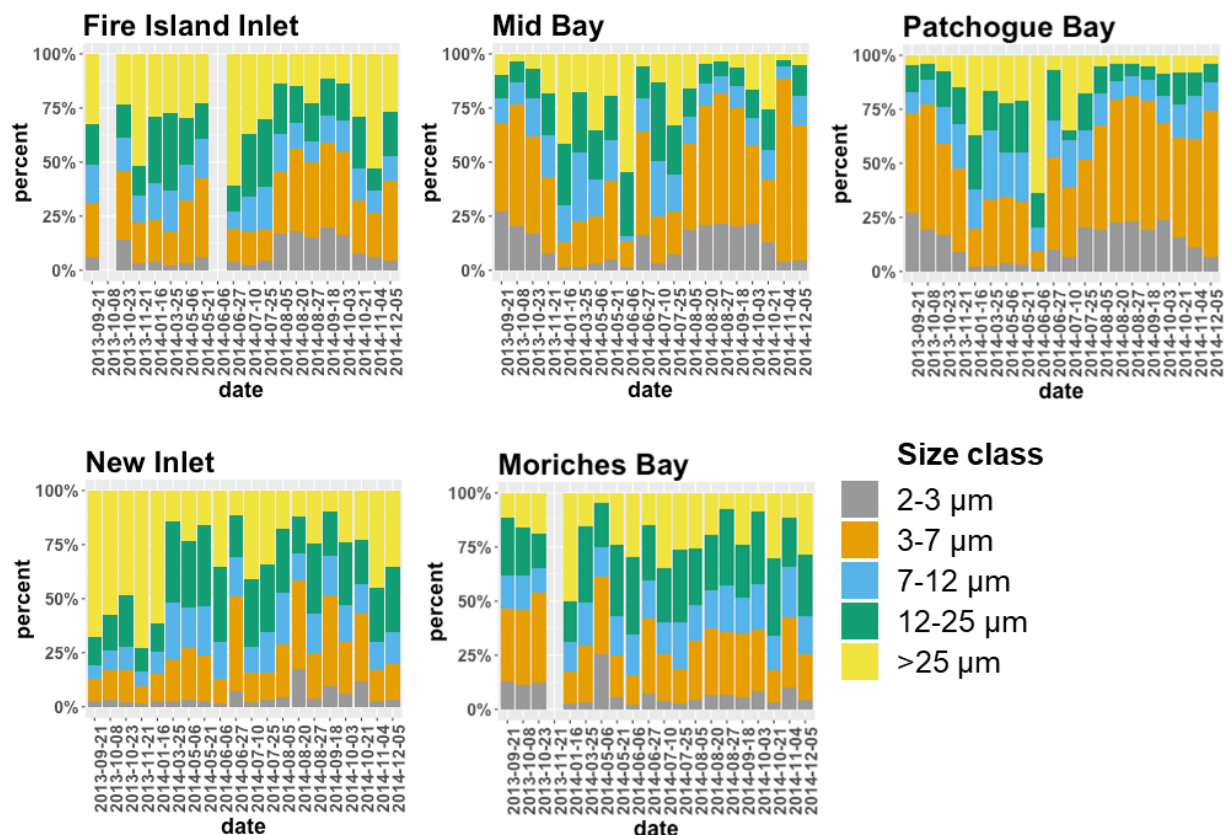


Figure 41. Normalized biomass (micrograms organic carbon per liter seawater) of live plankton in various size classes (equivalent spherical diameter, ESD, in micrometers) from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay) and Moriches Bay, Long Island, NY.

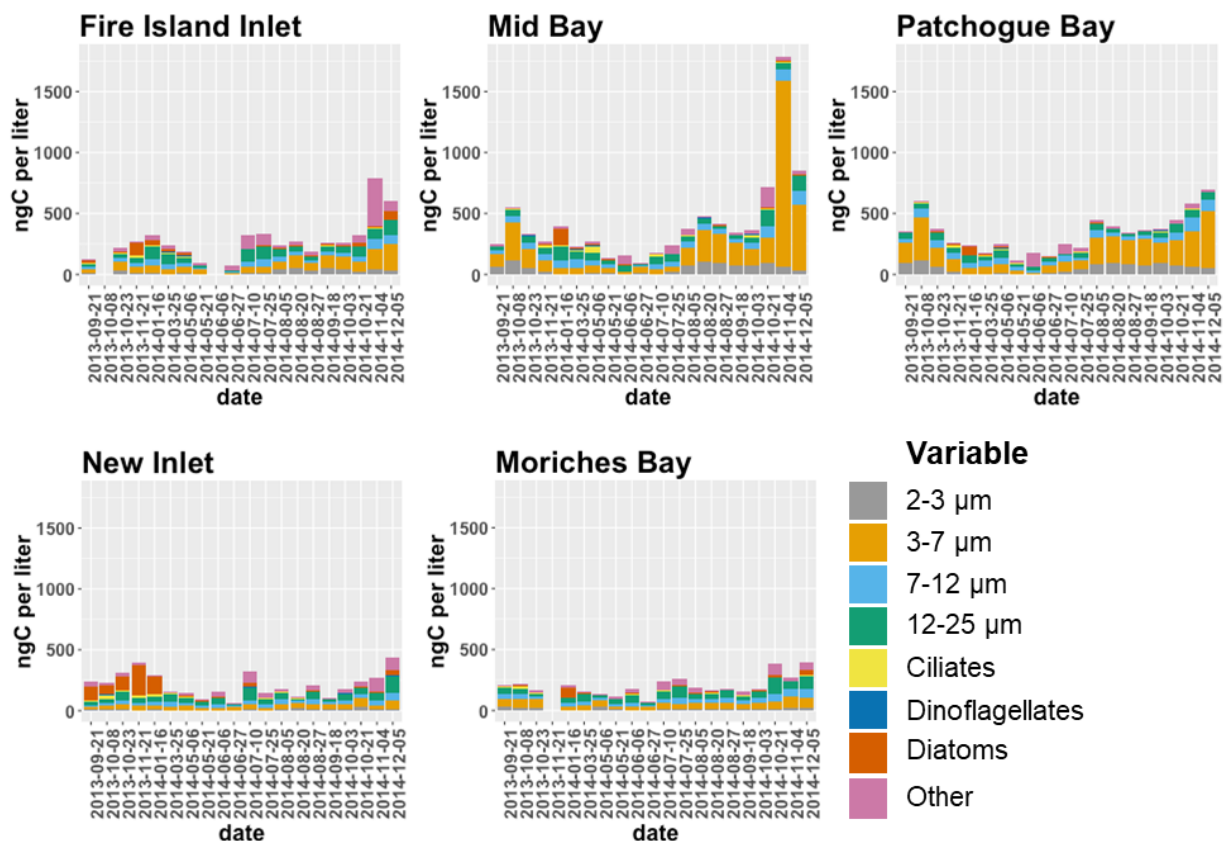


Figure 42. Absolute biomass (micrograms organic carbon per liter seawater) of live plankton in various size classes (equivalent spherical diameter, ESD, in micrometers) or categories for cells >25 micrometers from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay) and Moriches Bay, Long Island, NY.

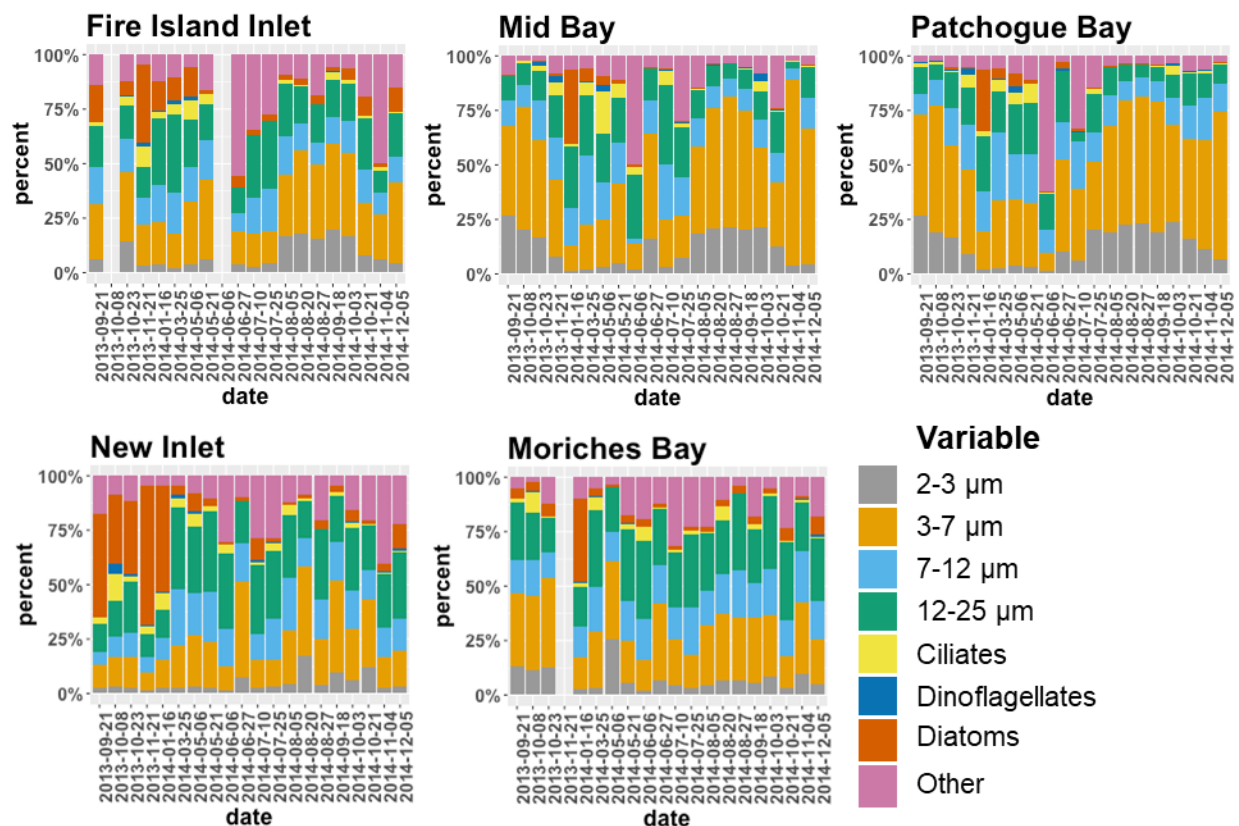


Figure 43. Normalized biomass (micrograms organic carbon per liter seawater) of live plankton in various size classes (equivalent spherical diameter, ESD, in micrometers) or categories for cells >25 micrometers from Great South Bay (Fire Island Inlet, New Inlet, Mid Bay and Patchogue Bay) and Moriches Bay, Long Island, NY.

16S and 18S sequence analyses

Normalization and relativization of the 16S and 18S sequence data resulted in datasets containing 1,365 OTUs (406 genera) in 114 samples for 16S and 1,022 OTUs (197 genera) in 122 samples for 18S. The 33 most abundant 16S genera were fairly consistent in relative abundance and accounted for approximately half of the sequences recovered (example of Bellport Bay in Figure 44), while the 20 most abundant 18S genera accounted for 50 to 80% of sequences and varied much more in relative abundance (example of Bellport Bay in Figure 45). These simple visualizations do not reveal obvious differences between pre- and post-breach plankton communities, so more subtle relationships in these complex datasets were visualized using nonmetric multidimensional scaling (NMS).

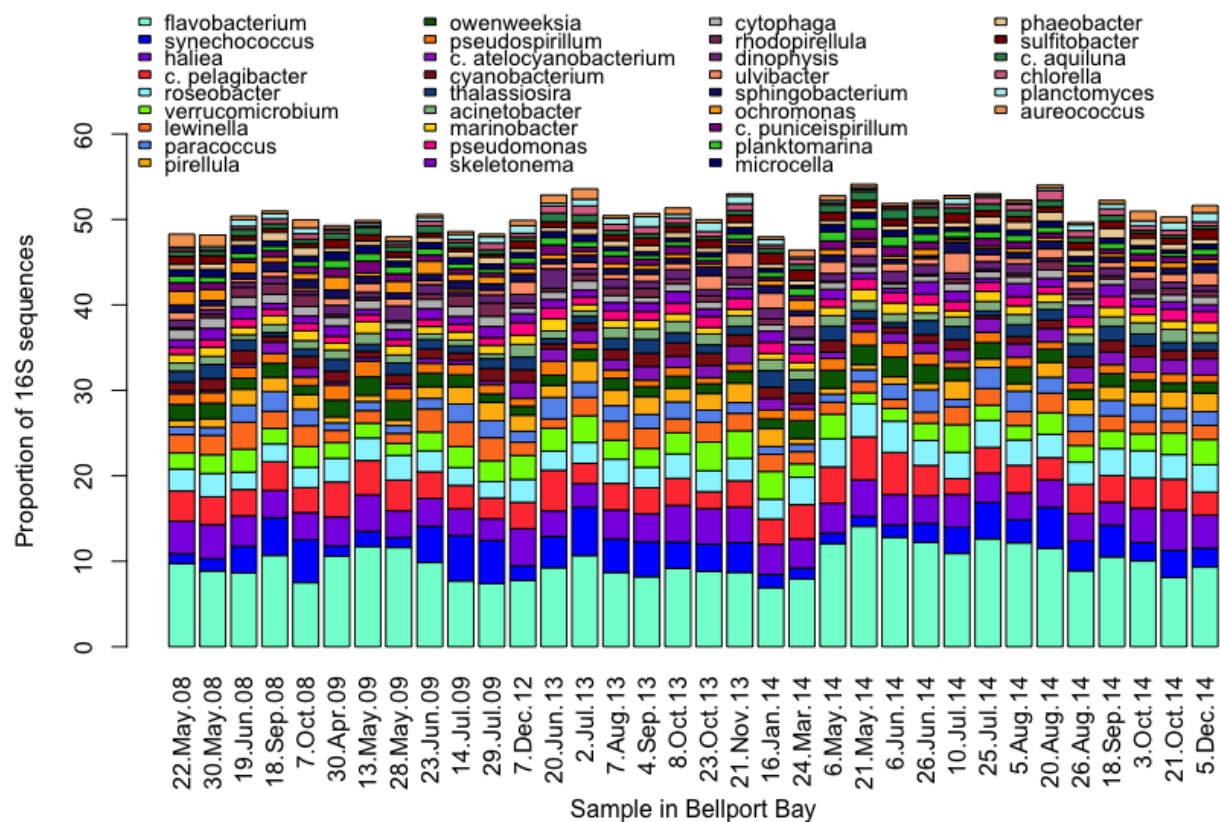


Figure 44. Representation of the top 33 most abundant genera in the 16S amplicon sequence dataset at Bellport Bay, Long Island, NY.

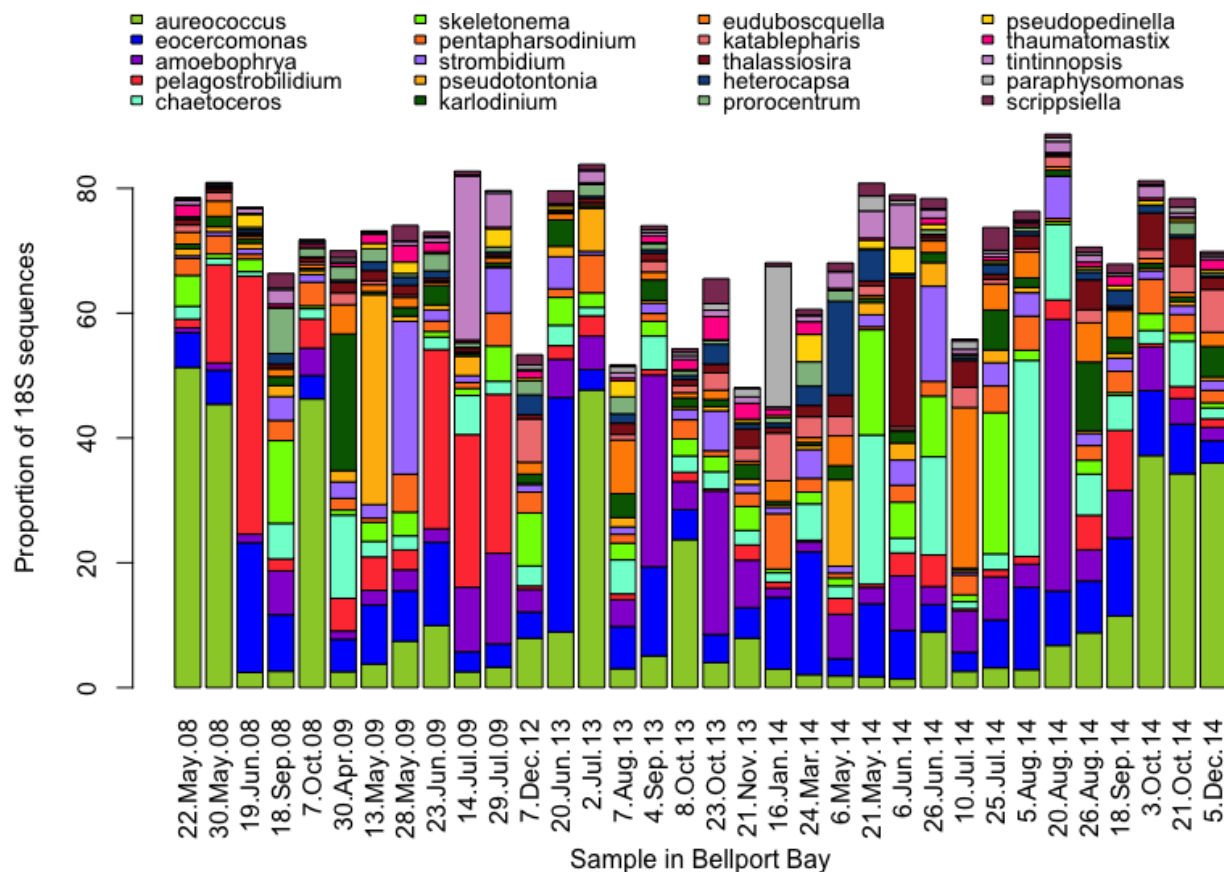


Figure 45. Representation of the top 20 most abundant genera in the 18S amplicon sequence dataset at Bellport Bay, Long Island, NY.

For each location and time period (e.g., Bellport Bay pre-breach or Mid-Bay post-breach), NMS analysis of 16S rRNA gene sequences generally captured a large proportion (>90%) of the variance among samples and revealed seasonal shifts in plankton community composition associated with environmental parameters including temperature, salinity, freshwater input and winds (not shown). Combined ordination of all 16S samples showed a clear separation between pre- and post-breach samples along an axis associated with salinity and river discharge summed over the previous 3 or 6 months (Figure 46, axis 3). According to MRPP, samples in the groups “pre-breach” and “post-breach” were significantly different in separate ordinations of only Bellport Bay 16S ($p < 0.001$) and only Mid-Bay 16S ($p < 0.001$). The close association of pre- vs post-breach 16S community structure with salinity and river discharge could be an indication that interannual variability in precipitation, rather than (or in addition to) increased ocean exchange, affected bacterial community structure in GSB.

For 18S rRNA gene sequences, NMS ordinations explained less of the variance (~50%), and environmental parameters were less strongly related to ordination axes, likely reflecting the greater variation in eukaryotic community members and strong influences of unmeasured factors. While MRPP showed that samples in the groups “pre-breach” and “post-breach” were significantly different for the Bellport Bay ($p < 0.01$) and Mid-Bay ($p < 0.02$) 18S datasets, analysis of all 18S

samples together did not show a clear separation of pre- vs post-breach. The abundance of *Aureococcus anophagefferens* was one of the factors most strongly and consistently related to the 18S ordinations, suggesting that brown tide may be one of the strongest determining factors of plankton community structure in GSB, especially for other eukaryotic plankton, both before and after the formation of the breach.

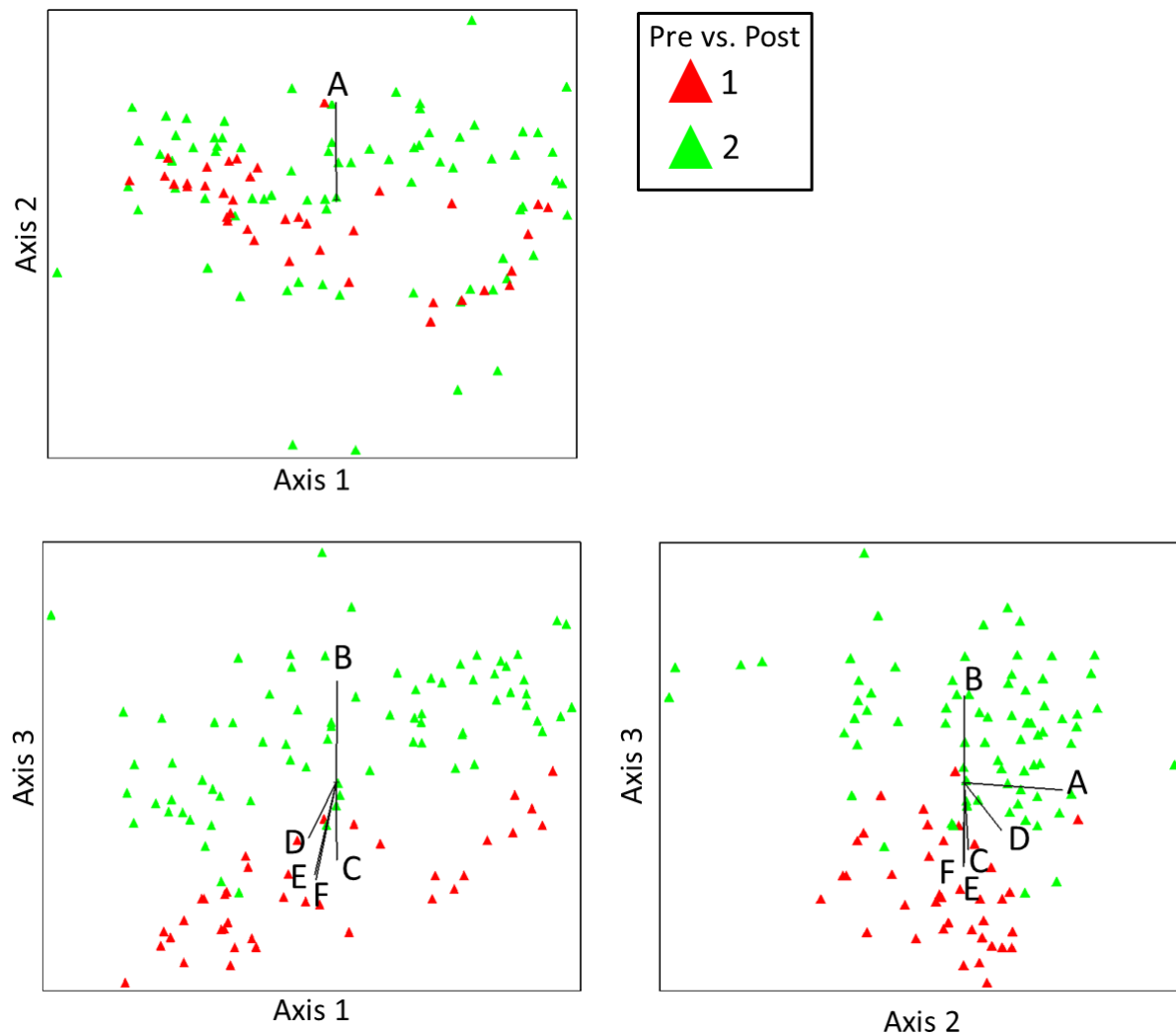


Figure 46. NMS ordination for all 16S genera and samples. Pre-breach samples are denoted by (1) red, and post-breach samples are denoted by (2) green, Long Island, NY. Parameters are denoted by A (temperature), B (salinity), C (riverine discharge over prior three months), D (riverine discharge over prior six months), E and F (amount of DNA extracted from each filter).

Overall, NMS and MRPP analysis showed that the 16S and 18S microbial communities of Bellport Bay and Mid-Bay were significantly different after the formation of the breach, but they did not reveal the cause of this change.

Phytoplankton pigments

Concentrations of alloxanthin, a marker of cryptophytes, followed a seasonal trend of low concentrations ($<0.2 \mu\text{g L}^{-1}$) during the winter months and elevated concentrations during the summer months, beginning in early June (Figure 47). During summers of 2013-2015, concentrations were lower at the Fire Island Inlet and the New Inlet than other sites. The highest concentrations of alloxanthin occurred at Mid-Bay, peaking at approximately 0.39, 0.44, and 0.63 $\mu\text{g L}^{-1}$ in 2013, 2014, and 2015, respectively (Figure 47). On average, concentrations of alloxanthin at Mid-Bay were significantly higher than the other sites (Tukey test; $p<0.05$). There were no significant differences in concentrations among the other sites ($p>0.05$). Concentrations of but-fucoxanthin were a good marker of the brown tide alga, *A. anophagefferens*, during this study with peaks and declines mimicking cell densities (Figure 25).

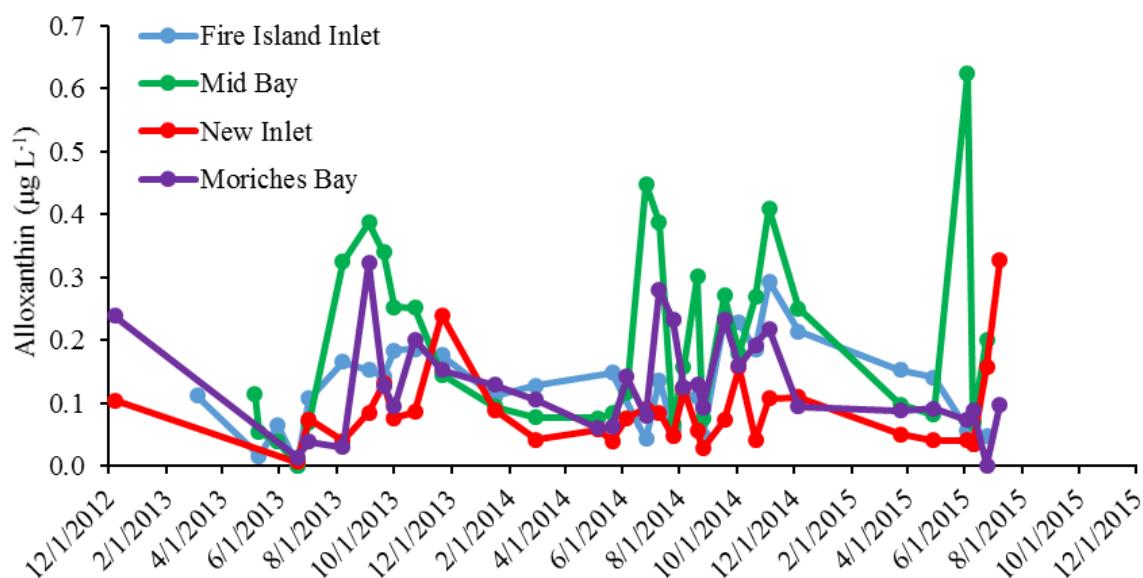


Figure 47. Post-breach alloxanthin concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

The highest concentrations occurred at Mid-Bay during the summer of 2015 and over the whole study, concentrations of but-fucoxanthin were significantly higher within the Mid-Bay site than Moriches Bay and the New Inlet (Figure 48; Tukey test; $p<0.05$).

Concentrations of fucoxanthin, a marker of diatoms, did not appear to follow any distinct seasonal trends. On average, concentrations of fucoxanthin at Mid-Bay were significantly higher than the other sites (Figure 49; Tukey test; $p<0.05$).

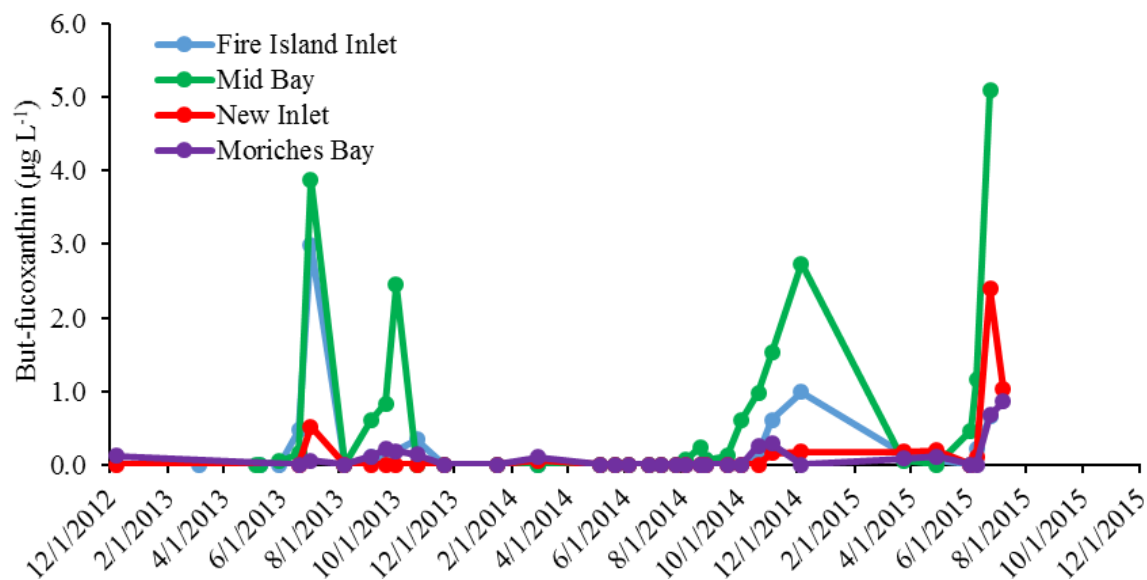


Figure 48. Post-breach but-fucoanthin concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

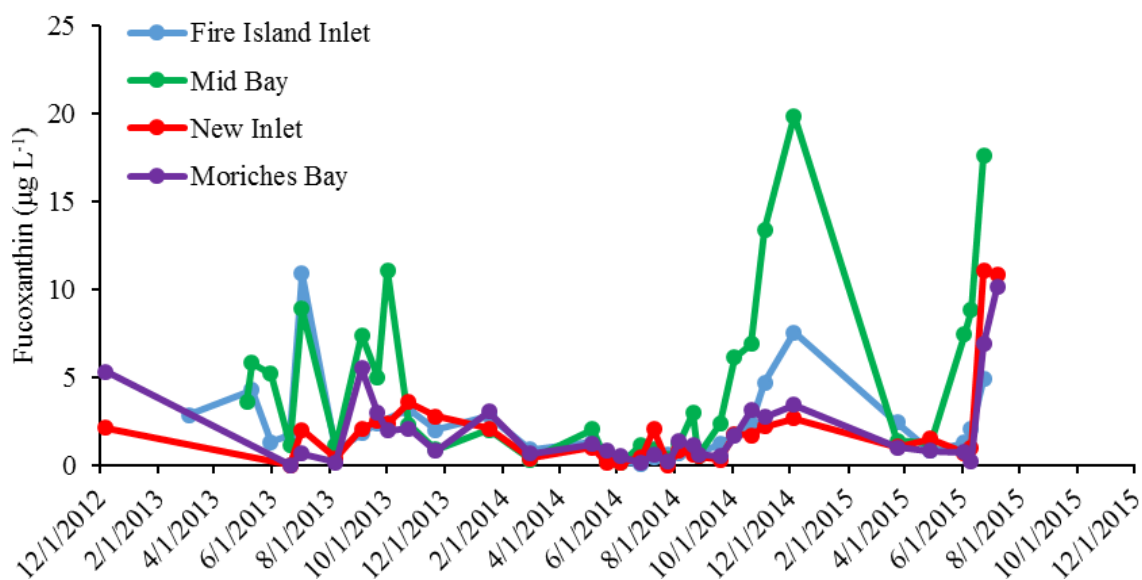


Figure 49. Post-breach fucoxanthin concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

Lutein is a marker of chlorophytes and during this study its levels peaked during summer and were significantly higher at the Mid-Bay site than all other sites (Figure 50; Tukey test; $p < 0.05$).

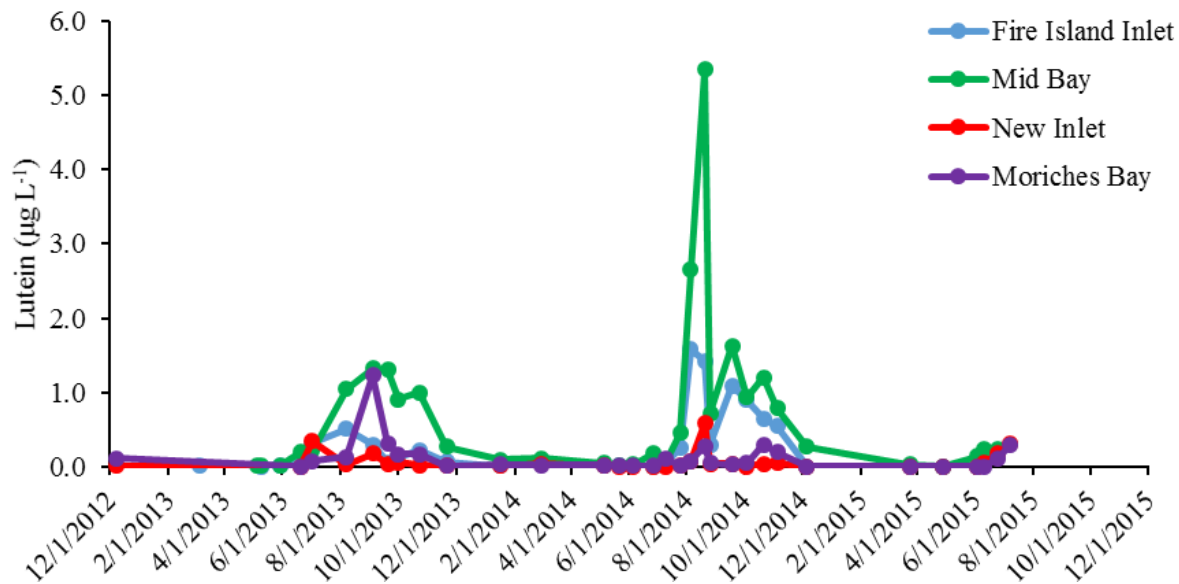


Figure 50. Post-breach lutein concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

Zeaxanthin is a tracer of cyanobacteria and displayed a trend highly similar to flow cytometric cyanobacterial cell counts with peaks during summer that persisted through fall and concentrations at Mid-Bay significantly higher than the other sites (Figure 51; Tukey test; $p < 0.05$).

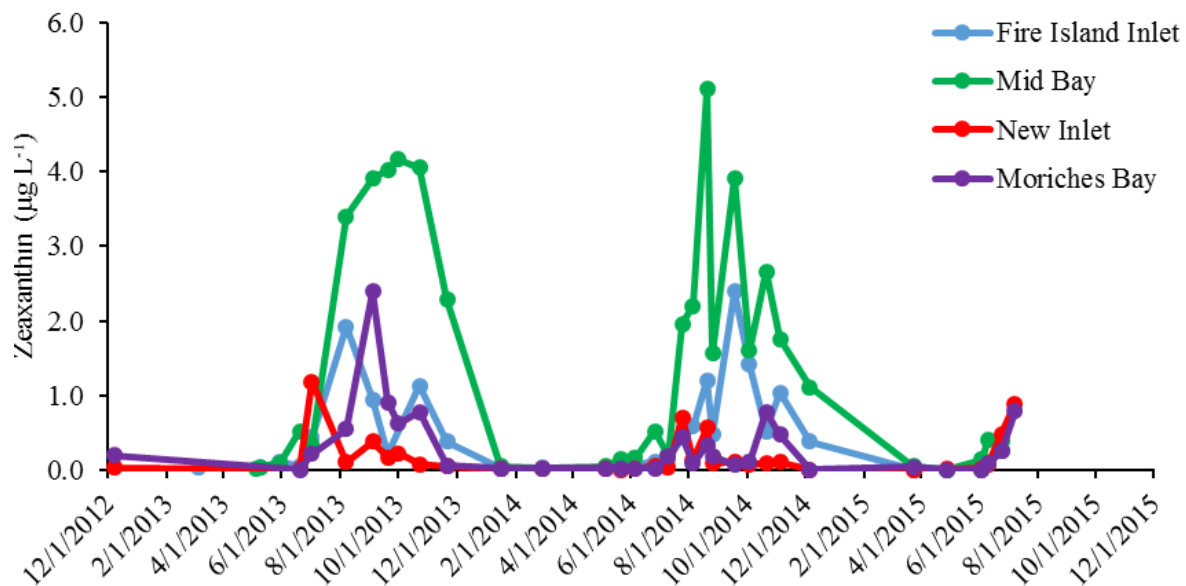


Figure 51. Post-breach zeaxanthin concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

Levels of perdinin, a pigment found only in dinoflagellates, showed peaks likely indicative of dinoflagellate blooms that occurred at different times at each of the study sites (Figure 52). There were no significant differences in concentrations of perdinin among sites (Tukey test; $p < 0.05$).

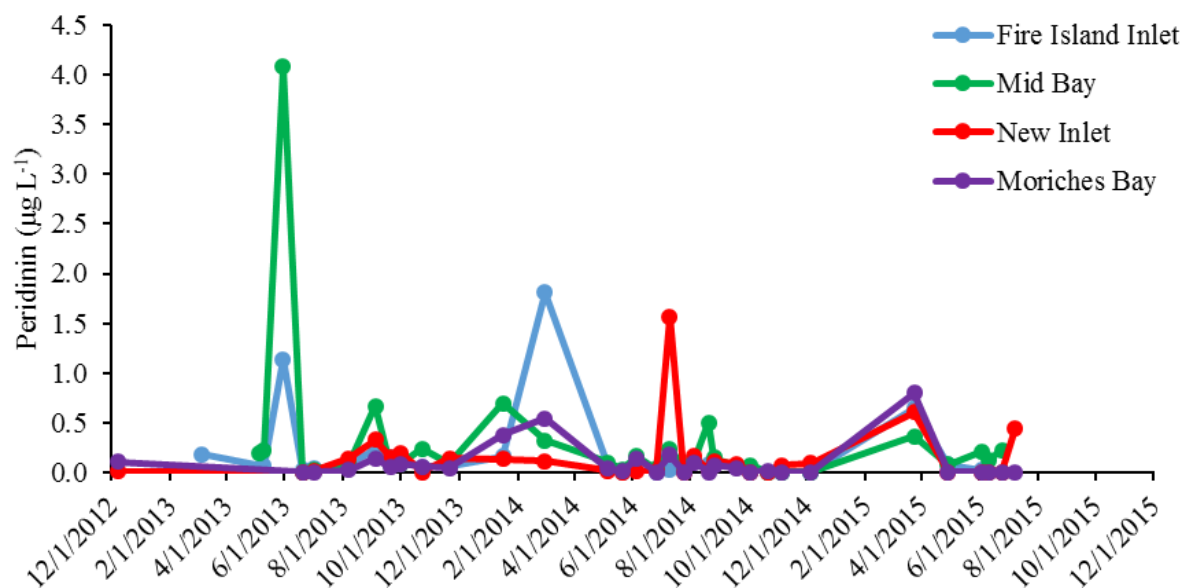


Figure 52. Post-breach peridinin concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY.

Zooplankton

Ciliates were the most abundant microzooplankton in GSB, and four of the most abundant genera identified in the 18S sequencing were ciliates (*Pelagostrobilidium*, *Strombidium*, *Pseudotontonia*, *Tintinnopsis*; Figure 45). There were not overly clear seasonal or spatial trends in ciliate concentrations with ~ 20 individuals mL^{-1} generally present at most sites over the study (Figure 53). Ciliate concentrations at Fire Island Inlet were significantly higher than at the New Inlet (Figure 53; Tukey test; $p < 0.05$) but did not differ among other sites ($p > 0.05$). Copepods were the most abundant mesozooplankton in GSB during this study.

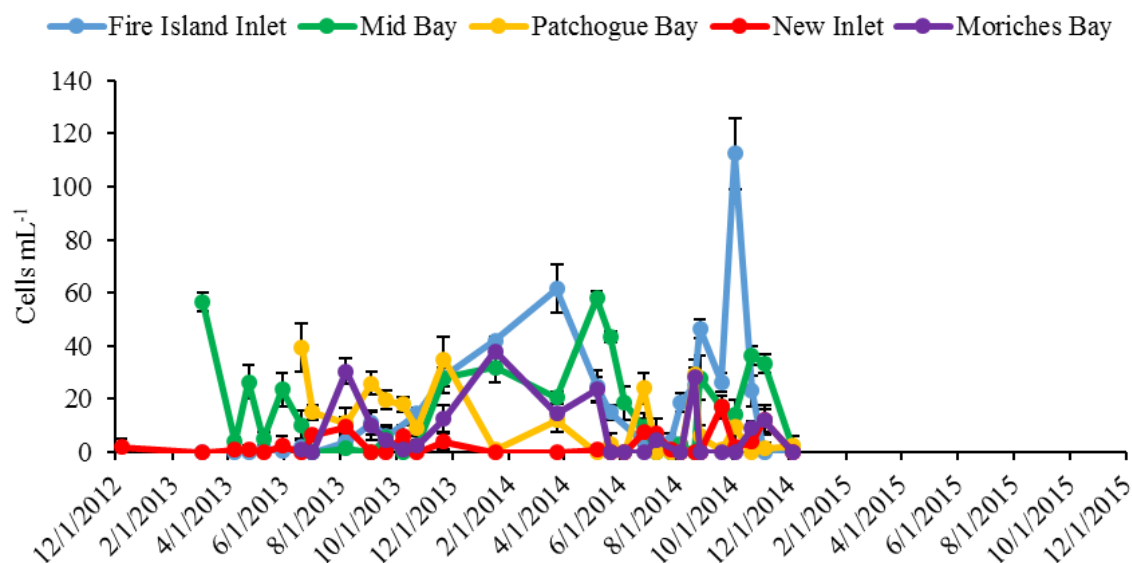


Figure 53. Post-breach ciliate concentrations for various sampling sites across Great South Bay and Moriches Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Copepod concentrations were high at Mid-Bay and the New Inlet during late June 2013, with approximate concentrations of 1.9×10^5 and 9.7×10^4 individuals m^{-3} , respectively (Figure 54). At the Fire Island Inlet, the highest concentration occurred on 2-July-2013, with an approximate concentration of 2.8×10^4 individuals m^{-3} . After July 2013, concentrations remained below 3.0×10^4 individuals m^{-3} at all sites. There was no significant difference in the concentration of copepods among the sites (Figure 54; Tukey test; $p > 0.05$).

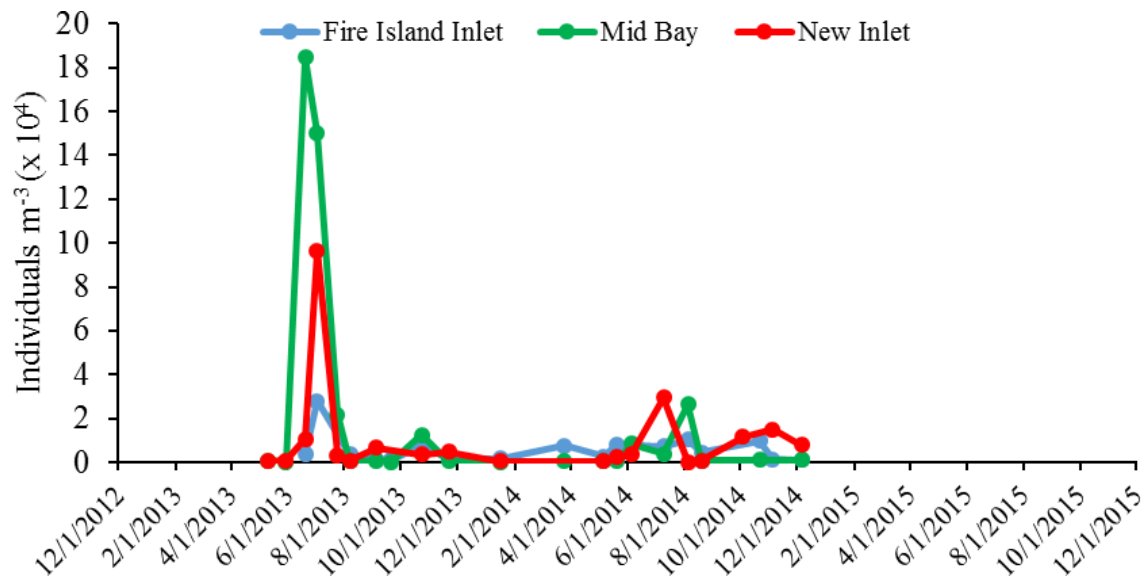


Figure 54. Post-breach copepod concentrations for various sampling sites across Great South Bay, Long Island, NY.

Copepod nauplii concentrations peaked in early July 2013 at all sites, one month after the adult copepod peak (Figure 55). After July 2013, concentrations remained below 1.0×10^5 individuals m^{-3} at all sites and there was no significant difference in the concentration of copepod nauplii among the sites (Figure 55; Tukey test; $p > 0.05$).

Bivalve larvae levels were relatively low throughout 2013 and the first half of 2014, being, on average, about 2500 individuals m^{-3} (Figure 56). However, on 5-August-2014, there was a peak concentration of over 2.3×10^4 individuals m^{-3} at the Mid-Bay site. There was no significant difference in the concentration of bivalve larvae among the sites (Figure 56; Tukey test; $p > 0.05$).

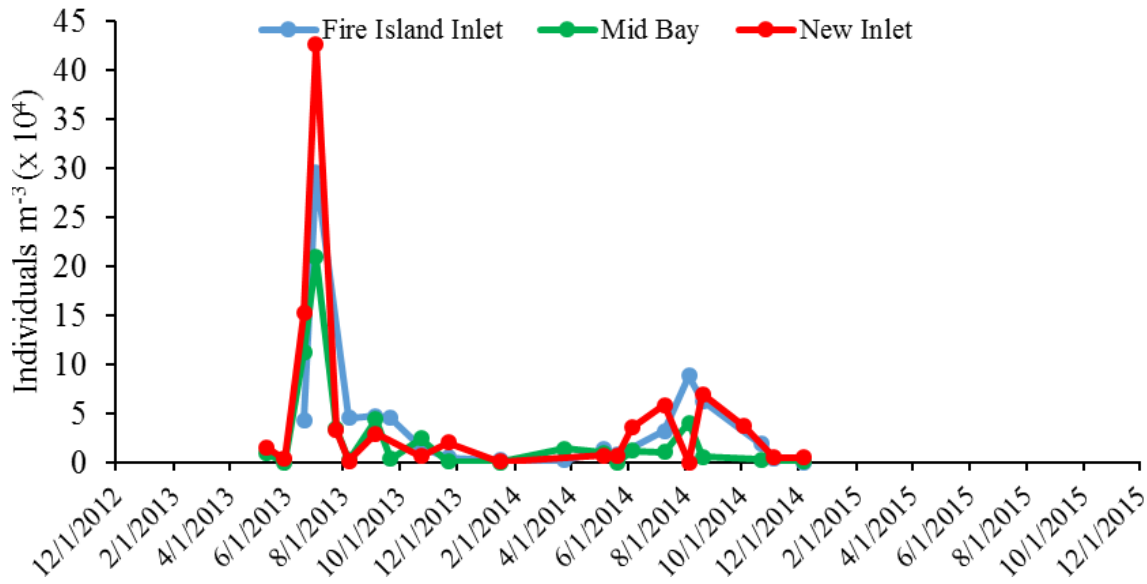


Figure 55. Post-breach copepod nauplii concentrations for various sampling sites across Great South Bay, Long Island, NY.

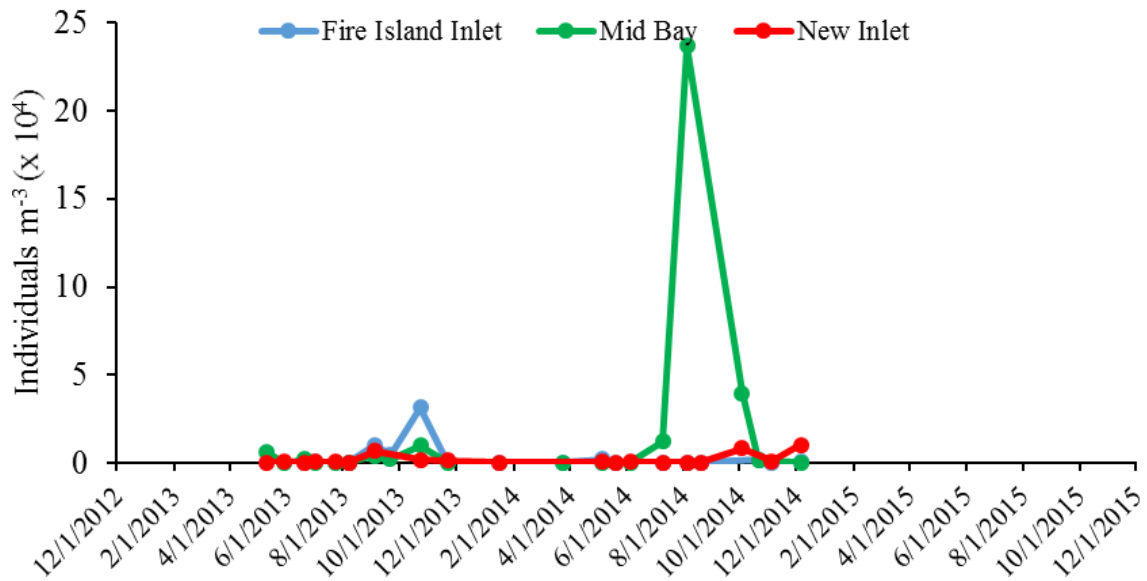


Figure 56. Post-breach bivalve larvae concentrations for various sampling sites across Great South Bay, Long Island, NY.

Peaks in other forms of zooplankton were mostly detected at Mid-Bay throughout 2013 and 2014 although there was no significant difference in the concentration among the sites (Figure 57; Tukey test; $p > 0.05$).

Finally, unlike the non-gelatinous zooplankton, ctenophores reached peak abundances through summer and fall of 2013 and 2014 at the New Inlet and Mid Bay sites, although there was no significant difference in the biovolume of ctenophores among the sites (Figure 58; Tukey test; $p > 0.05$).

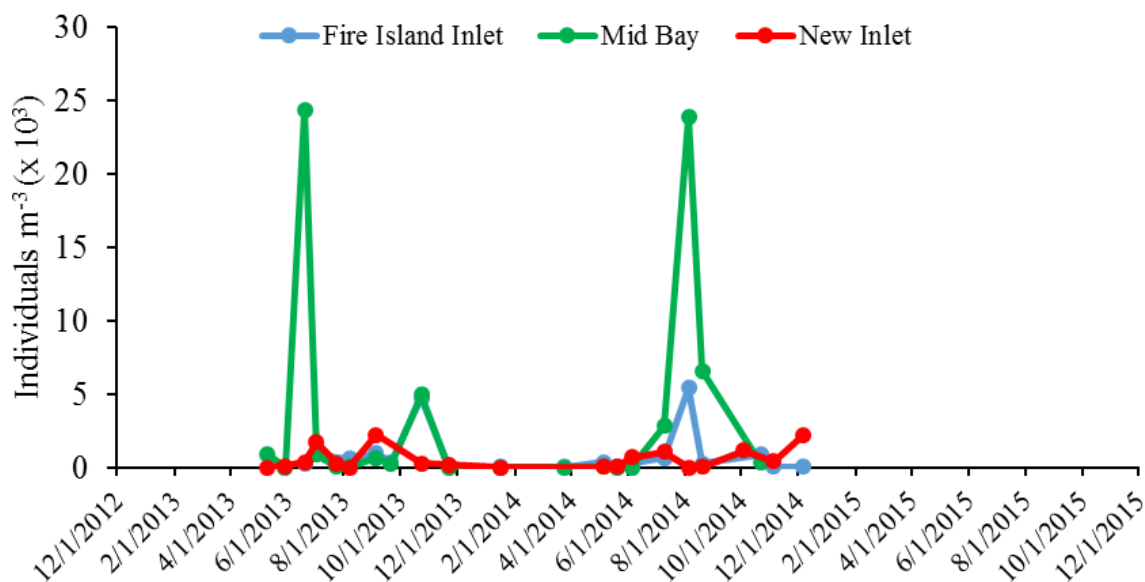


Figure 57. Post-breach other zooplankton concentrations for various sampling sites across Great South Bay, Long Island, NY. Other zooplankton included fish eggs (*Anchoa mitchilli*, *Brevoortia tyrannus*, *Menidia menidia*, *Prionotus* spp.) and larvae (*Menidia menidia*), isopods (*Idotea* spp.), crustaceans (*Oxyurostylus smithi*, *Pseudoleptocuma minus*), crustacean megalopa (*Cancer irroratus*), zoea (*Pinnixa* spp.), and larvae (*Pagurus* spp., *Crangon septemspinosa*, *Palaemonetes* spp., *Squilla empusa*), polychaete larvae (*Owenia fusiformis*), tunicates (*Oikopleura* spp.), and other various larvae (Cnidaria, Echinoderm, Gastropod).

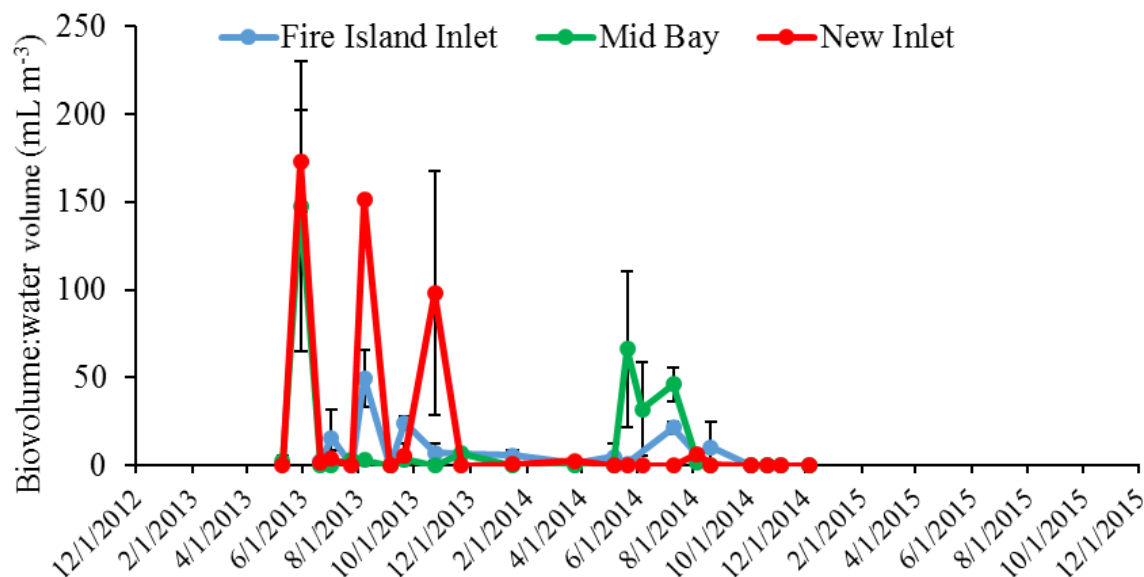


Figure 58. Post-breach ctenophore concentrations for various sampling sites across Great South Bay, Long Island, NY. Data points represent means $\pm$ standard deviation.

Parameter correlations

There were several correlations between physical water quality and biological parameters. There were strong inverse correlations between secchi disk depth (water clarity) and total chlorophyll *a*

concentrations ($\rho = -0.583$; $p < 0.001$; Table 1), PC cyanobacteria ($\rho = -0.465$; $p < 0.01$; Table 1), and *Aureococcus anophagefferens* ($\rho = -0.437$; $p < 0.01$; Table 1). There were inverse correlations between temperature and $>5\mu\text{m}$ chlorophyll *a* ($\rho = -0.221$; $p < 0.01$; Table 1), pennate diatoms ($\rho = -0.291$; $p < 0.05$; Table 1), dinoflagellates ($\rho = -0.251$; $p < 0.01$; Table 1), and all plankton groups $>7\mu\text{m}$ as measured via the Flow Cam (plankton 7-12 μm , plankton 12-25 μm , plankton $>25\mu\text{m}$, ciliates $>25\mu\text{m}$, copepods $>25\mu\text{m}$, diatoms $>25\mu\text{m}$, dinoflagellates $>25\mu\text{m}$; $\rho = -0.343, -0.368, -0.340, -0.403, -0.359, -0.436$, and -0.351 , respectively; $p < 0.001$ for all; Table 1). Furthermore, there were significant positive correlations between temperature and $<2\mu\text{m}$ and 2-5 μm chlorophyll *a* ($\rho = 0.211$ and 0.527 , respectively; both $p < 0.01$; Table 1), as well between temperature and both types of cyanobacteria (PE and PC), autotrophic pico-eukaryotes, heterotrophic bacteria, and *Aureococcus anophagefferens* cell densities ($\rho = 0.396, 0.552, 0.480, 0.350$, and 0.376 , respectively; $p < 0.00001$ for all; Table 1). Dinoflagellate densities were inversely correlated with salinity ($\rho = -0.216$; $p < 0.05$; Table 1), and positively correlated with concentrations of alloxanthin ($\rho = 0.287$; $p < 0.01$; Table 1). There was a positive correlation between total chlorophyll *a* concentrations and *Aureococcus anophagefferens* concentrations ($\rho = 0.727$; $p < 0.001$; Table 1). Finally, there were negative correlations between adult copepods and pennate diatoms ($\rho = -0.271$; $p < 0.05$; Table 1) and between copepod nauplii and dinoflagellates ($\rho = -0.403$; $p < 0.01$; Table 1).

Table 1. Results of a Spearman's rank order to determine the correlation of various parameters in Great South Bay and Moriches Bay, Long Island, NY, after the formation of the New Inlet by Hurricane Sandy.

Parameters compared	Number of samples	Correlation coefficient (ρ)	P-value
Secchi disk depth : Total chlorophyll <i>a</i>	35	-0.583	<0.001
Secchi disk depth : PC cyanobacteria	36	-0.465	0.005
Secchi disk depth : <i>Aureococcus anophagefferens</i>	35	-0.437	0.009
Water temperature : $<2\mu\text{m}$ chlorophyll <i>a</i>	161	0.211	0.007
Water temperature : 2-5 μm chlorophyll <i>a</i>	165	0.527	<0.001
Water temperature : $>5\mu\text{m}$ chlorophyll <i>a</i>	164	-0.221	0.005
Water temperature : Pennate diatoms	106	-0.291	0.003
Water temperature : Dinoflagellates	106	-0.251	0.010
Water temperature : Plankton 7-12 μm	80	-0.343	0.002
Water temperature : Plankton 12-25 μm	80	-0.368	0.001
Water temperature : Plankton $>25\mu\text{m}$	81	-0.340	0.002
Water temperature : Ciliates $>25\mu\text{m}$	81	-0.403	<0.001
Water temperature : Copepods $>25\mu\text{m}$	81	0.359	0.001
Water temperature : Diatoms $>25\mu\text{m}$	81	-0.436	<0.001
Water temperature : Dinoflagellates $>25\mu\text{m}$	81	-0.351	0.001
Water temperature : PC cyanobacteria	172	0.552	<0.001
Water temperature : PE cyanobacteria	172	0.396	<0.001
Water temperature : Autotrophic pico-eukaryotes	172	0.480	<0.001

Table 1 (continued). Results of a Spearman's rank order to determine the correlation of various parameters in Great South Bay and Moriches Bay, Long Island, NY, after the formation of the New Inlet by Hurricane Sandy.

Parameters compared	Number of samples	Correlation coefficient (ρ)	P-value
Water temperature : Heterotrophic bacteria	171	0.350	<0.001
Water temperature : <i>Aureococcus anophagefferens</i>	146	0.376	<0.001
Dinoflagellates : Salinity	106	-0.216	0.026
Dinoflagellates : Alloxanthin	99	0.287	0.004
Dinoflagellates : Copepod nauplii	54	-0.403	0.003
Total chlorophyll a : <i>Aureococcus anophagefferens</i>	163	0.727	<0.001
Adult copepods : Pennate diatoms	54	-0.407	0.002

Comparing plankton communities before (2004-05) and after (2013-15) the New Inlet

There were several differences in the characteristics of GSB when comparing 2004-05 to 2013-15. As noted in the SCDHS data set, mean summer temperature was significantly higher at the New Inlet site in 2004-05 (20.5°C) than in 2013-15 (15.7°C) (Figure 59; Table 2; T-test; $p < 0.05$).

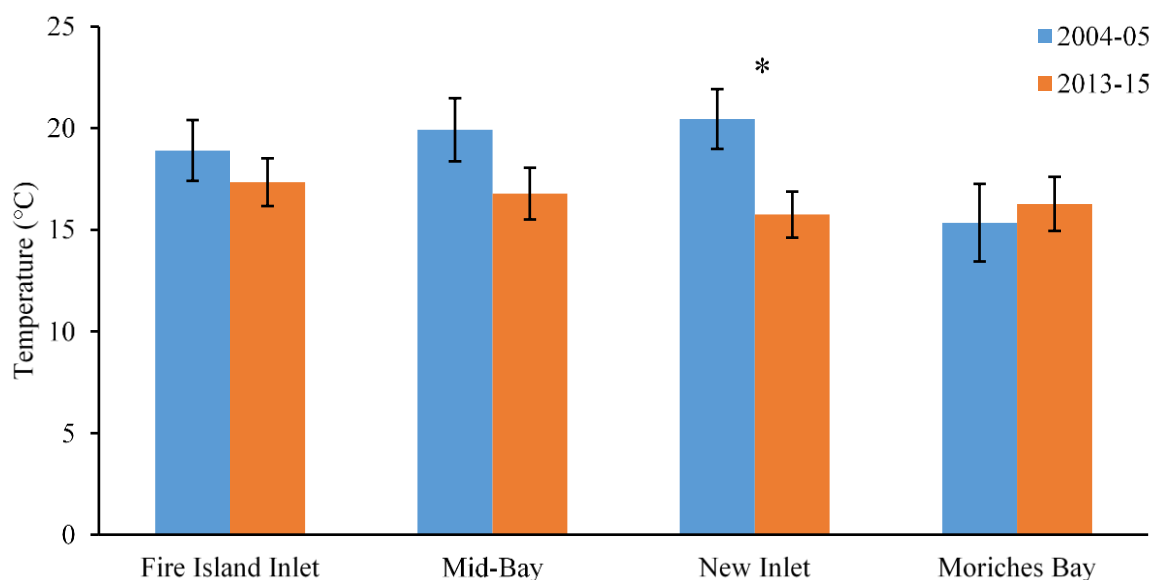


Figure 59. Pre-breach (2004-05) and post-breach (2013-15) summer mean water temperature across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Table 2. Comparisons of various parameters at stations in Great South Bay and Moriches Bay before and after the formation of the New Inlet, Long Island, NY. Upward (↑) and downward (↓) arrows represent significant (T-test; $p < 0.05$) increases or decreases in the parameter compared to before the formation of the New Inlet, respectively. Horizontal (↔) arrows represent no significant changes (T-test; $p > 0.05$) in the parameter. Pre-breach data was taken from Curran (2006).

Parameter	Fire Island Inlet	Mid-Bay	New Inlet	Moriches Bay
Alloxanthin	↔	↔	↓	↑
Alloxanthin:chlorophyll a	↓	↔	↓	↔
Ammonium	↑	↔	↔	↔
Autotrophic nano-eukaryotes	↑	↔	↔	↑
Autotrophic pico-eukaryotes	↑	↑	↔	↑
Centric diatoms	↑	↔	↔	↑
Chlorophyll a (<2μm)	↑	↑	↔	↔
Chlorophyll a (>5μm)	↔	↓	↓	↔
Chlorophyll a (2-5μm)	↑	↔	↔	↔
Chlorophyll a (Whole)	↔	↔	↓	↔
Ciliates	↔	↔	↓	↑
Dinoflagellates	↓	↓	↓	↓
DON	↓	↓	↓	↓
Fucoxanthin	↔	↑	↓	↑
Fucoxanthin:chlorophyll a	↔	↓	↔	↓
Lutein	↑	↑	↔	↑
Lutein:chlorophyll a	↑	↑	↑	↑
Nitrate	↑	↓	↓	↓
PE & PC cyanobacteria	↑	↑	↑	↔
Pennate diatoms	↑	↑	↔	↔
Peridinin	↔	↔	↓	↔
Peridinin:chlorophyll a	↓	↔	↓	↔
Phosphate	↑	↔	↑	↑
Salinity	↔	↑	↑	↑
Silicate	↓	↔	↓	↓
Temperature	↔	↔	↓	↔
Zeaxanthin	↑	↑	↔	↑
Zeaxanthin:chlorophyll a	↑	↑	↔	↔

Salinity was significantly higher at the Mid-Bay, New Inlet, and Moriches Bay sites in 2013-15 (28.3, 30.8, and 30.1, respectively) than 2004-05 (25.0, 23.9, and 29.0, respectively) (Figure 60; Table 2; T-test; $p < 0.05$).

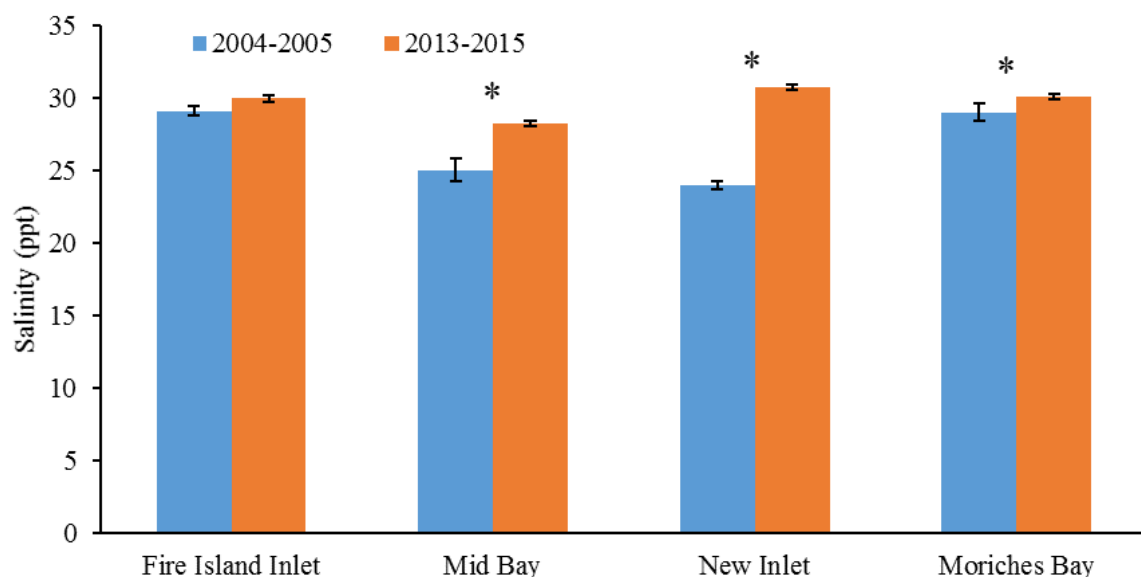


Figure 60. Pre-breach (2004-05) and post-breach (2013-15) summer mean salinity across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates

Summer mean whole chlorophyll *a* was found to be slightly (but insignificantly) higher at all sites in 2013-15 than in 2004-05, with the exception of the New Inlet where levels were significantly lower in 2013-15 ($6.2 \mu\text{g L}^{-1}$) than in 2004-05 ($10.4 \mu\text{g L}^{-1}$; Figure 61; Table 2; T-test; $p < 0.05$).

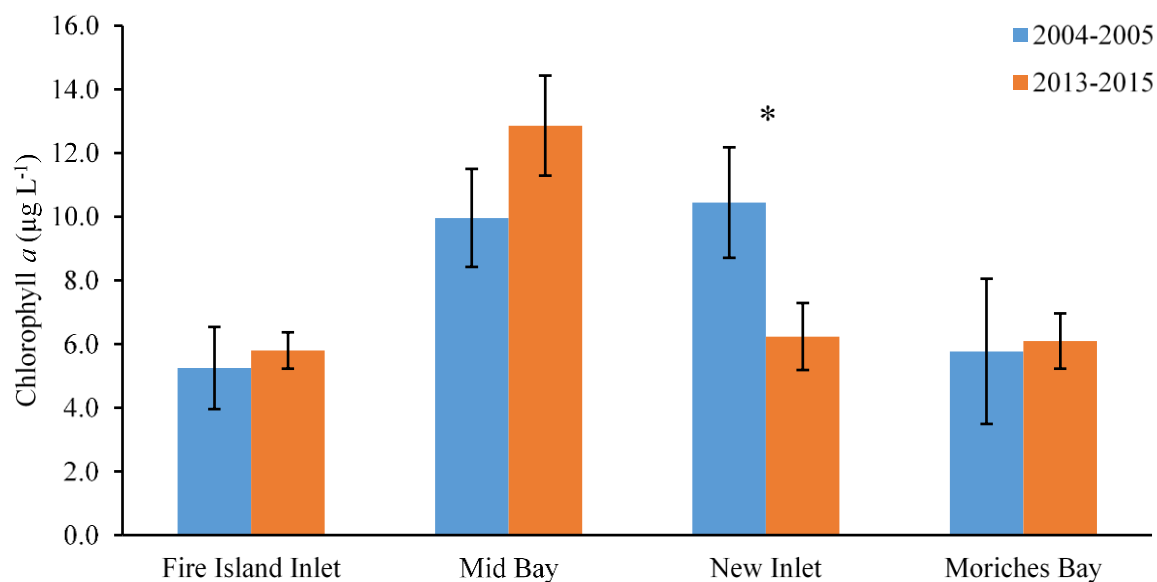


Figure 61. Pre-breach (2004-05) and post-breach (2013-15) summer mean whole chlorophyll *a* concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Less than $2 \mu\text{m}$ chlorophyll *a* was significantly higher at the Fire Island Inlet and Mid-Bay in 2013-15 (4.1 and $7.1 \mu\text{g L}^{-1}$, respectively) than in 2004-05 (2.1 and $4.5 \mu\text{g L}^{-1}$, respectively) (Figure 62;

Table 2; T-test; $p < 0.05$), with no significant differences reported at the New Inlet or Moriches Bay ($p > 0.05$).

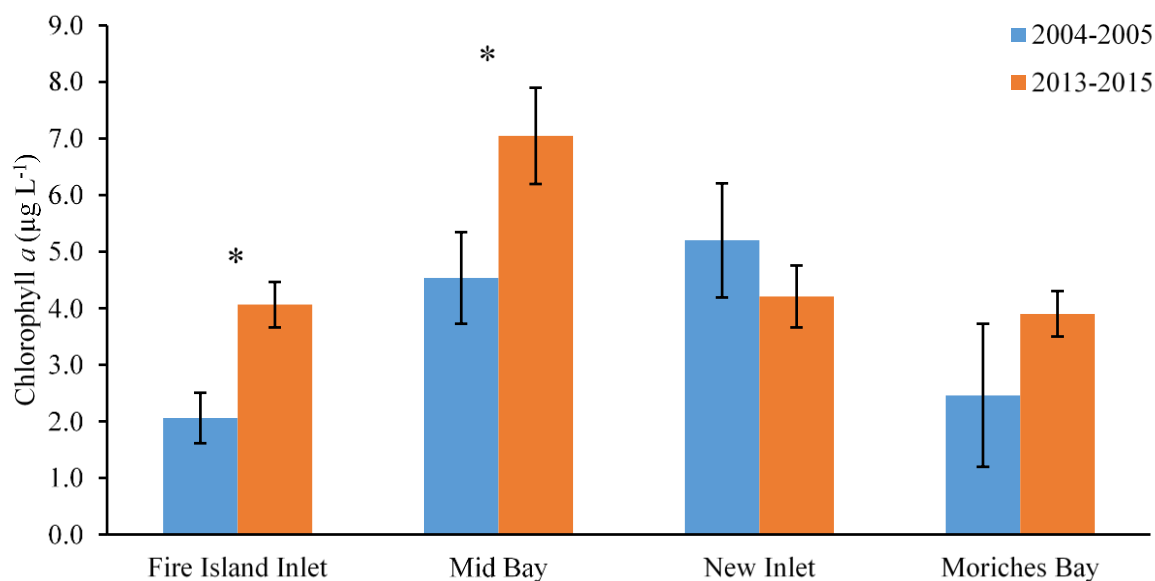


Figure 62. Pre-breach (2004-05) and post-breach (2013-15) summer mean $<2\mu\text{m}$ chlorophyll a concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Chlorophyll a at $2-5\mu\text{m}$ was significantly higher at the Fire Island Inlet in 2013-15 ($1.4 \mu\text{g L}^{-1}$) than in 2004-05 ($0.4 \mu\text{g L}^{-1}$; Figure 63; Table 2; T-test; $p < 0.05$).

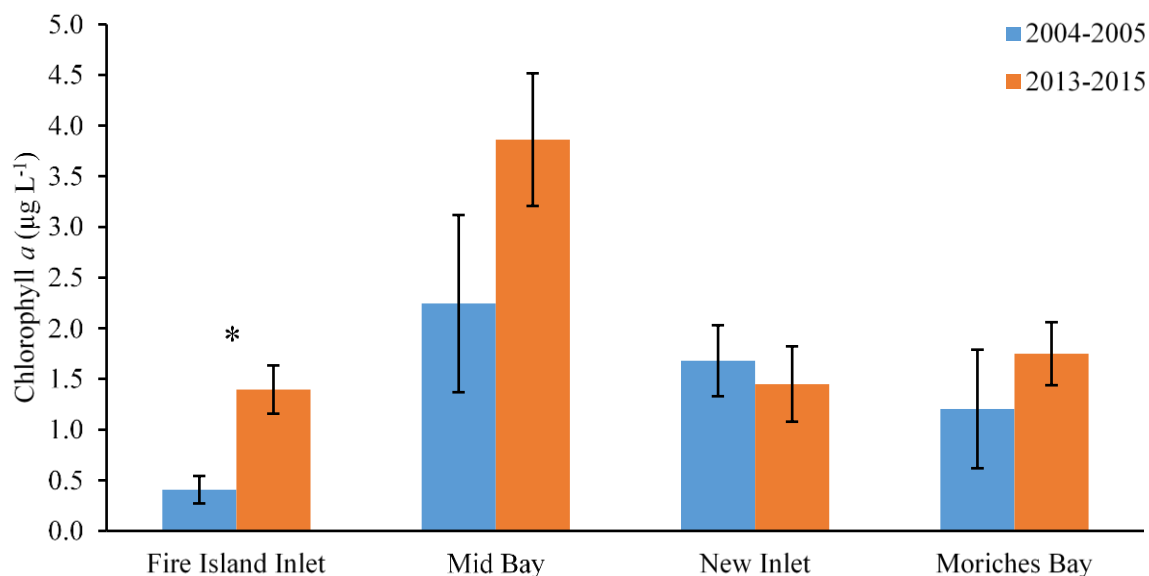


Figure 63. Pre-breach (2004-05) and post-breach (2013-15) summer mean $2-5\mu\text{m}$ chlorophyll a concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Greater than 5 μm chlorophyll *a* was significantly lower at Mid-Bay and the New Inlet in 2013-15 (2.3 and 2.6, $\mu\text{g L}^{-1}$, respectively) than in 2004-05 (6.4 and 5.2, $\mu\text{g L}^{-1}$, respectively; Figure 64; Table 2; T-test; $p<0.05$). As previously noted, the percent of total chlorophyll *a* in $<2\mu\text{m}$, 2-5 μm , and $>5\mu\text{m}$ size fractions in 2013-15 was 52%, 25%, and 23%, respectively. In 2004-05, the percent of total chlorophyll *a* between $<2\mu\text{m}$, 2-5 μm , and $>5\mu\text{m}$ was 48%, 12%, and 40%, respectively. So, while $<2\mu\text{m}$ as a fraction of total chlorophyll *a* has not changed much post-breach, there was a significantly lower and higher fraction of 2-5 μm and $>5\mu\text{m}$ chlorophyll *a*, respectively, post-breach.

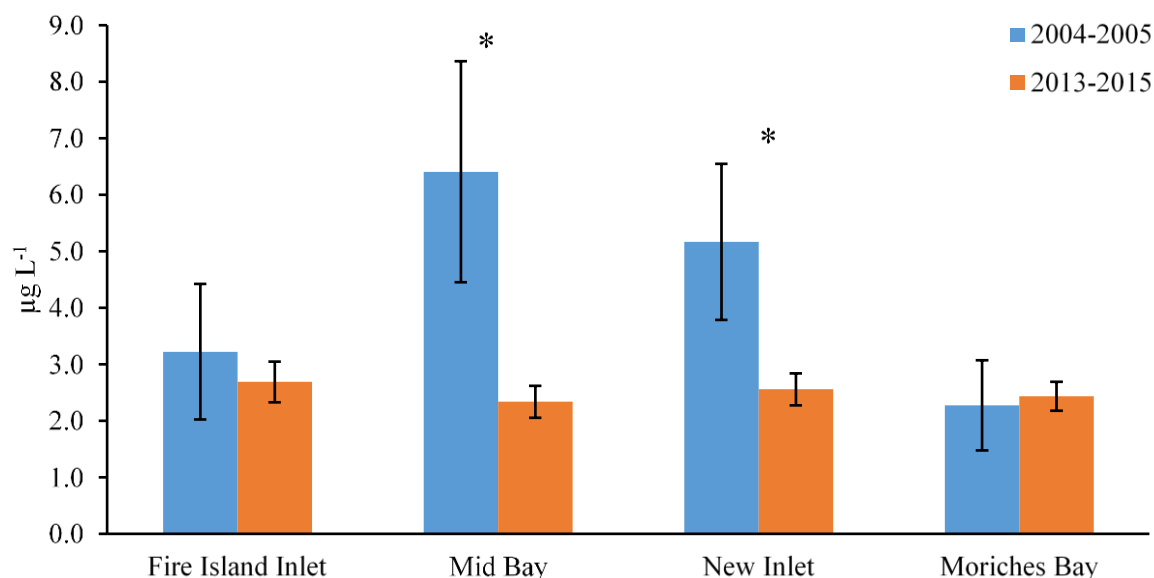


Figure 64. Pre-breach (2004-05) and post-breach (2013-15) summer mean $>5\mu\text{m}$ chlorophyll *a* concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p<0.05$.

Concentrations of PE cyanobacteria were found to be significantly higher at the Fire Island Inlet, Mid-Bay, and the New Inlet in 2013-15 (1.9×10^5 , 4.9×10^5 , and 7.9×10^4 cells mL^{-1} , respectively) than in 2004-05 (3.8×10^4 , 5.4×10^4 , and 3.3×10^4 cells mL^{-1} , respectively; Figure 65; Table 2; T-test; $p<0.05$).

Concentrations of autotrophic nano-eukaryotes ($>2\mu\text{m}$) were found to be significantly higher at the Fire Island Inlet and Moriches Bay in 2013-15 (2.0×10^4 and 7.2×10^4 cells mL^{-1} , respectively) than in 2004-05 (6.3×10^3 and 5.2×10^3 cells mL^{-1} , respectively; Figure 66; Table 2; T-test; $p<0.05$).

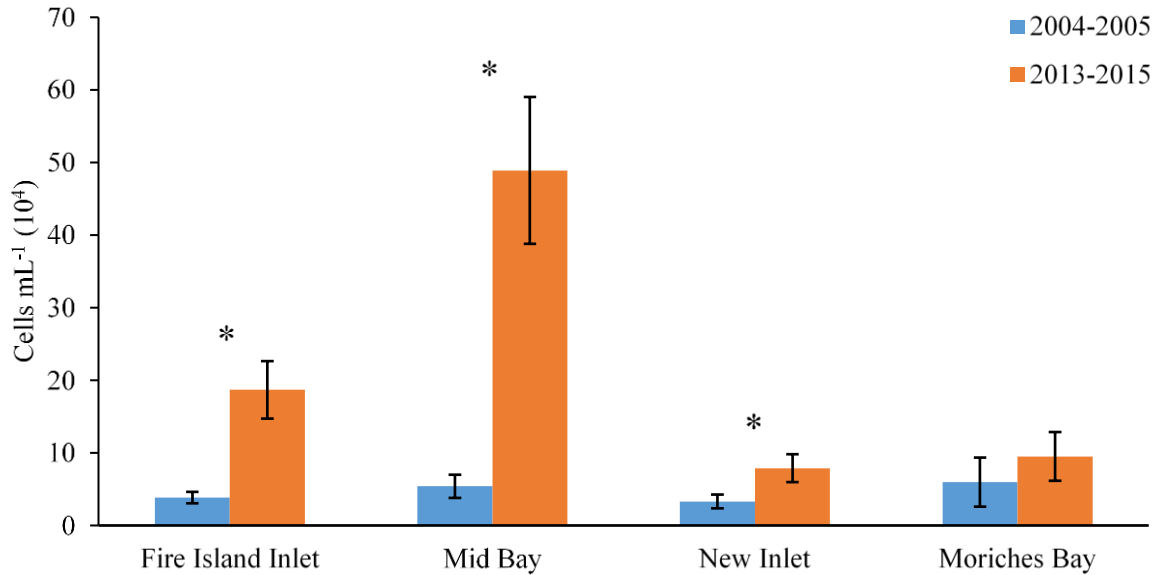


Figure 65. Pre-breach (2004-05) and post-breach (2013-15) summer mean cyanobacteria concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

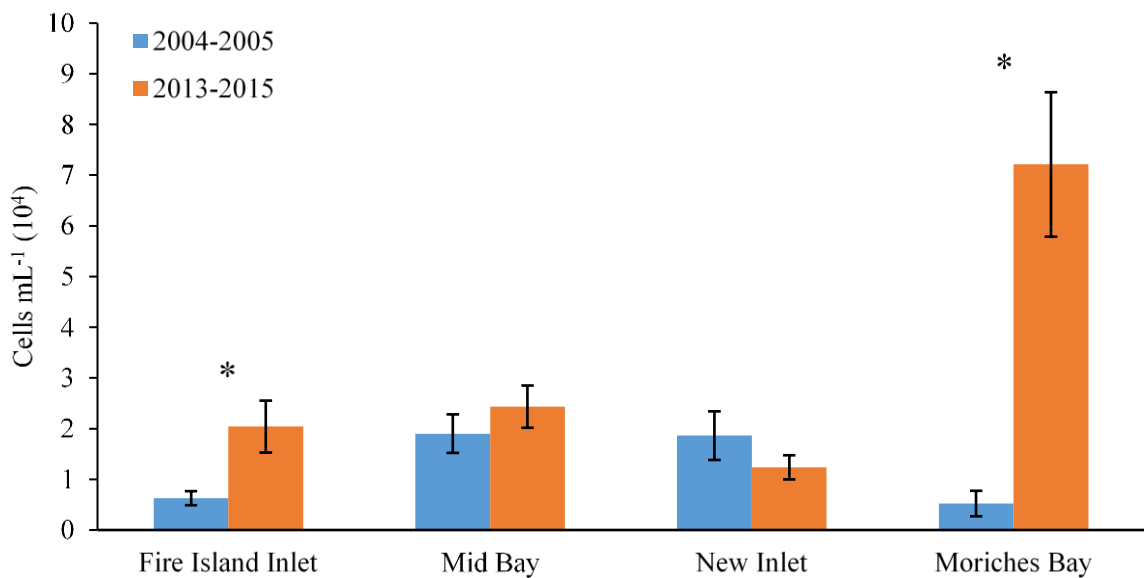


Figure 66. Pre-breach (2004-05) and post-breach (2013-15) summer mean autotrophic nano-eukaryote concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of autotrophic pico-eukaryotes were found to be significantly higher at Fire Island Inlet, Mid-Bay, and Moriches Bay in 2013-15 (2.7×10^5 , 6.2×10^5 , and 1.9×10^5 cells mL⁻¹, respectively) than in 2004-05 (5.6×10^4 , 8.5×10^4 , and 2.6×10^4 cells mL⁻¹, respectively; Figure 67; Table 2; T-test; $p < 0.05$).

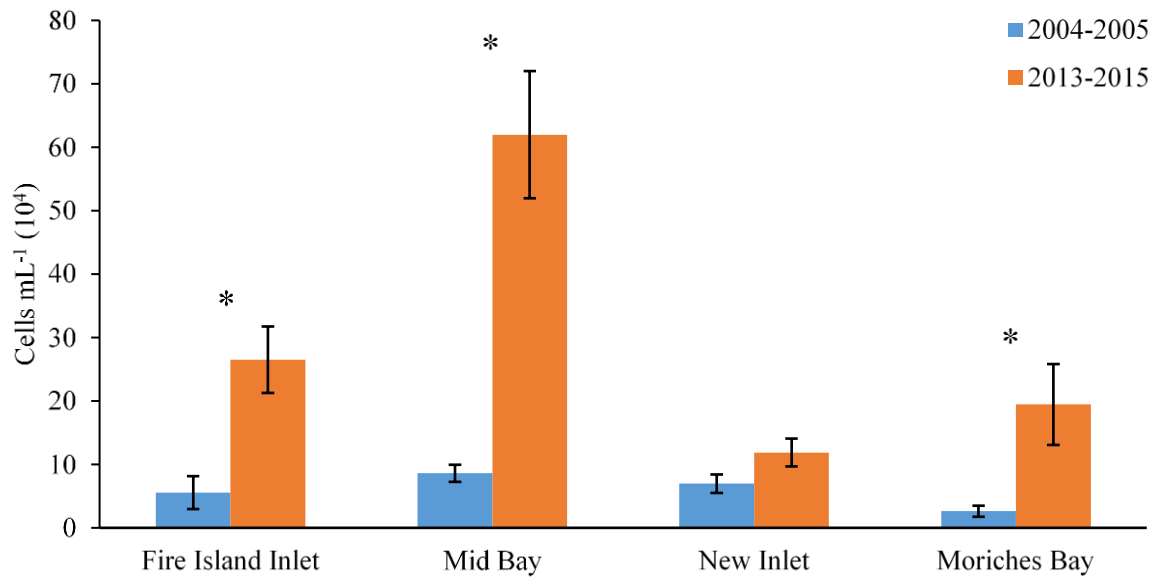


Figure 67. Pre-breach (2004-05) and post-breach (2013-15) summer mean autotrophic pico-eukaryote concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Centric diatoms were found to be significantly more abundant at the Fire Island Inlet and Moriches Bay in 2013-15 (2.6×10^3 and 1.6×10^3 cells mL⁻¹, respectively) than in 2004-05 (550 and 690 cells mL⁻¹, respectively) (Figure 68; T-test; $p < 0.05$).

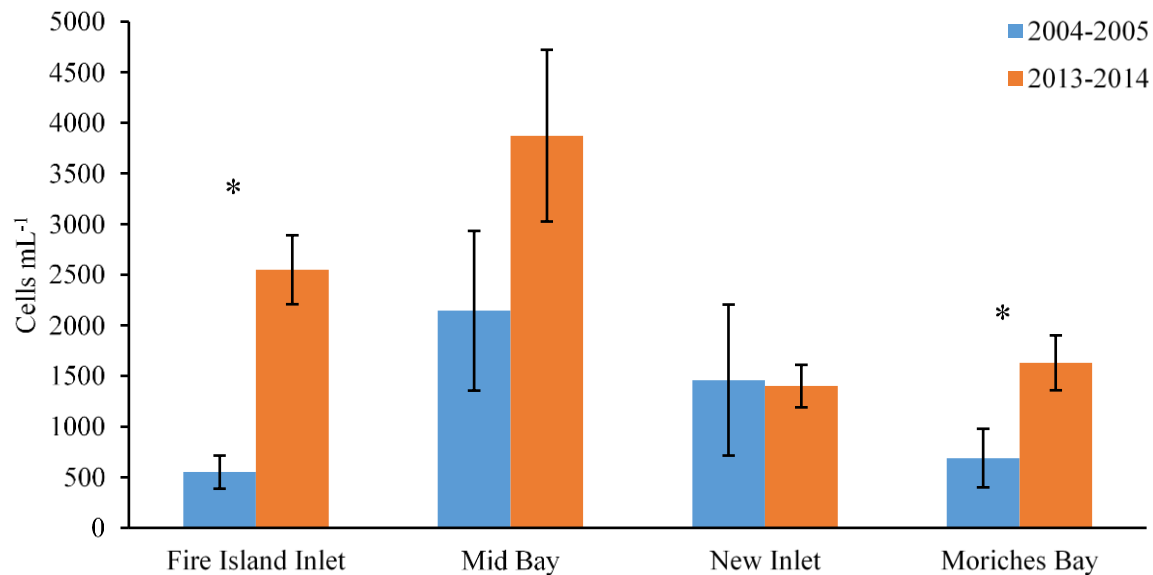


Figure 68. Pre-breach (2004-05) and post-breach (2013-15) summer mean centric diatom concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of pennate diatoms were significantly higher at the Fire Island Inlet and Mid-Bay in 2013-15 (1.5×10^3 and 1.5×10^3 cells mL^{-1} , respectively) than in 2004-05 (130 and 220 cells mL^{-1}) (Figure 69; T-test; $p < 0.05$).

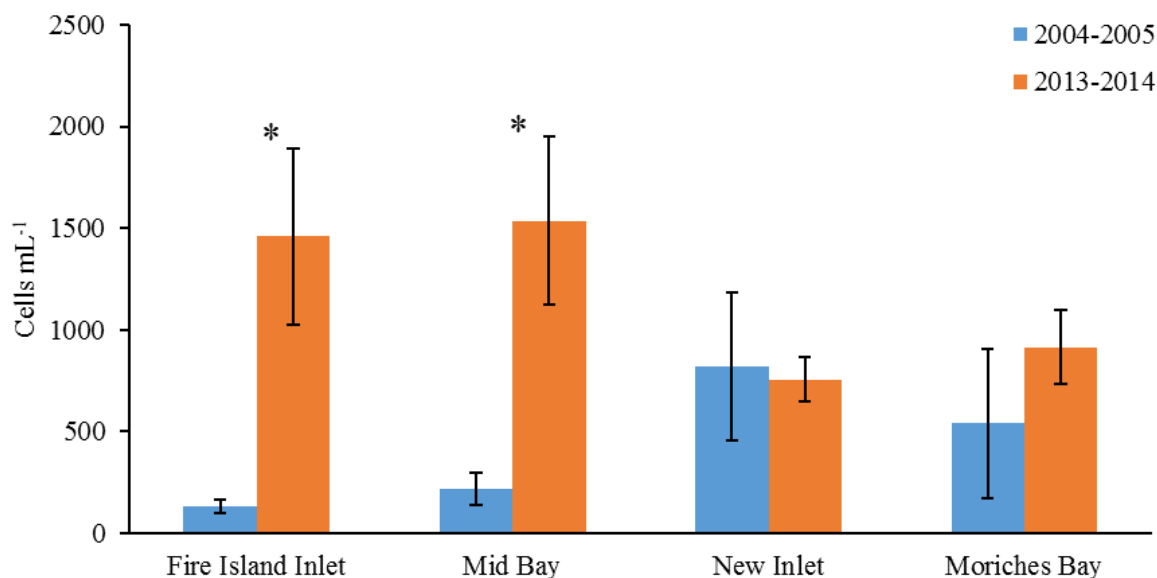


Figure 69. Pre-breach (2004-05) and post-breach (2013-15) summer mean pennate diatom concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of dinoflagellates were significantly lower at the Fire Island Inlet, Mid-Bay, New Inlet and Moriches Bay in 2013-15 (120, 150, 80, and 50 cells mL^{-1} , respectively) than in 2004-05 (500, 1500, 1940, and 440 cells mL^{-1} , respectively) (Figure 70; T-test; $p < 0.05$).

Concentrations of ciliates were significantly lower at the New Inlet in 2013-15 (< 10 cells mL^{-1}) than in 2004-05 (30 cells mL^{-1}), and higher at Moriches Bay in 2013-15 (10 cells mL^{-1}) than in 2004-05 (< 10 cells mL^{-1}) (Figure 71; T-test; $p < 0.05$).

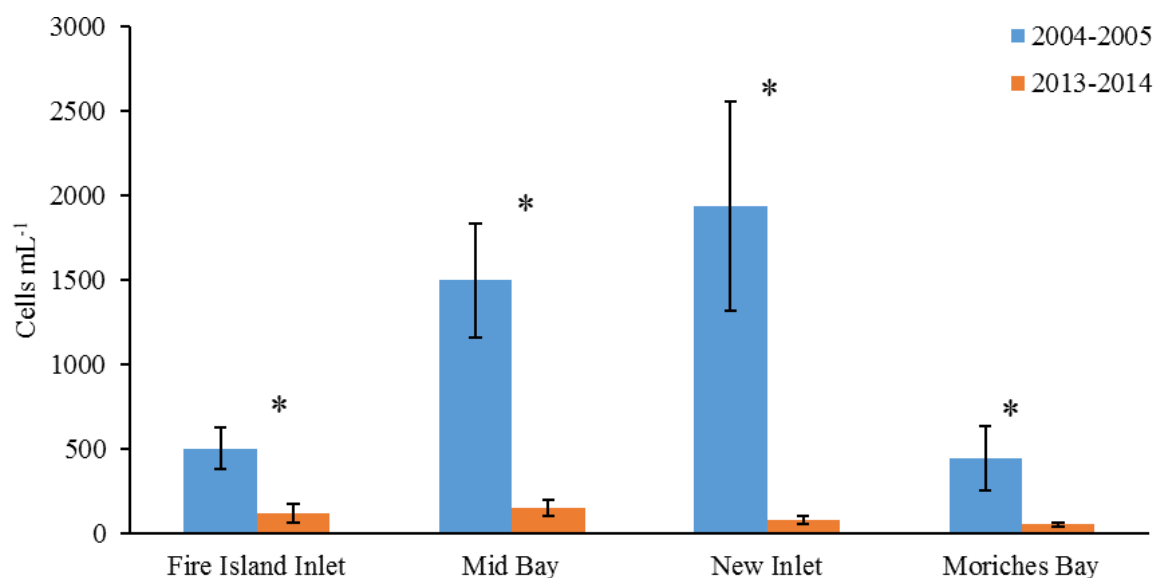


Figure 70. Pre-breach (2004-05) and post-breach (2013-15) summer mean dinoflagellate concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

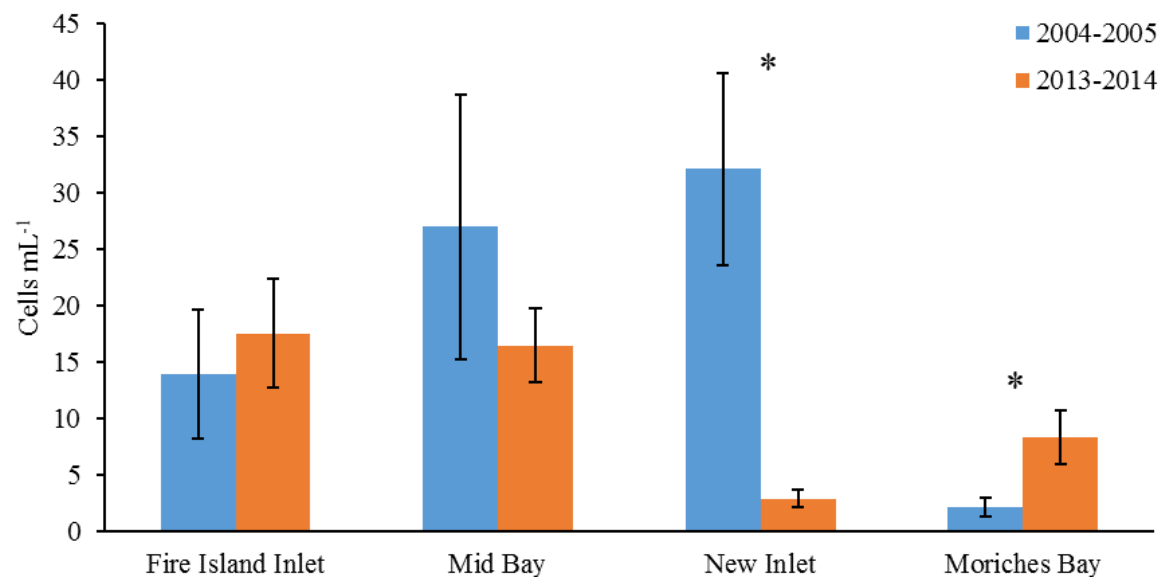


Figure 71. Pre-breach (2004-05) and post-breach (2013-15) summer mean ciliate concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Regarding pigments, concentrations of zeaxanthin were significantly higher at the Fire Island Inlet, Mid-Bay, and Moriches Bay in 2013-15 (0.56, 1.72, and 0.34 $\mu\text{g L}^{-1}$, respectively) than in 2004-05 (0.09, 0.23, and 0.04 $\mu\text{g L}^{-1}$, respectively; Figure 72; Table 2; T-test; $p < 0.05$).

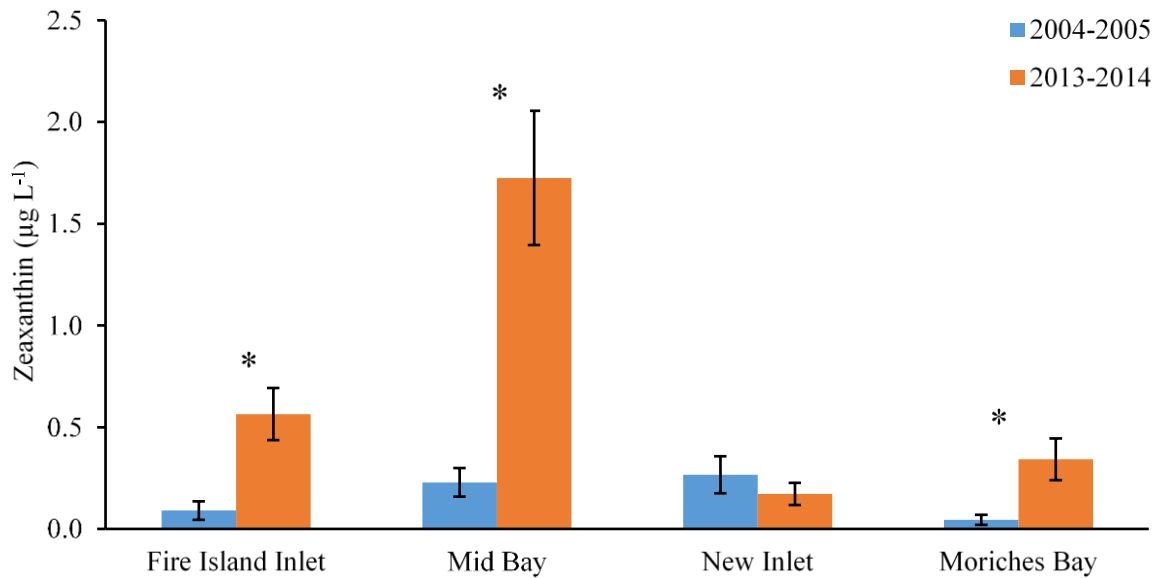


Figure 72. Pre-breach (2004-05) and post-breach (2013-15) summer mean zeaxanthin concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of alloxanthin were significantly lower at the New Inlet in 2013-15 ($0.08 \mu\text{g L}^{-1}$) than in 2004-05 ($0.46 \mu\text{g L}^{-1}$) but significantly higher in Moriches Bay in 2013-15 ($0.14 \mu\text{g L}^{-1}$) than in 2004-05 ($0.05 \mu\text{g L}^{-1}$; Figure 73; Table 2; T-test; $p < 0.05$).

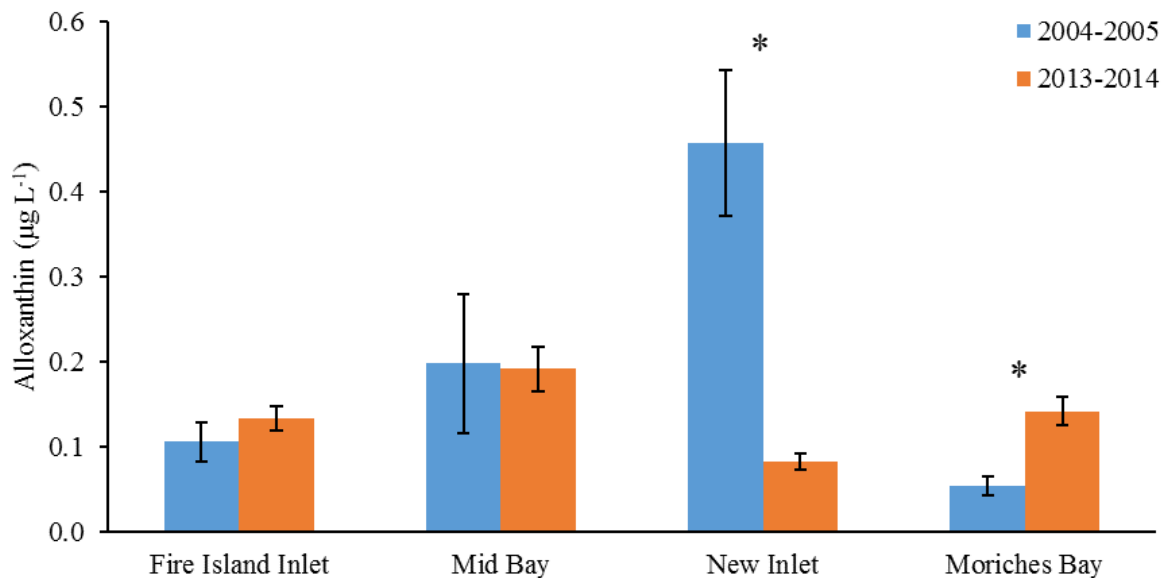


Figure 73. Pre-breach (2004-05) and post-breach (2013-15) summer mean alloxanthin concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of lutein were found to be significantly higher at the Fire Island Inlet, Mid-Bay, and Moriches Bay in 2013-15 (0.34, 0.79, and 0.14 $\mu\text{g L}^{-1}$, respectively) than in 2004-05 (0.04, 0.03, and 0.00 $\mu\text{g L}^{-1}$, respectively; Figure 74; Table 2; T-test; $p < 0.05$).

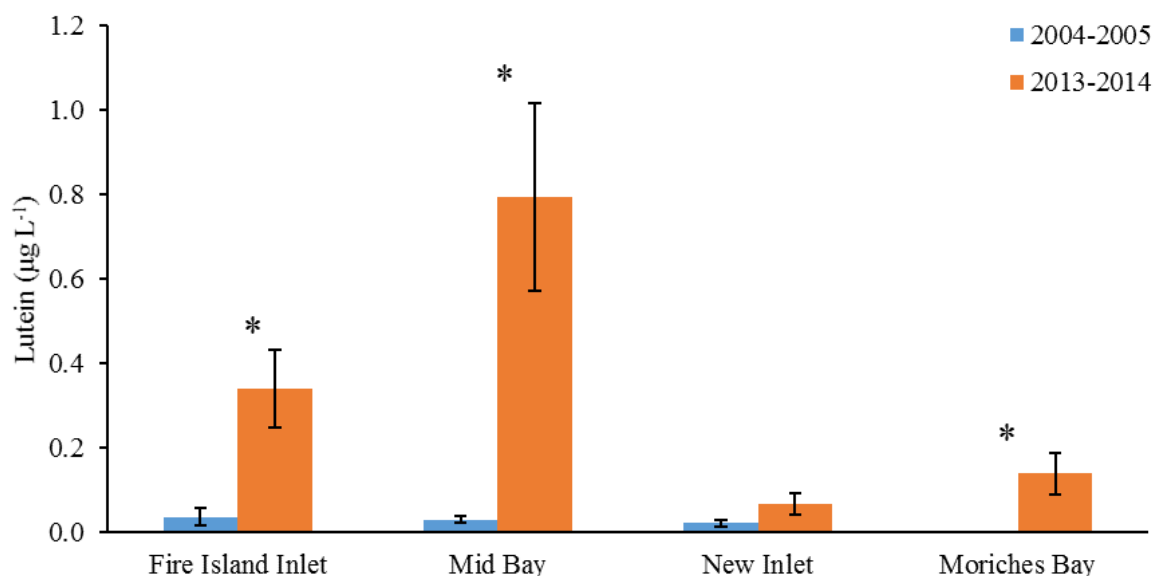


Figure 74. Pre-breach (2004-05) and post-breach (2013-15) summer mean lutein concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of peridinin were significantly lower at the New Inlet in 2013-15 (0.10 $\mu\text{g L}^{-1}$) than in 2004-05 (0.75 $\mu\text{g L}^{-1}$; Figure 75; Table 2; T-test; $p < 0.05$).

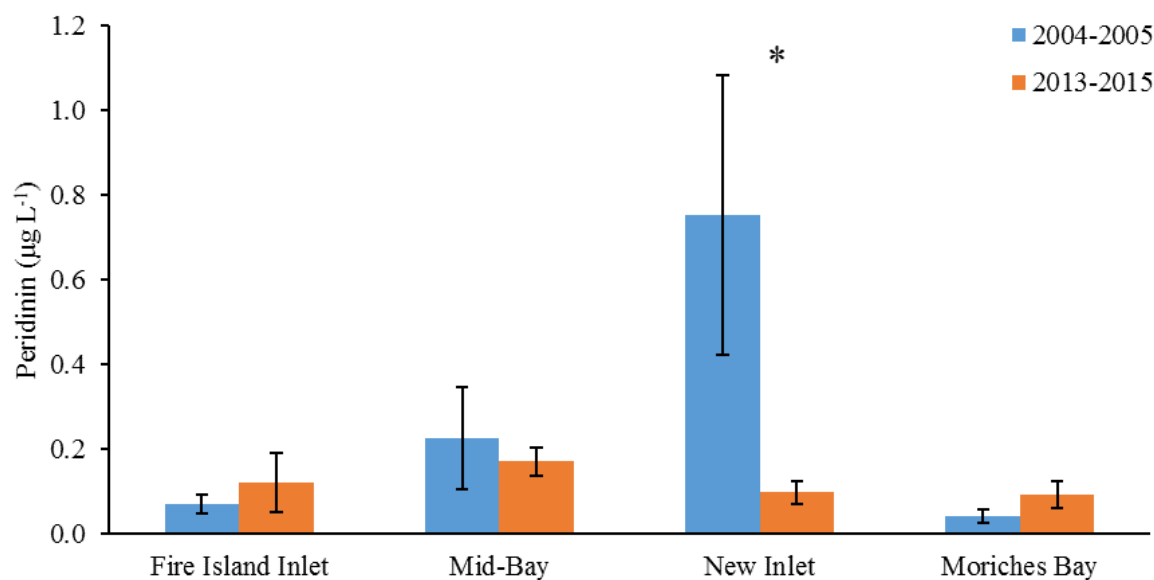


Figure 75. Pre-breach (2004-05) and post-breach (2013-15) summer mean peridinin concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Concentrations of fucoxanthin were significantly higher at Mid-Bay and Moriches Bay in 2013-15 (5.15 and 2.11 $\mu\text{g L}^{-1}$, respectively) than in 2004-05 (2.73 and 1.03 $\mu\text{g L}^{-1}$, respectively), and lower at the New Inlet in 2013-15 (1.41 $\mu\text{g L}^{-1}$) than in 2004-05 (2.80 $\mu\text{g L}^{-1}$; Figure 76; Table 2; T-test; $p < 0.05$).

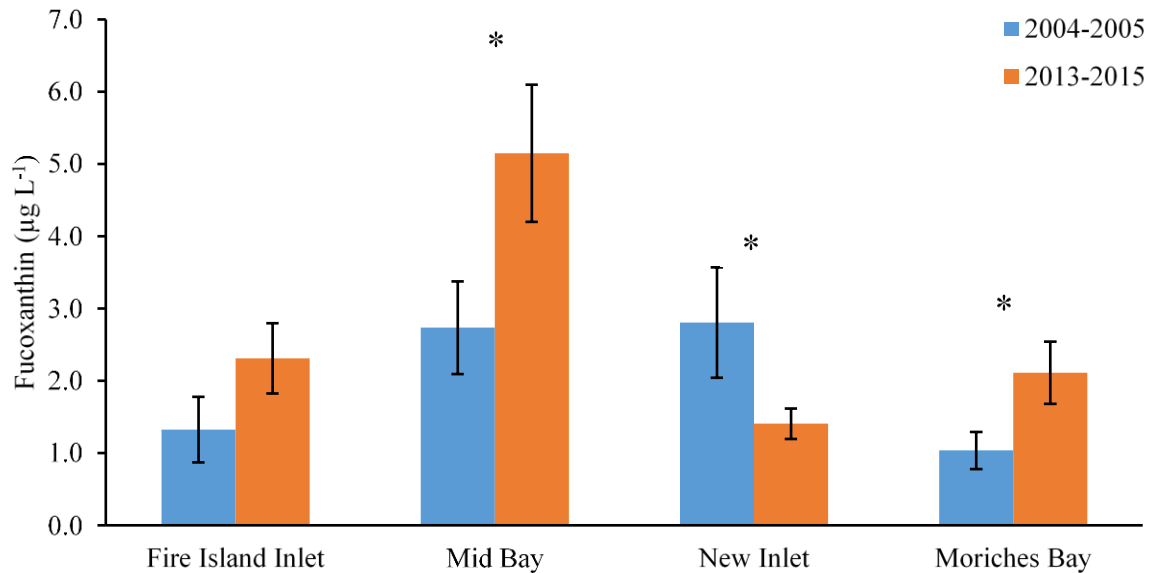


Figure 76. Pre-breach (2004-05) and post-breach (2013-15) summer mean fucoxanthin concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Regarding pigment ratios, the zeaxanthin:chlorophyll *a* ratio was significantly higher at the Fire Island Inlet and Mid-Bay in 2013-15 (0.05 and 0.09, respectively) than in 2004-05 (0.01 and 0.04, respectively; Figure 77; Table 2; T-test; $p < 0.05$).

The lutein:chlorophyll *a* ratio was significantly higher at the Fire Island Inlet, Mid-Bay, New Inlet and Moriches Bay in 2013-15 (0.031, 0.037, 0.011 and 0.015, respectively) than in 2004-05 (0.008, 0.006, 0.002, and 0.000, respectively; Figure 78; Table 2; T-test; $p < 0.05$).

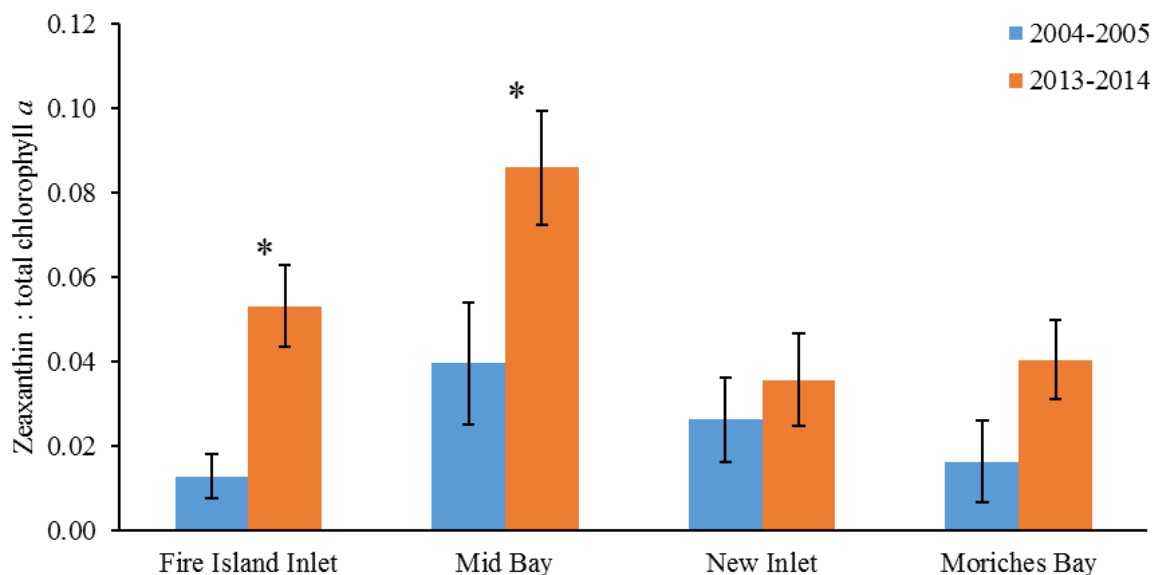


Figure 77. Pre-breach (2004-05) and post-breach (2013-15) summer mean zeaxanthin:chlorophyll *a* ratio across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

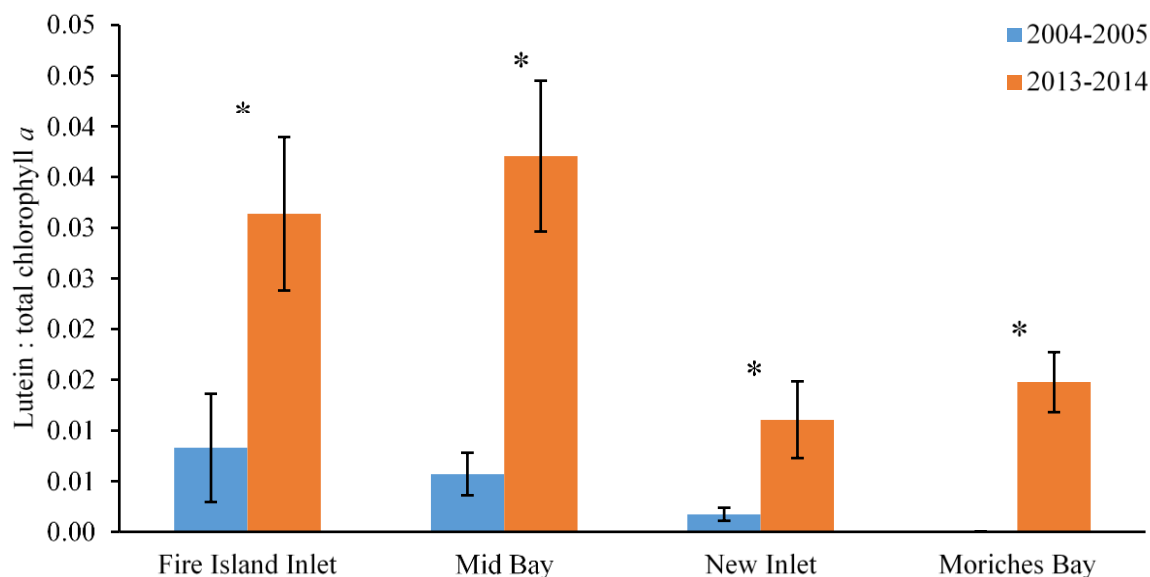


Figure 78. Pre-breach (2004-05) and post-breach (2013-15) summer mean lutein:chlorophyll *a* ratio across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

The perdinin:chlorophyll *a* ratio was found to be significantly lower at the Fire Island Inlet and New Inlet in 2013-15 (0.010 and 0.013, respectively) than in 2004-05 (0.186 and 0.043, respectively; Figure 79; Table 2; T-test; $p < 0.05$).

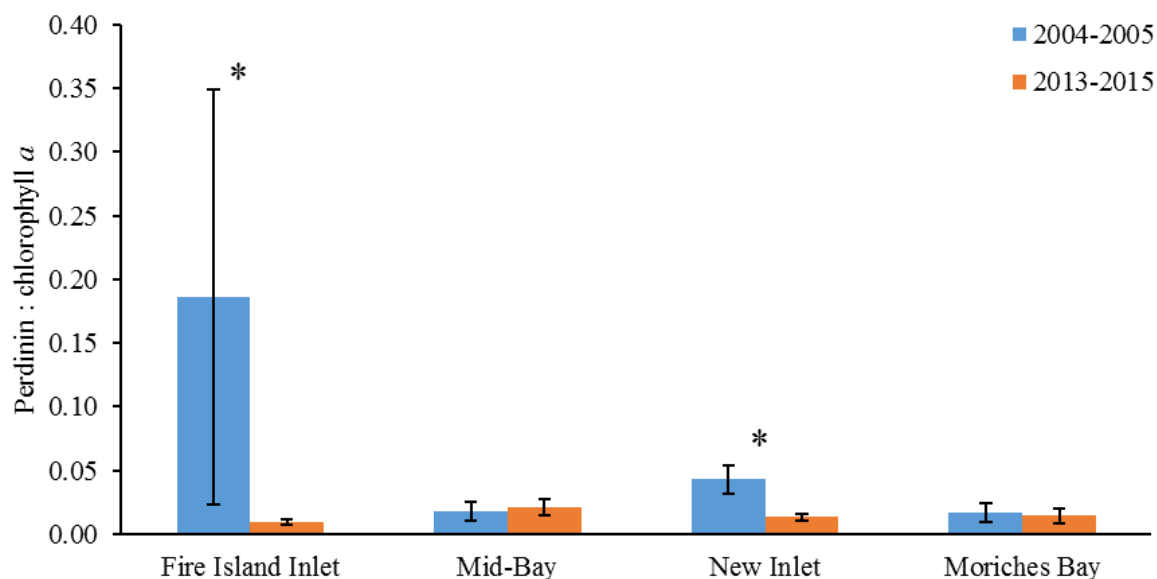


Figure 79. Pre-breach (2004-05) and post-breach (2013-15) summer mean peridinin:chlorophyll *a* ratio across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

The fucoxanthin:chlorophyll *a* ratio was significantly higher at Mid-Bay and Moriches Bay in 2004-05 (0.33 and 0.32, respectively) than in 2013-15 (0.18 and 0.20, respectively; Figure 80; Table 2; T-test; $p < 0.05$).

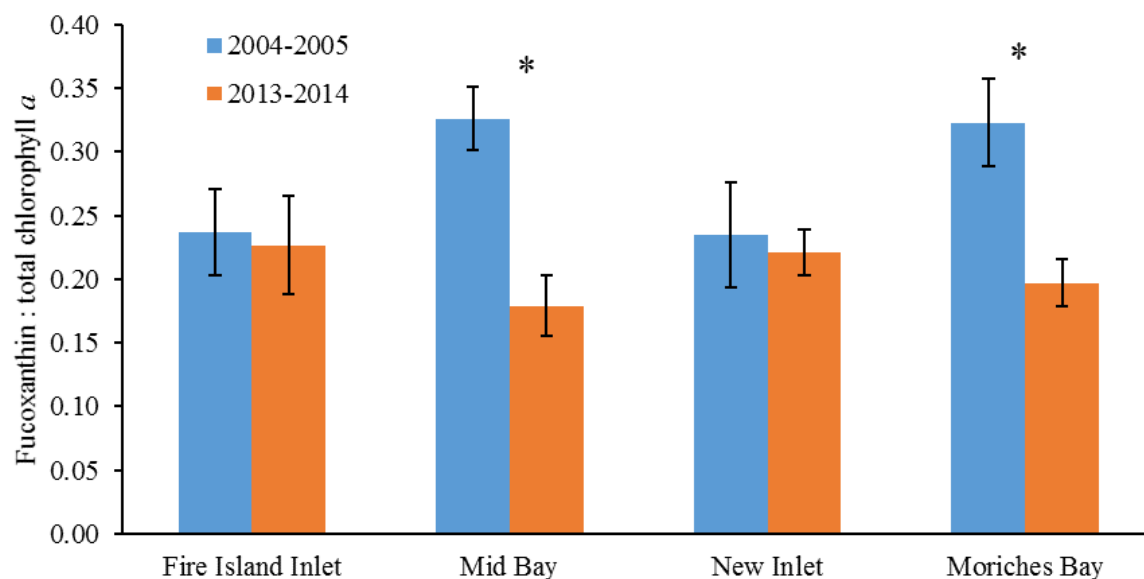


Figure 80. Pre-breach (2004-05) and post-breach (2013-15) summer mean fucoxanthin:chlorophyll *a* ratio across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

The alloxanthin:chlorophyll *a* ratio was significantly higher at the New Inlet and at Fire Island Inlet in 2004-05 (0.06) than in 2013-15 (0.02; Figure 81; Table 2; T-test; $p < 0.05$).

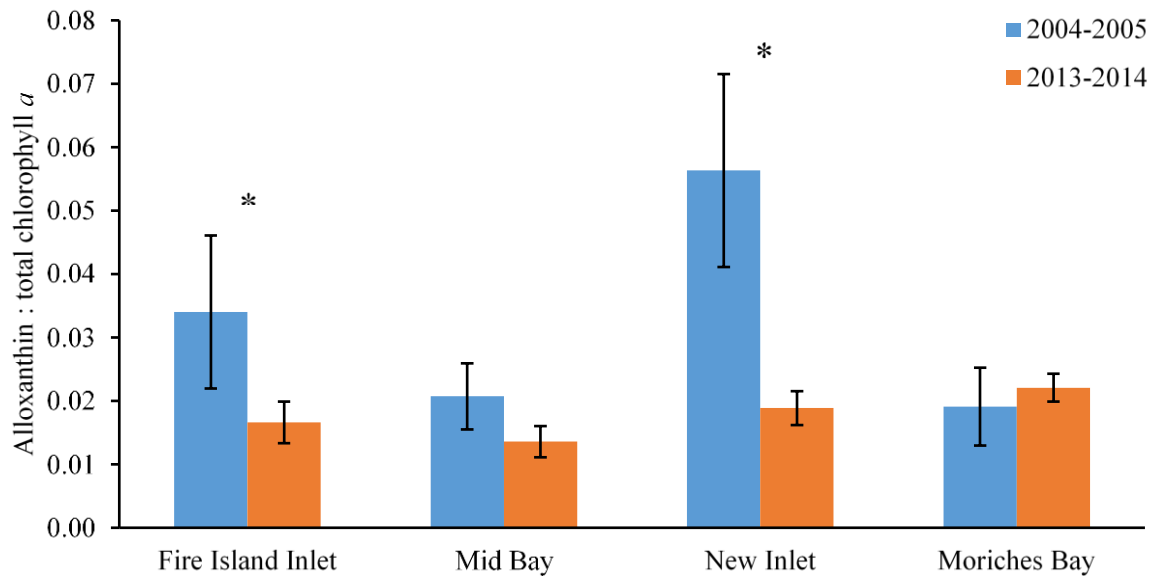


Figure 81. Pre-breach (2004-05) and post-breach (2013-15) summer mean alloxanthin:chlorophyll a ratio across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Nitrate concentrations were significantly higher at Fire Island Inlet in 2013-15 (1.05 μM) compared to 2004-05 (0.60 μM); Figure 82; Table 2; T-test; $p < 0.05$). However, concentrations were significantly higher at Mid-Bay, New Inlet, Moriches Bay in 2004-5 (2.36, 2.92, and 3.07 μM , respectively) than in 2013-15 (0.62, 1.22, and 0.92 μM , respectively; Figure 82; Table 2; T-test; $p < 0.05$).

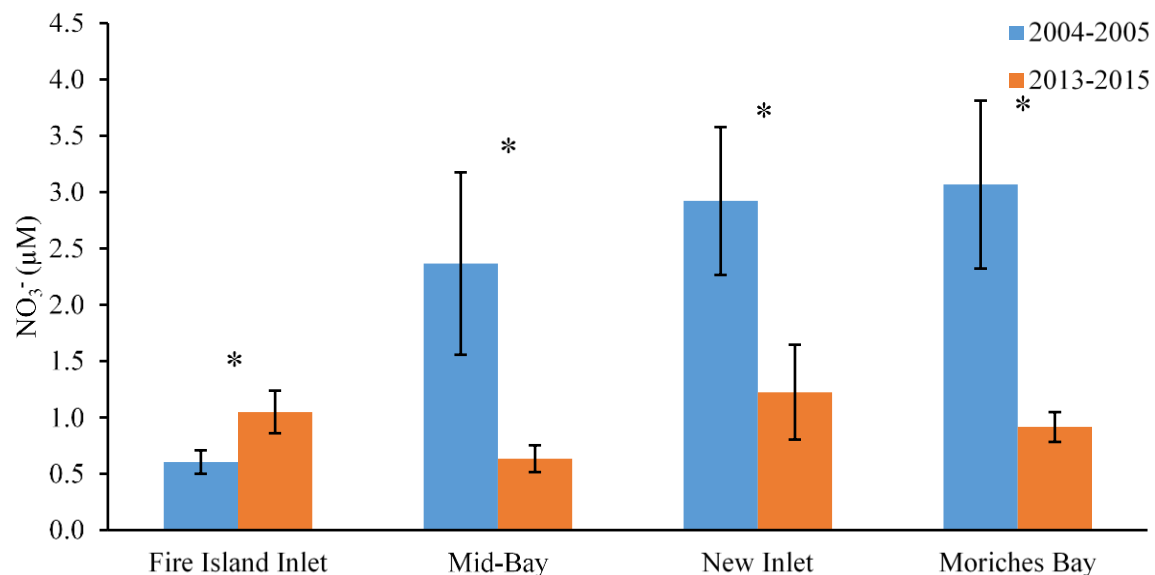


Figure 82. Pre-breach (2004-05) and post-breach (2013-15) nitrate concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Phosphate concentrations were significantly higher at Fire Island Inlet, New Inlet, and Moriches Bay in 2013-15 (0.66, 0.64, and 0.74 μM , respectively) than in 2004-05 (0.43, 0.34, and 0.44 μM , respectively; Figure 83; Table 2; T-test; $p < 0.05$).

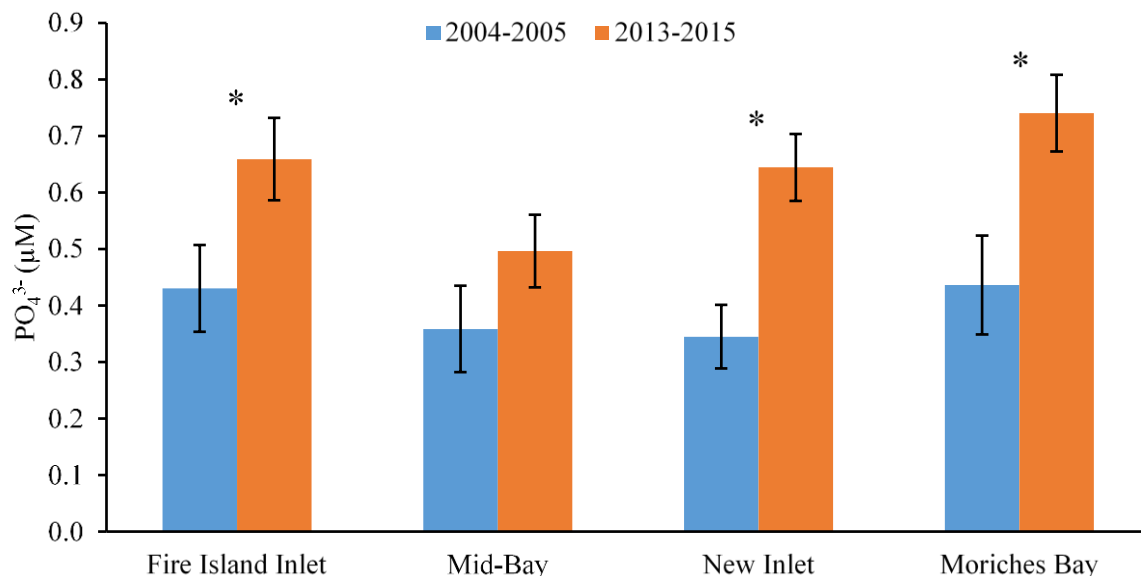


Figure 83. Pre-breach (2004-05) and post-breach (2013-15) phosphate concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Ammonium concentrations were significantly higher at Fire Island Inlet in 2013-15 (2.33 μM) than in 2004-05 (1.06 μM ; Figure 84; Table 2; T-test; $p < 0.05$) but were not significantly different at Mid-Bay, New Inlet, or Moriches Bay between 2004-05 and 2013-15 (T-test; $p > 0.05$).

DON concentrations were significantly higher at Fire Island Inlet, Mid-Bay, New Inlet and Moriches Bay in 2004-05 (20.19, 28.71, 30.59, and 13.38 μM , respectively) than in 2013-15 (9.94, 16.30, 9.60, and 9.09 μM , respectively; Figure 85; Table 2; T-test; $p < 0.05$).



Figure 84. Pre-breach (2004-05) and post-breach (2013-15) ammonium concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

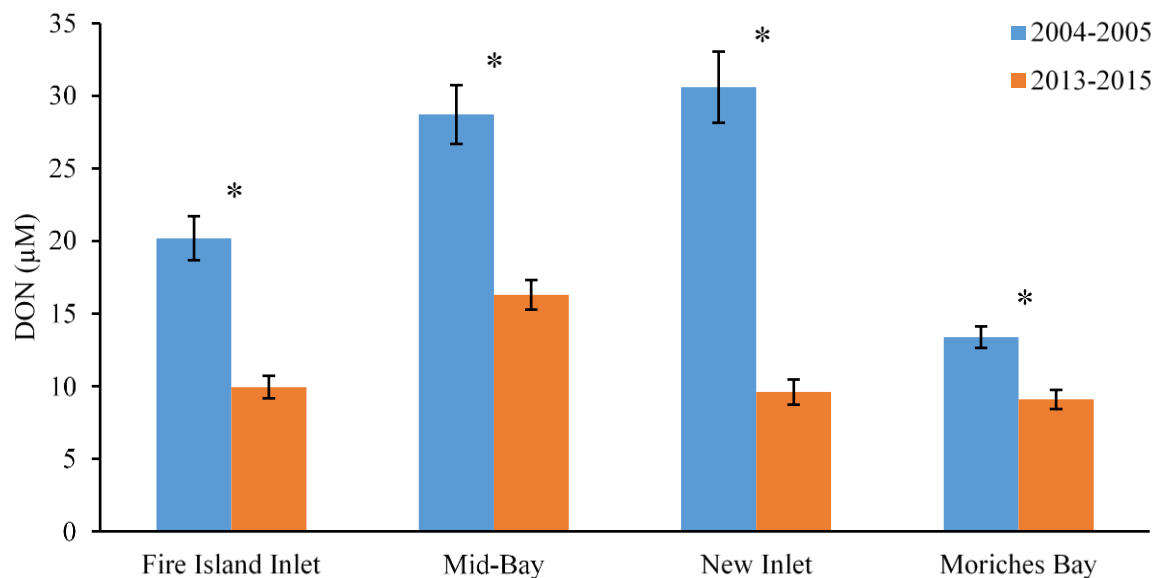


Figure 85. Pre-breach (2004-05) and post-breach (2013-15) dissolved organic nitrogen concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Silicate concentrations were found to be significantly higher at Fire Island Inlet, New Inlet, and Moriches Bay in 2004-05 (18.28, 66.63, and 38.30 μM , respectively) than in 2013-15 (10.49, 16.30, and 14.39 μM , respectively; Figure 86; Table 2; T-test; $p < 0.05$).

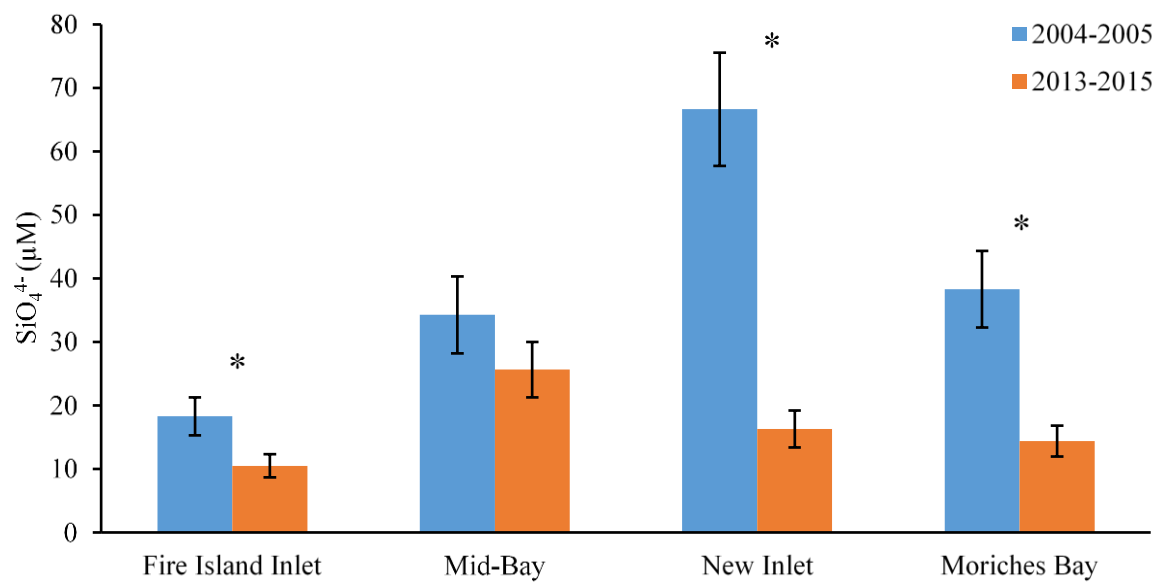


Figure 86. Pre-breach (2004-05) and post-breach (2013-15) silicate concentrations across various sites in Great South Bay and Moriches Bay, Long Island, NY. Columns represent means $\pm$ standard deviation. Asterisks indicates significant difference $p < 0.05$.

Discussion

The New Inlet in GSB had a series of clear and significant effects on water quality and plankton communities within the vicinity of eastern GSB and western Moriches Bay including significant decreases in algal biomass, summer water temperatures, and nitrogen concentrations as well as significant increases in salinity, summer dissolved oxygen, and water clarity. At the same time, it appears levels of phytoplankton biomass and salinity have risen within the central portion of GSB. Our in-depth examination of plankton communities also revealed a series of distinct changes in multiple populations across eastern and western GSB. The most dramatic changes in water quality and plankton communities were generally confined to Bellport Bay, the region closest to the New Inlet. In most cases, changes seemed to be a simple function of the dilution of bay water by ocean water that had lower algal biomass, summer water temperatures, and nitrogen concentrations along with higher salinity, summer dissolved oxygen, and water clarity, a hypothesis supported by our horizontal mapping of four of the ocean inlet regions of the south shore lagoons. In other cases, however, changes were more widespread (e.g. salinity increases across all of GSB and Moriches Bay, a shift in the Mid Bay plankton community structure) and less intuitive (e.g. increases in algal biomass in central GSB), and could reflect signals from interannual variation in weather and/or longer-term changes in the GSB ecosystem; longer records of post-breach conditions would be required to separate these drivers. Collectively, this study provides new insight regarding the effects of barrier island breaches on lagoonal estuaries in the context of changes and fluctuations driven by other forces.

Changes in physicochemical and biogeochemical conditions

Our comparisons of measurements made before and after the formation of the New Inlet by both municipal monitoring programs (SCDHS, 1976-2015) and academic laboratories (Curran, 2006) provide detailed information on how the New Inlet and other factors are impacting the GSB and Moriches Bay ecosystems. While salinity increases were detected throughout all GSB and western Moriches Bay after the formation of the New Inlet, changes in other water quality aspects were more limited with a gradient in the extent of changes. For example, dissolved nitrogen and summer temperature were reduced through the eastern half of GSB and all western Moriches Bay (Figures 3, 8) but were largely unchanged elsewhere. In contrast, chlorophyll a and total nitrogen decreased within Bellport Bay, Narrow Bay, and western Moriches Bay but increased in central and western GSB (Figures 6-7). Similarly, increases in water clarity and dissolved oxygen were isolated to Bellport Bay and Narrow Bay only (Figures 4-5). While temperature and salinity are conservative tracers that represent physical processes and circulation only, changes in nitrogen, chlorophyll a, and dissolved oxygen are also influenced by concurrent biological processes as well as each other. For example, lower nitrogen availability may have restricted the accumulation of algal biomass (Lively et al., 1983; Gobler et al., 2002, 2004) and limited community respiration rates thus allowing for higher dissolved oxygen. Alternatively, the cooler water in this region would also be higher in dissolved oxygen. Hence, changes in these parameters were likely influenced by both physical and biological processes.

To understand the extent to which changes in water quality characteristics were a function of more rapid flushing time of GSB and Moriches Bay following the formation of the New Inlet, residence times were calculated using a salt balance approach. Following the formation of the New Inlet, all regions of GSB and Moriches Bay had shorter residence times (Table 3). The most dramatic changes, however, occurred within the regions closest to the New Inlet including Moriches Bay, Narrow Bay, and Bellport Bay where residence times decreased by 60-90% (Table 3). In contrast, residence times in the middle regions of GSB changed by the smallest amount, only 20% (Table 3). The greater decline in residence time of GSB West and Nicoll Bay (nearly 50%) could reflect the effects of the dredging of Fire Island Inlet that occurred in 2013. These changes are broadly consistent with the changes in water characteristics such as dissolved nitrogen and chlorophyll a that displayed large and significant declines in Moriches Bay, Narrow Bay, and Bellport Bay but increases in other parts of GSB. Hence, while changing nutrient levels may alter levels of algal biomass and thus dissolved oxygen and water clarity, it seems likely that physical flushing had a prime organizing effect on changes in water quality in these water bodies. In support of this concept, changes in dissolved nitrogen, total nitrogen, chlorophyll a, secchi disc depth, salinity, and summer temperatures were all significantly correlated with the percent change in residence time following the formation of the New Inlet.

Table 3. Changes in salt-balance calculated residence times for multiple basins within Great South Bay and Moriches Bay following the creation of the New Inlet, New York.

Residence times in days	Great South Bay West (GSB W)	Nicoll Bay (NCB)	Nicoll Bay East (NCB E)	Patchogue (PB)	Bellport West (BP W)	Bellport East (BP E)	Narrow Bay (NWB)	Moriches (MOR)
Before breach	66	143	130	87	62	54	38	25
After breach	37	76	105	67	16	7	17	9
Percent change	-44%	-47%	-19%	-23%	-74%	-88%	-56%	-62%

The changes in residence times for GSB and Moriches Bay as well as changes in water characteristics following the formation of the New Inlet indicate that the New Inlet is not exchanging equally to the east and west but rather is primarily exchanging to the east toward the Moriches Inlet (Figure 87). For example, levels of nitrogen and chlorophyll a decreased in regions north and east of the New Inlet but increased to the west of the inlet. This pattern of ocean exchange is consistent with at least two other ocean inlets on the south shore of Long Island, the Shinnecock Inlet and Jones Inlet, both of which strongly exchange and flush ocean water to the east, but significantly less so to the west (SCDHS, 1976-2015; Swanson et al., 2013). This asymmetrical ocean flushing of the New Inlet was not predicted following its formation and thus represents one of its unanticipated consequences.

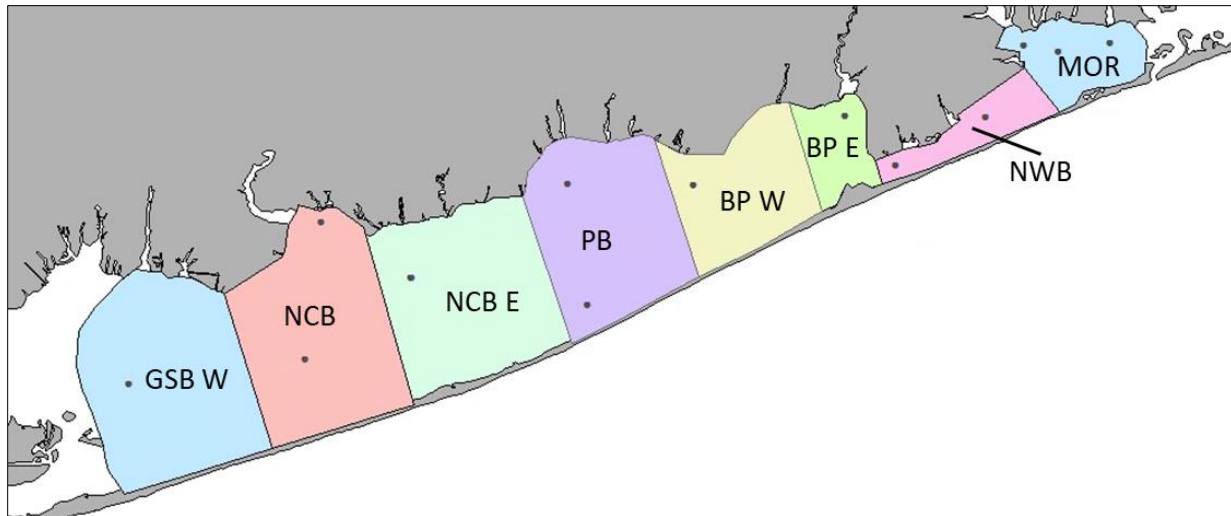


Figure 87. Locations of basins within Great South Bay and Moriches Bay, New York.

Shifts in plankton communities

While the long-term monitoring data from SCDHS revealed an obvious decline in chlorophyll *a* concentrations in eastern GSB and western Moriches Bay as well as increases in central GSB, our detailed analyses of plankton communities from 2004 – 2005 (Curran, 2006) and again from 2012 to 2015 (this study) revealed how individual plankton populations have changed. While the New Inlet greatly increased the flushing rate of eastern GSB and Moriches Bay (up to 90%), mid-GSB sites saw only minor changes in residence times (~20%). Consistent with this, compared to the sites located closer to ocean inlets, the Mid-Bay and/or Patchogue Bay sites monitored during 2013 – 2015 had significantly higher levels of total chlorophyll *a*, <2µm chlorophyll *a*, brown tide (*Aureococcus anophagefferens*) cells and pigment (but-fucoxanthin), pennate diatoms and their pigment (fucoxanthin), cyanobacteria and their pigment (zeaxanthin), autotrophic eukaryotes, the cryptophyte pigment alloxanthin, the green algal pigment lutein, and densities of heterotrophic bacteria. This is a significant departure from the prior study of this region in 2004 and 2005 when the New Inlet region (Bellport Bay) and the Mid-Bay region had nearly identical levels of total chlorophyll *a*, <2µm chlorophyll *a*, diatoms and their pigment (fucoxanthin), cyanobacteria and their pigment (zeaxanthin), autotrophic eukaryotes, and the green algal pigment lutein (Curran, 2006). Comparing plankton populations from 2004-2005 with those from 2013 – 2015 for individual sampling sites, during 2013 – 2015 the New Inlet site had lower levels of chlorophyll *a*, dinoflagellates and their pigment peridinin, fucoxanthin, and alloxanthin, consistent with the enhanced flushing of this region. These trends in pigment data suggest the declines in algal biomass in this region were being driven by reductions in dinoflagellates, cryptophytes, chrysophytes and diatoms (Wright et al., 1991; Millie et al., 1993). This may have mixed effects on the food web, as diatoms are associated with enhanced fisheries production while dinoflagellates are associated with lowered food web production (Frederiksen et al., 2006). In contrast, since the formation of the New Inlet, the central and western regions of GSB displayed significantly higher levels of chlorophyll *a*, <2µm chlorophyll *a*, diatoms and their pigment (fucoxanthin), cyanobacteria and their pigment (zeaxanthin), autotrophic pico-eukaryotes, and the green algal pigment lutein. Ribosomal RNA (rRNA) gene sequence-based

comparisons of plankton communities collected in 2008 and 2009 with post-breach samples similarly showed a significant change in community composition overall, and in both Bellport Bay and Mid Bay individually.

Our time series analyses revealed that beyond spatial variation in plankton communities, there was also a clear seasonal trend, with distinct cool and warm weather populations identified. Specifically, larger ($>5\mu\text{m}$) plankton were more dominant in cooler months as there was an inverse correlation between temperature and $>5\mu\text{m}$ chlorophyll *a*, pennate diatoms, dinoflagellates, and all plankton groups $>7\mu\text{m}$ as measured via the Flow Cam (plankton 7-12 μm , plankton 12-25 μm , plankton $>25\mu\text{m}$, ciliates $>25\mu\text{m}$, copepods $>25\mu\text{m}$, diatoms $>25\mu\text{m}$, dinoflagellates $>25\mu\text{m}$) suggesting that these groups were mostly abundant during the cooler months. As the ecosystem warmed, the abundance of smaller ($<5\mu\text{m}$) phytoplankton increased. Specifically, there were significant positive correlations between temperature and $<2\mu\text{m}$ and 2-5 μm chlorophyll *a*, as well as significant correlations between temperature and both types of cyanobacteria (PE and PC), autotrophic pico-eukaryotes, heterotrophic bacteria, and *Aureococcus anophagefferens* cell densities. rRNA gene sequence-based analyses similarly revealed seasonal patterns in plankton community composition at each site. Temperate winter months were generally accompanied by strong mixing due to increased wind stress, low surface temperatures, and higher nutrient levels, conditions that tended to favor larger phytoplankton (Chen et al., 1988; Glibert et al., 2016). Prior studies performed in Long Island Sound have found that large diatoms prefer a well-mixed water column, whereas smaller phytoplankton prefer more stratified water columns (Peterson, 1986). In general, smaller phytoplankton will outcompete larger phytoplankton due to higher surface area-to-volume ratios, allowing for enhanced competition for nutrients in warmer waters where nutrients are lower (Lewis, 1976; Glibert et al., 2016).

One change among phytoplankton that was universal across all of GSB following the formation of the New Inlet was an order of magnitude decline in the densities of dinoflagellates as well significant declines in the concentrations of peridinin (accessory pigment of dinoflagellates) at the Mid-Bay and New Inlet sites. Prior to the formation of the New Inlet, dinoflagellate densities within GSB were inversely correlated with salinity and positively correlated with alloxanthin and inorganic nitrogen (Curran, 2006). This statistical grouping was driven largely by Bellport Bay that, at the time, had the highest levels of dinoflagellates, alloxanthin, and inorganic nitrogen and the lowest salinity across the entire south shore of Long Island (Curran, 2006). In the current study, dinoflagellate densities were again inversely correlated with salinity, and positively correlated with concentrations of alloxanthin. The most abundant free-living dinoflagellate genera found in the 18S rRNA sequences from 2008-09 and 2013-14 were *Pentaparsodinium*, *Karlodinium*, *Heterocapsa*, *Prorocentrum*, and *Scropsiella*. Elevated levels of nutrients delivered from groundwater and streams (leading to low salinity) likely support the growth of dinoflagellates (Gobler and Boneillo, 2003; Heisler et al., 2008) as well as cryptophytes (i.e. alloxanthin; McGowan et al., 2005) which are known to be a source of prey for mixotrophic dinoflagellates (Stoecker et al., 1997; Parrow and Burkholder, 2003; Johnson and Stoecker, 2005). The formation of the New Inlet enhanced ocean flushing which facilitated the dramatic decline of dinoflagellates by increasing salinity, decreasing nutrients, decreasing the abundance of cryptophytes, and altering the formerly ideal habitat for dinoflagellates in this region of

GSB. Given that some dinoflagellates form harmful algal blooms and cause fish kills (Anderson et al., 2002), this change is a clear ecosystem benefit for Bellport Bay.

A major difference in GSB and Moriches Bay during this study compared to the period prior to the New Inlet has been the more consistent recurrence of brown tides. The frequency of brown tides from 2013 to 2015 (66% of summer and fall seasons) was significantly greater than the frequency before the New Inlet (20%; 1985 – 2012; $p < 0.05$; G-test of independence). In 2016, a brown tide occurred in the fall but not summer. This outcome has a series of implications for interpreting the effects of the New Inlet on GSB and Moriches Bay. Given the statistical significance of this change in brown tide frequency, it might seem the New Inlet is making GSB more vulnerable to these HABs. Several factors may be driving this trend. Firstly, it is possible that prior to the formation of the New Inlet, the eastern region of GSB was less hospitable to brown tide due to the higher inorganic nutrient concentrations and lower salinity, conditions under which *Aureococcus anophagefferens* is at a physiological disadvantage relative to other phytoplankton (Gobler et al, 2005, 2011; Gobler and Sunda, 2012). Next, while our salt balance-based residence time calculations suggest that even the central region of GSB had a slight decline in residence times since the formation of the New Inlet, true residence times in GSB are controlled by additional factors including winds and subtidal volume fluxes (Wilson et al., 1991; Nixon et al., 1994). Given the higher densities of many phytoplankton populations including *A. anophagefferens* in central GSB since the formation of the New Inlet, it seems likely that the water in this region is more sluggish, favoring the occurrence of more frequent brown tides (Gobler et al., 2005). According to the 2015 annual report by the Suffolk County Comprehensive Water Resources Management Plan (SCCWRMP), it is possible that the decadal trend in increasing nitrogen loading to GSB is making it more vulnerable to brown tides.

The more frequent occurrence of brown tides in GSB since the formation of the New Inlet represents a confounding variable in understanding the effects of the New Inlet on the GSB and Moriches Bay plankton communities. There was positive correlation between total chlorophyll *a* concentrations and *Aureococcus anophagefferens* concentrations, indicating that brown tides host higher levels of algal biomass than non-bloom bay conditions. The collapse of brown tides leads to higher levels of organic nutrients than non-bloom conditions (Gobler et al., 2004, 2005), which is likely to affect post-bloom plankton communities and may be partly responsible for the higher levels of many plankton populations within the central regions of GSB since the formation of the New Inlet. Alternatively, this region may simply be more vulnerable to all types of phytoplankton growth due to poor flushing. We suspect both of these factors are promoting higher algal biomass in central GSB.

While phytoplankton and bacteria populations across GSB and Moriches Bay were strongly affected by the New Inlet, it is notable that many zooplankton populations were not. There were no significant differences among sites for any of the zooplankton populations quantified during this study, including ciliates, copepods, and copepod nauplii. This may be due, in part, to the ability of zooplankton to migrate vertically making them less influenced by tidal circulation and outgoing tides (Harris et al., 2000). There were significantly fewer ciliates at New Inlet post-breach, but significantly more at Moriches Bay. The 18S rRNA sequence data indicate a reduction in *Pelagostrobilidium* spp. and perhaps other ciliates in Bellport Bay. While the higher levels of algal

biomass within central GSB would be expected to translate into higher levels of zooplankton, this may be partly negated by the detrimental effects of brown tide (Gobler et al., 2002; Smith et al., 2008). Further, with regard to the greater abundance of other small phytoplankton within central GSB, primary production associated with picoplankton may cycle primarily through the microbial loop rather than reaching upper trophic levels and supporting fisheries (Chasar et al., 2005). Finally, there were negative correlations between adult copepods and pennate diatoms and copepod nauplii and dinoflagellates suggesting these phytoplankton were also harmful to these zooplankton and inhibited their productivity (Greenfield et al., 2005).

Ecosystem implications

Several of the collective physicochemical and biogeochemical changes documented here could have broad benefits to various aspects of the GSB-Moriches Bay ecosystem. For example, ocean flushing is enhancing water clarity in eastern GSB and western Moriches Bay, a change likely to benefit the resident seagrass community that has greatly diminished since the early 1980s in part due light limitation (Casper et al., 1987; Dennison et al., 1993; New York State Department of Environmental Conservation (NYSDEC), 2009). There was a strong inverse correlation between secchi disk depth (water clarity) and total chlorophyll *a* concentrations during this study indicating that the improved water clarity was largely a function of reduced phytoplankton biomass. Prior to the formation of the New Inlet, summer water temperatures in GSB had frequently risen above 25°C, a level known to be stressful to *Zostera marina* (Bintz et al., 2003, Touchette et al., 2003, Short et al., 2011) and hard clams (Pratt and Campbell, 1956; Grizzle and Lutz, 1988; Weiss et al., 2007). Since then, summer temperatures have been significantly lower, a change that may also benefit eelgrass populations.

Seasonal analyses revealed that changes in several water characteristics (temperature, dissolved oxygen) were most profound in spring and summer months, when improved water quality is most critical for marine resources. Early life stage finfish and shellfish, that are spawned during late spring and early summer (Kraeuter and Castagna, 2001; Shumway and Parsons, 2011), are generally more sensitive to stressors such as low dissolved oxygen (Gobler et al., 2014; DePasquale et al., 2015). These seasons are also typically when general coastal water quality problems arise, such as harmful algal blooms and summer hypoxia (Gobler et al., 2005, 2008, Wallace et al., 2014) and are also periods when coastal waters bodies are used extensively for recreational and commercial purposes. Reducing the severity of these phenomena may reverse declining abundances in key fisheries such as hard clams and bay scallops (NYSDEC, 1950-2013).

To some extent, the lower levels of nitrogen and algal biomass within eastern GSB following the formation of the New Inlet represent a reversal of decadal trends of increasing nitrogen and harmful algal blooms in NY's coastal waters (Gobler et al., 2005, 2008, Hattenrath et al., 2010, SCCWRMP, 2015) and as stated, this could have broad ecosystem benefits. In contrast, however, central regions of GSB have experienced more frequent brown tides, conditions that have negative implications for bivalves, zooplankton, and seagrasses (Gobler et al., 2005). Along with the asymmetrical longitudinal distribution of tidal exchange, more frequent brown tides in central GSB also represents an unexpected occurrence in GSB since the formation of the New Inlet.

The intensification of algal blooms in central GSB following the formation of the New Inlet has important managerial implications. While the New Inlet has provided relief from HABs and other water quality problems in eastern GSB, this improvement has been limited in scale with regions west of the New Inlet experiencing an intensification of brown tides. Given that these same regions are also experiencing higher total nitrogen levels and that high levels of organic nitrogen can intensify brown tides (Gobler and Sunda, 2012), mitigation of excessive watershed delivery of nitrogen may be needed to mitigate these HABs and improve water quality in these locations.

Conclusions

The New Inlet in GSB created by Hurricane Sandy has had a series of expected as well as unexpected consequences for water quality and plankton communities in GSB and Moriches Bay. In locales north and east of the New Inlet, bay residence times, summer water temperatures, total and dissolved nitrogen, chlorophyll *a*, diatoms, cryptophytes, and dinoflagellates decreased, while salinity, dissolved oxygen, and water clarity increased. These changes are expected to improve the performance of resident seagrasses and bivalves. In contrast, regions west of the New Inlet within the center of GSB experienced little change in residence times, increases chlorophyll *a*, pennate diatoms, cryptophytes, heterotrophic bacteria, and pico-phytoplankton including harmful brown tides, cyanobacteria, chlorophytes, and decreases in water clarity and summer dissolved oxygen levels. These changes could have negative consequences for vital resources including zooplankton, bivalves, and seagrasses. Therefore, while the New Inlet has provided regional ecosystem benefits, the results of this study suggest broader scale, watershed-based management may be required to improve conditions elsewhere in GSB.

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525