HARBOR HEALTH STUDY

Harbor Watch | 2017

Harbor Health Study: 2017

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This report includes data on:
Demersal fish study in Norwalk Harbor and dissolved oxygen studies in Stamford Harbor, Five Mile Harbor, Norwalk Harbor, Saugatuck Harbor, Lewis Gut, and New Haven Harbor

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Introduction

Harbor Watch is a water quality research program based out of Earthplace in Westport, CT. Our mission is to provide the people of Connecticut with the data, knowledge, and field expertise necessary to safeguard our waterways, educate citizens about watershed issues, and train volunteers and student interns through hands-on research. In this report, we present research conducted in 2017 on the fish community in Norwalk Harbor, Connecticut, as well as water quality conditions in six harbors along the Connecticut coast.

Harbor Watch began conducting a dissolved oxygen profile study in Norwalk Harbor in 1986. A fish study of that harbor was added in 1990 under the guidance of the State of Connecticut's Department of Environmental Protection (now known as the CT Department of Energy and Environmental Protection) Fisheries Bureau. Since then, the program has grown to include the study of up to 6 harbors annually for dissolved oxygen conditions and up to 3 harbors annually for fish.

From May through October 2017, water quality data were collected in six harbors (Stamford, Five Mile, Norwalk, Saugatuck, Johnson's Creek/Lewis Gut, and Quinnipiac), and the fish study was conducted in one harbor (Norwalk). All six harbors were monitored for dissolved oxygen, salinity, water temperature, turbidity and chlorophyll *a*. Dissolved oxygen is important for the survival of estuarine species; low oxygen or hypoxic conditions can impede the use of a harbor as habitat. Water temperature is another critical ecosystem parameter because many species require specific temperature ranges for spawning in and inhabiting an area. Turbidity is a measurement of water clarity, which can indicate sediment loading or water column productivity. Chlorophyll *a* measures the presence of phytoplankton and other photosynthetic organisms in the water, which are important food resources. Finally, fish can be used as an indicator of harbor health and the harbor's functionality as a refuge.

1. Benthic Fish Study

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Norwalk Harbor is an active harbor, used year-round both commercially and recreationally. The harbor is most recognized for its renowned shellfishing industry, which has risen to prominence since beginning in the 1800s. Within the local community, the harbor is also known for its beaches, dining, boating, and other attractions. Positioned just outside the harbor are the Norwalk Islands, which help to protect the inner harbor from extreme weather events like hurricanes. These islands are part of the Stewart B. McKinney National Wildlife Refuge and serve valuable and important environmental roles to the harbor (Steadman et al., 2016).

During Harbor Watch's 27 years of studying fish in the harbor, there has been a notable increase in development along the harbor banks. As a result of the resulting shoreline hardening, there has been a reduction in riparian buffer and loss of salt marshes (personal observations, R. Harris). These factors have potentially contributed to an altered composition of the benthos, from healthy microalgal populations to a silty bottom, particularly in the upper harbor. A shift in animal species found in Norwalk Harbor has also been observed. There appears to have been an increase of Canada geese, osprey, swans, and cormorants (R. Harris, personal observations). Similarly, Harbor Watch has observed changes in fish diversity since 1990 (Figure 1.4). Estuaries provide refuge, habitat, and other services to many species. Because of their sensitivity to environmental conditions, fish can be used as an indicator to assess the health of an estuary. In Norwalk Harbor, *Pseudoplueronectes americanus* (winter flounder) is of particular interest because it is a commercially viable species that uses embayments to spawn.

Harbor Watch and a dedicated network of volunteers, including the Wilton High School Marine Biology Club, have been quantifying the abundance and species composition of fish in Norwalk Harbor, focusing on demersal species. Sampling was conducted from 1990 through 1994. Trawling was not conducted from 1995-2001, but was resumed in 2002 and has continued since. It should be noted that the inner harbor was dredged in 2006 and the outer harbor was dredged in 2010 which may have impacted the study (Figure 1.5).

Methods

Trawling was conducted from the R.V. Annie, a 26' converted oyster scow equipped with a winch and pulley for trawl retrieval. The crew was comprised of 2 Harbor Watch staff members who served as pilot and deck hand. They were joined by up to 6 additional trained volunteers to assist the deck hand. A grid system that divided the harbor into twenty 300m² sampling areas (Figure 1.1) was used to identify the location in the harbor where each trawl was conducted. This grid system was established by the CT DEEP in 1990 when the study started. During each trawling session, 3 of those 20 boxes were selected to trawl, one in the upper harbor (box A-F), one in the middle harbor (box G-N), and one in the outer harbor (box O-T). When the research vessel was properly positioned within a box, the 1m beam trawl was launched off the starboard stern. The trawl, which was connected to the boat by approximately 13 meters of line, was equipped with a tapered ¼" mesh net, tickler chain, and rescue buoy. Each box was trawled for 3 minutes at 3 miles per hour. Coordinates were recorded where the trawl was launched and where it was retrieved. At the end of 3 minutes, the trawl was pulled back onto the boat using a winch. The net was removed from the trawl and emptied into a sorting bin. The catch was recorded by species and the number of individuals caught. For one particular species of interest, winter flounder (*Pseudopleuronectes americanus*), the total length of each individual caught was also recorded to the nearest millimeter using a ruler. Invertebrates were also identified and counted. All organisms present in each trawl net were returned to the harbor following identification and counting.

Over the study's 27 years there has been slight variance in data collection due to weather patterns, fish kills, boat repairs, and occasional requests from the CT DEEP for Harbor Watch to trawl outside of Norwalk Harbor, which disrupted trawling activity. To standardize the data and enable comparisons from year to year, data are reported as "catch per trawl" or the total number of fish caught in a period of time divided by the total number of trawls conducted during that same time period.

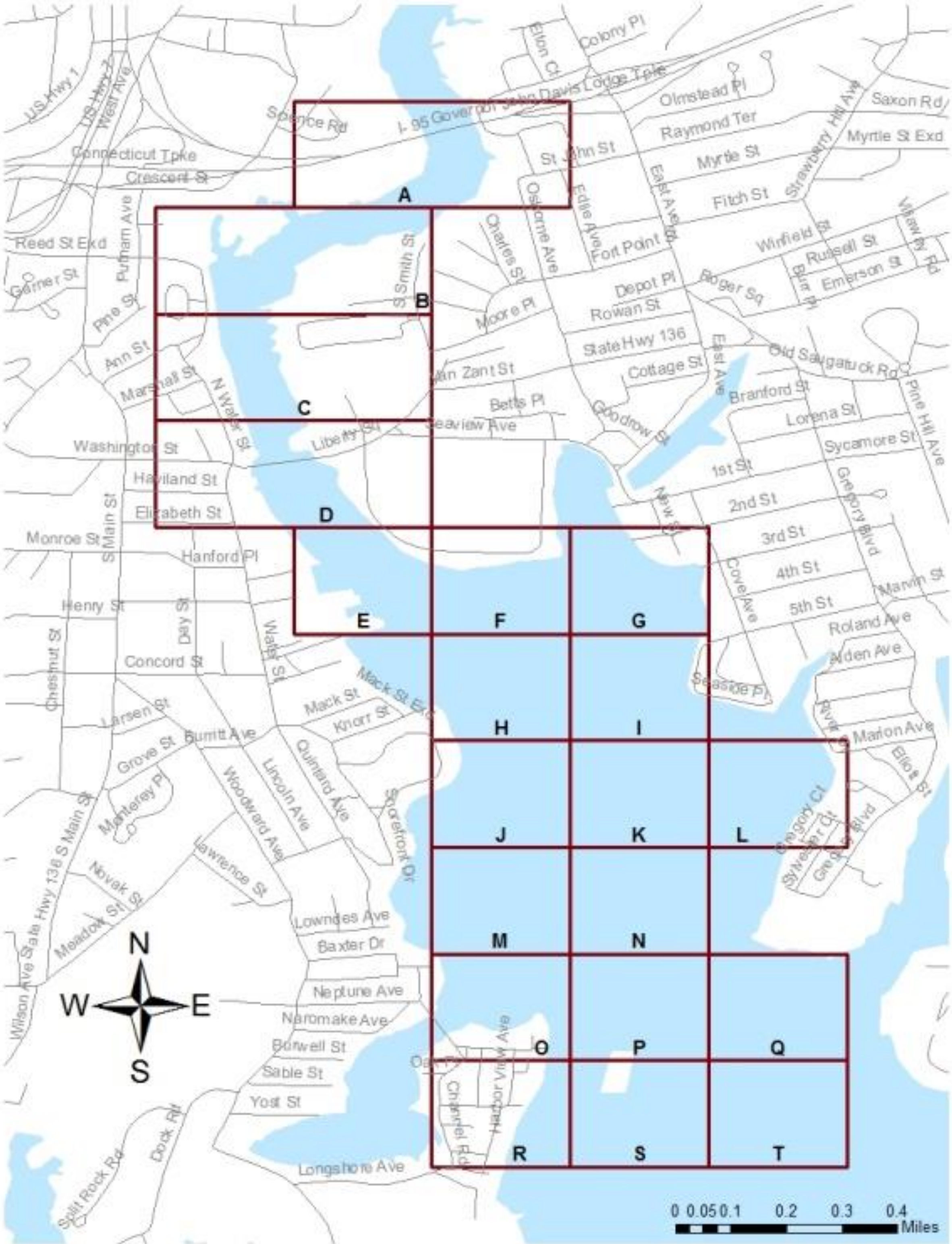

Figure 1.1. Location of trawl boxes within Norwalk Harbor.

Results and Discussion

Fish

During the 2017 sampling season, 168 individual fish from 17 different species were caught in Norwalk Harbor. The three most abundant species caught in 2017 were cunner (*Tautogolabrus adspersus*), northern searobin (*Prionotus carolinus*), and northern pipefish (*Syngnathus fuscus*), making up over 68% of the total number of individuals (Figure 1.2). Fish were observed in 18 of the 20 boxes sampled. Boxes "C" and "M" were sampled but no fish were observed. Box "P" had the greatest number of individuals during 2017, with 31 fish caught in total (Figure 1.3). While sampling was conducted in the upper, middle, and outer harbor during each trawling trip, tidal cycles impeded access to some of the boxes during some sampling sessions as they were inaccessible during low tide (becoming mud flats; Table 1.2).

Table 1.1. Common names for fish codes

Code	Common Name
EEL	American Eel
ASS	Atlantic Silverside
BSB	Black Sea Bass
BKF	Blackfish
CUN	Cunner
NKG	Naked Goby
PIP	Northern Pipefish
PUF	Northern Puffer
NSR	Northern Searobin
PGY	Porgy (Scup)
SHE	Seahorse
SMF	Smallmouth Flounder
SPT	Spot
SFL	Summer Flounder
WEK	Weakfish
WF0	Winter Flounder
WPF	Windowpane Floudner
ZZZ	No Fish Caught

Table 1.2. Total number of trawls per box, May through September 2017

Box	# of Trawls
A	5
B	4
C	4
E	7
F	5
G	9
H	5
I	6
J	5
K	10
L	5
M	2
N	4
O	4
P	5
Q	5
R	5
S	8
T	8
Total	106

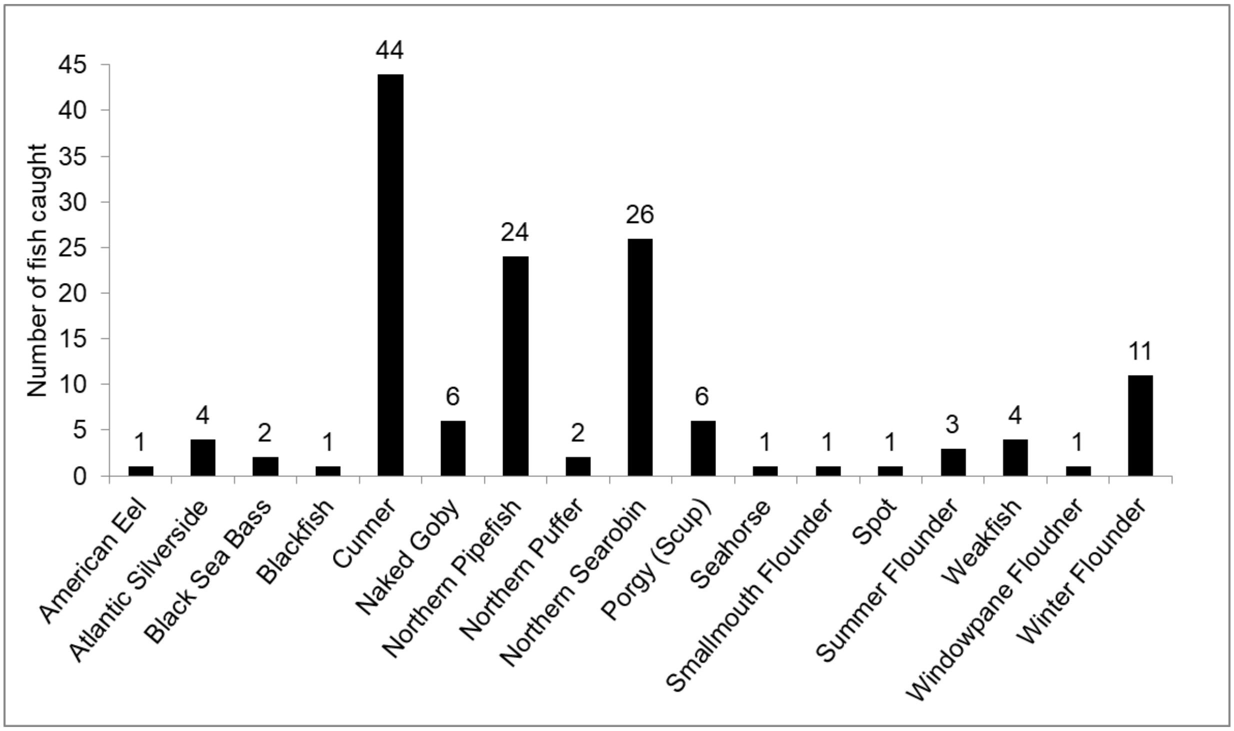

Figure 1.2. Total number of fish caught by species in Norwalk Harbor, May through October 2017.

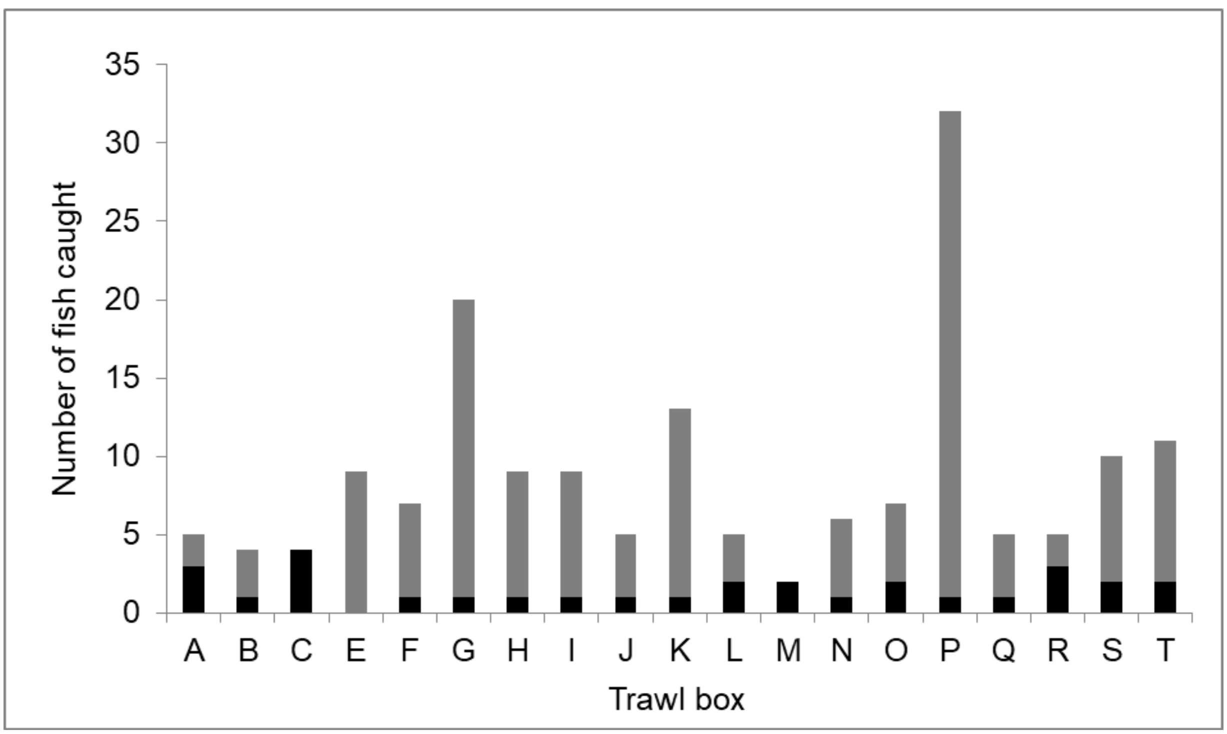

Figure 1.3. Number of fish caught and trawls with empty nets in each box in Norwalk Harbor, May through October 2017. Common names for the species codes are listed in Table 1.1.

The overall number of fish per trawl in 2017 was 1.58 fish. This was a slight increase from 2016, but is still the fourth lowest recorded number of fish per trawl in the study's 27 years of data (Table 1.3, Figure 1.4). The other years where a lower number of fish per trawl was recorded were 2006, 2010, and 2016. Potential drivers of the apparent decline in catch may include increasing water temperatures, low dissolved oxygen values, or predation from other species inhabiting the estuary. Additional research is needed to evaluate the contribution of these and other factors, and this study is expected to continue in 2018.

The 2017 season had the second lowest number of fish per trawl ever observed in this study for winter flounder. The only season with a lower number of fish per trawl was in 2002, but this is likely an artifact resulting from the fact that very few trawls were conducted. There were only 11 winter flounder caught in total in 2017 and one of these was believed to be a one year old fish and not a young-of-the-year fish as are typically observed. In 2017, cunner was the species observed most frequently, with 0.42 fish per trawl observed. However, the majority of this observed abundance resulted from one trawl where 24 fish were observed in box "P" (Figure 1.3).

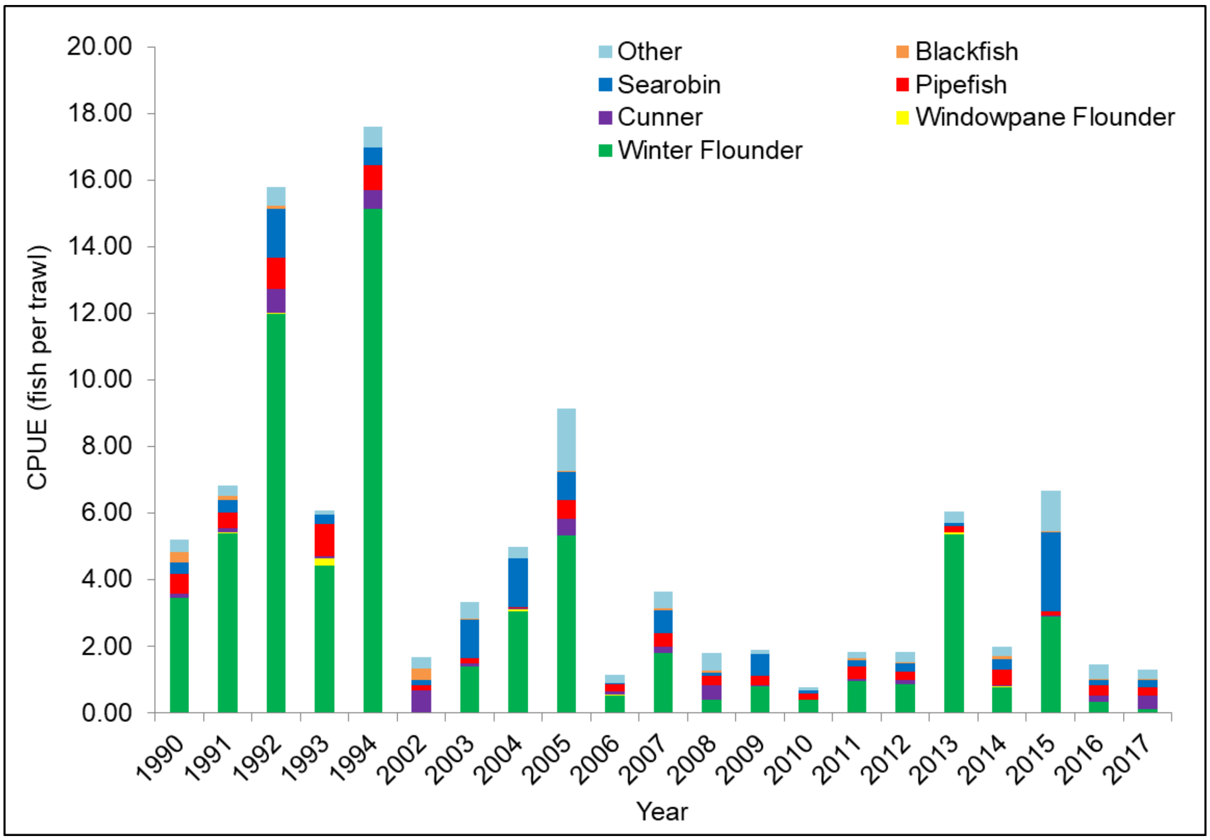

Figure 1.4. Catch per trawl from 1990 to 2017 in Norwalk Harbor.

Table 1.3. Catch per trawl for select species of interest from 1990 to 2016 in Norwalk Harbor

	Winter Flounder	Windowpane Flounder	Cunner	Pipefish	Searobin	Blackfish
1990	3.44	0.00	0.14	0.58	0.35	0.30
1991	5.38	0.03	0.12	0.48	0.36	0.12
1992	11.97	0.05	0.70	0.93	1.47	0.10
1993	4.42	0.23	0.07	0.96	0.26	0.01
1994	15.14	0.00	0.55	0.76	0.52	0.00
2002	0.00	0.00	0.67	0.17	0.17	0.33
2003	1.39	0.00	0.09	0.17	1.15	0.02
2004	3.05	0.05	0.03	0.03	1.17	0.00
2005	5.33	0.00	0.48	0.56	0.83	0.04
2006	0.51	0.03	0.12	0.20	0.01	0.00
2007	1.78	0.00	0.22	0.39	0.70	0.04
2008	0.38	0.02	0.44	0.26	0.10	0.06
2009	0.79	0.00	0.03	0.29	0.66	0.00
2010	0.41	0.00	0.00	0.16	0.00	0.00
2011	0.97	0.00	0.05	0.38	0.18	0.05
2012	0.87	0.00	0.13	0.22	0.28	0.03
2013	5.37	0.03	0.02	0.16	0.12	0.00
2014	0.76	0.05	0.01	0.47	0.32	0.10
2015	2.88	0.01	0.03	0.13	2.36	0.03
2016	0.32	0.00	0.20	0.33	0.15	0.02
2017	0.10	0.01	0.42	0.23	0.25	0.01

Crustaceans

3,122 individual crustaceans representing 13 species were observed in 2017. The catch was dominated by shore shrimp, black fingered mud crabs, and long clawed hermit crabs, with those three species accounting for approximately 94% of the total (Figure 1.5).

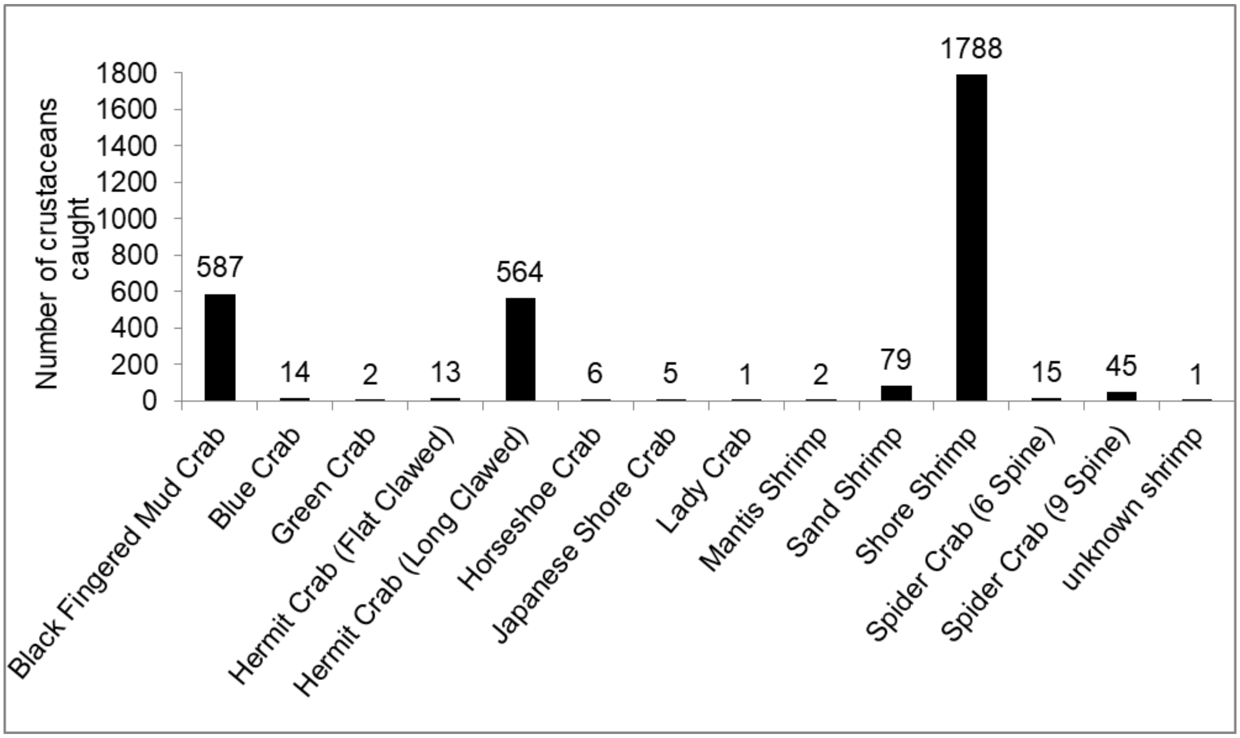

Figure 1.5. Total number of crustaceans caught by species in Norwalk Harbor, May through October 2017.

2. Dissolved Oxygen Surveys

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Norwalk Harbor, Saugatuck Harbor, Five Mile Harbor, Stamford Harbor, Johnson Creek/Lewis Gut Harbors, and Quinnipiac Harbors were studied in 2017. These harbors are used year-round for recreational activities such as boating, swimming, and fishing as well as for commercial activities and play an important role in the Long Island Sound shellfish industry. In 2017, monitoring of these 6 harbors was led by Richard Harris (formerly the Director of Harbor Watch, now on staff at Copps Island Oysters), with assistance from Harbor Watch staff and volunteers.

Dissolved oxygen surveys were conducted to evaluate harbor health and assess their ability to support marine life and in particular shellfish beds. The parameters measured in this study included dissolved oxygen, salinity, water temperature, and chlorophyll *a*.

The harbors monitored in this study are estuaries, which are marine embayments with a fresh water source (resulting in brackish water). The mixing of these freshwater and salt water sources in many harbors consists of a tidal wedge (Figure 2.1), which is comprised of salt water underlying a freshwater surface layer, which is usually incoming water from a river. The more dense salt water layer moves laterally within the harbor in response to the semidiurnal tides. Because of this density-driven stratification within estuaries, the bottom water often becomes depleted of dissolved oxygen. As freshwater moves seaward above the tidal wedge, salt water is entrained in the freshwater layer, reducing the stratification. This mixing of fresh and salt water occurs along the length of a harbor, with the salinity of the surface layer increasing as the distance from the freshwater source increases. Removing salt water from the tidal wedge (Figure 2.1) causes a net flow of fresh marine water to enter the estuary, bringing nutrients and oxygen-rich water with it.

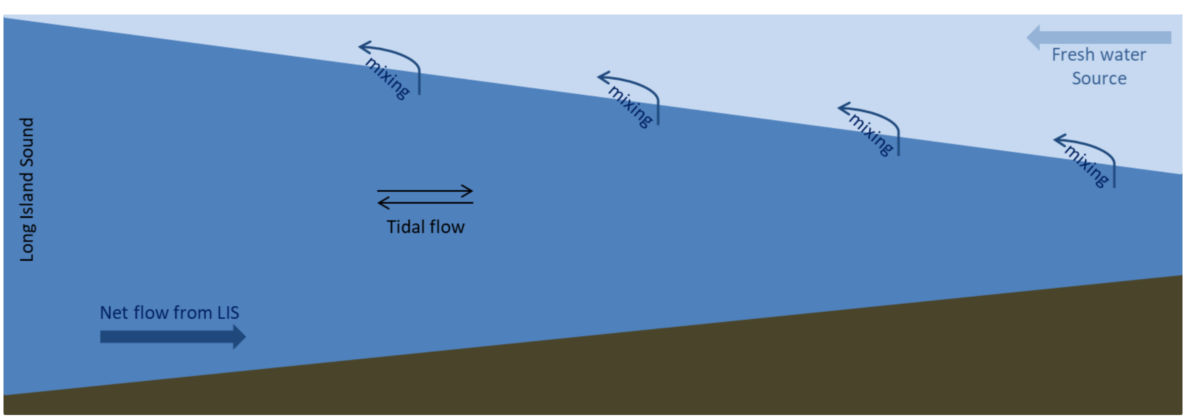


Figure 2.1. Sketch of estuary tidal wedge, water flow, and water column mixing.

Another factor assisting with the flushing of an estuary is the presence of salt marshes. Marshes provide large expanses of low-lying land that serve as a filter for the water flowing over and through them during flood tides. Ebb tides return this large volume of marine water to the main harbor channel, where it is then flushed out of the estuary. Unfortunately, all too often these valuable natural resources are often filled in for shoreline development are replaced with man-made bulk-heading. Two harbors monitored in this study, where large marshlands are present and contribute to flushing efficiency are the Quinnipiac and the Lewis Gut. In many harbor throughout New England, the majority of historic salt marshes have been lost.

Two natural forces that can affect flushing the harbor are winds and air temperature. Strong winds especially from the north facilitate the movement of the surface layer of water seaward, and decreases in air temperatures can drive mixing by increasing the density of the surface water layers causing them to sink. As the surface waters sink, it causes the (often oxygen-depleted) bottom waters to be forced upward. This movement of water can help to increase oxygen concentrations at the bottom.

Rainfall can have negative and positive effects on hypoxia in the harbors. Rain adds water to the system, which increases the flow and turbulence of the water on the surface which is one way for rivers and harbors to capture oxygen. Rain also increases flow within a river system which can cause vertical mixing, in turn increasing dissolved oxygen levels. Conversely, rain can be a conduit for nutrients and other pollutants into a waterway via runoff which negatively impacts dissolved oxygen levels. Excess nutrients can cause plant growth which will initially add oxygen to the system, but as the plants begin to die and decompose, the decomposers consume the available oxygen, resulting in depressed dissolved oxygen conditions.

Rainfall totals varied along the coast. The largest amount of rainfall fell during May averaging 5.4 inches of rain with the smallest accumulation in June with 2.02 inches of rain on average (Figure 2.2). Rainfall totals were highest in the Norwalk area, totaling 20.49 inches from May through September (“Historical Weather”, “Norwalk Health Department Raingauge”). In 2017, rainfall accumulations in Stamford were lower than those 2016, while Norwalk, Bridgeport, and New Haven had slightly higher accumulations during the same time period in 2016. Five Mile River Harbor, Norwalk Harbor, and Saugatuck Harbor rainfall data were based off of rainfall totals recorded at the Norwalk Health Department Rain Gauge.

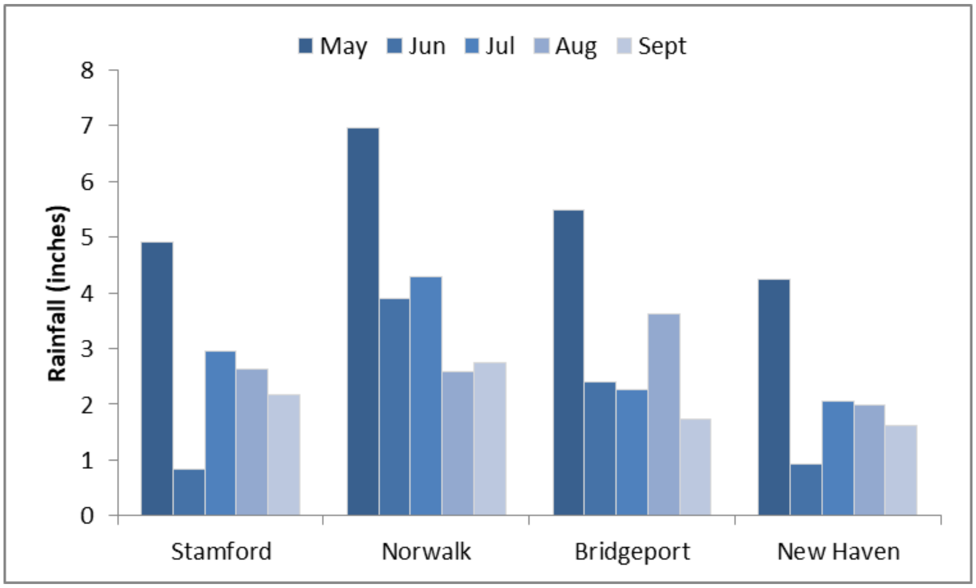


Figure 2.2. Rainfall totals for each geographical area monitored. Stamford, Bridgeport and New Haven precipitation data was collected from Wunderground.com while Norwalk precipitation data was collected from the Norwalk rain gauge.

Chlorophyll *a* can indicate the quantity of phytoplankton in a marine environment, and is used as a measure of the primary productivity of the system. Many different environmental conditions affect the volume of phytoplankton present such as available nutrients, sunlight, temperature and turbidity. Other influential factors can include harbor flushing rates, water depth and the number of grazing animals in the water column. Phytoplankton blooms and seasonal die-off cycles should be considered when conducting a chlorophyll *a* assessment of an estuary (Bricker et al., 2003). The chlorophyll *a* results presented here should be considered a preliminary assessment only for the period of May through September. Additional year-round studies will be needed to fully assess the productivity status of these six harbors using chlorophyll *a*.

Across the 6 harbors studied in 2017, 81% of sampling stations had dissolved oxygen values at the harbor bottom above 3 mg/L for the entire season (Figure 2.3). During the monitoring season, fewer hypoxic events were observed than had been observed in previous monitoring seasons (Crosby et al., 2017a). Norwalk Harbor had the greatest number of sampling days where bottom dissolved oxygen values dropped below 3 mg/L (Figure 2.3). This harbor has a history of poor flushing and extended periods of hypoxia in the upper reaches of the harbor. Hypoxia was not observed in Saugatuck Harbor or Quinnipiac Harbor during this sampling. In the following pages, a detailed analysis of each harbor will be discussed.

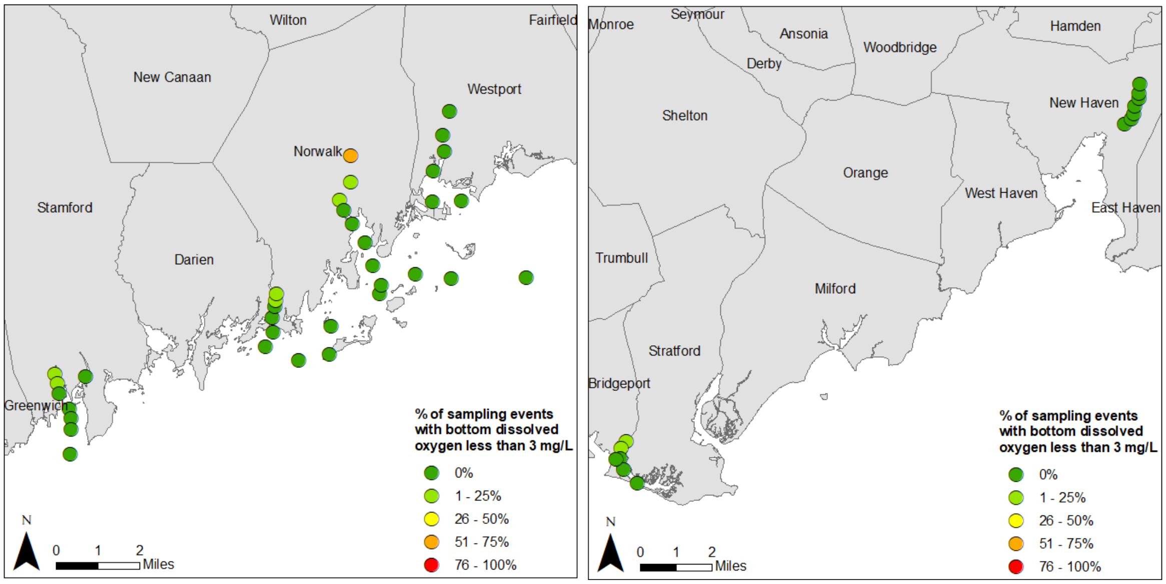


Figure 2.3. Percentage of sampling days where bottom dissolved oxygen values fell below 3 mg/L in the western harbors (left) and the eastern harbors (right).

Methods

Dissolved Oxygen Profiling:
Seasonal monitoring was conducted in each of the six harbors from May through October by Richard Harris accompanied by Harbor Watch staff, high school and college interns, employees of Norm Bloom and Son (Copps Island Oysters), and volunteers. Each harbor had five to eight monitoring stations which were tested a minimum of 6 times. Protocols used in all harbor surveys followed those in Quality Assurance Project Plan (QAPP) RFA #14057 for Norwalk, Five Mile River and Saugatuck Harbors approved by the EPA on 5/30/14 for 5 years.

Testing for each harbor began between 7:00 AM and 8:30 AM on each monitoring day. A research vessel, staffed with a project leader/captain (Richard Harris) and a crew of at least two trained staff or volunteers proceeded to the northernmost station in the estuary to begin testing. The dissolved oxygen meter was calibrated at the first station according to the manufacturer's recommendation (as in the QAPP). The salinity and dissolved oxygen probes were then securely attached to a weighted PVC platform which facilitated vertical descent of the probes into the water column, especially where strong currents existed. The platform was lowered over the side of the research vessel at each station and readings for dissolved oxygen, salinity, and temperature were recorded at the surface. Then the platform was lowered to one half meter below the surface and readings were recorded again. Readings were then then recorded at each full meter interval below the surface until the bottom was reached. Ancillary data collection included readings for barometric pressure (first and last station only), wind speed with a Dwyer wind speed gauge, water clarity with a Secchi disk, air temperature with a Fisher brand pocket thermometer, and a visual estimate of wave height.

Monitoring was conducted sequentially downstream for all stations until each was profiled. The calibration was checked on the dissolved oxygen meter at the end of each survey to assure that significant calibration drift (± 5%) did not occur. Harbor surveys were completed in approximately 2 hours on each monitoring day. Testing in the outer Norwalk Harbor was conducted by trained Coast Guard Flotilla 72 volunteers. The Coast Guard Flotilla 72 volunteers followed the same protocols for data collection, except for the timing of their surveys.

Chlorophyll a *Sampling:*
Chlorophyll *a* samples were collected a minimum of 4 times for each harbor over the course of the monitoring season. On days when samples were collected, two water samples were taken at each station using a grab sampler for collecting a surface sample, and a 2.2 liter silicone Kemmerer water sampler for collecting a sample at 2 meters below the surface. All samples were collected in clean, opaque, one-liter plastic bottles, and stored on ice in a cooler. Upon returning to shore, water samples were transported to the water quality lab at the Norm Bloom and Son oyster facility in East Norwalk. Using a graduated cylinder, 50 mL of water from each sample bottle was poured into a filtration apparatus and vacuumed through a 20 mm glass filter. The filter was then folded in half, wrapped in aluminum foil, and labeled with harbor station information and date of collection. Filters were frozen at -20 °C for storage. The filters

were transported in batches on ice in a cooler to the National Oceanic and Atmospheric Administration Laboratory, Milford, CT to be analyzed for chlorophyll *a* concentrations by Dr. Julie Rose.

Filtered samples were processed at the NOAA Milford Laboratory using a Turner Design Model IDAU filter fluorometer employing a testing method modified by Welschmeyer (1994). Results were compared to the estuarine classification system described in Bricker et al., 2003 (Table 2.1).

Table 2.1. Chlorophyll *a* surface concentrations and resulting classifications for estuaries (from Bricker et al., 2003)

Classification	Concentration µg/L
Hyper-eutrophic	> 60 µg/L
High (eutrophic)	> 20 µg/L, ≤ 60 µg/L
Medium (eutrophic)	> 5 µg/L, ≤ 20 µg/L
Low (eutrophic)	> 0 µg/L, ≤ 5 µg/L

Rainfall:
Rainfall data were collected at individual rain stations and reported online. Rainfall for Norwalk, Saugatuck, and Five Mile River Harbors was assessed using the Norwalk Health Department website ("Norwalk Health Department Raingauge"). Stamford, Bridgeport, and New Haven rainfall was taken from the Weather Underground website ("Historical Weather").

Results and Discussion

A. Stamford Harbor

Stamford Harbor is a large estuary with two freshwater sources. The harbor has two main channels, the east branch and the west branch. The west branch receives the freshwater discharge of the Rippowam River, whereas the east branch receives approximately 24 million gallons per day in discharge of treated effluent from the Stamford waste water treatment plant ("How the Plant Works"). With the exception of differences in fresh water input, both east and west branches are very similar regarding anthropogenic use of the shoreline. Both channels are devoid of any natural riparian features, which have long since been replaced by shoreline fill and commercial bulk-heading that has been punctuated with storm drain outfalls. Large sand and gravel and industrial facilities are located near their northern ends on both branches (Figure 2.A.1). These locations represent the most environmentally sensitive areas of the harbor. Industrial uses require barge deliveries and tug boat traffic can be heavy at times in these restricted waterways. Extra barges are usually anchored near the harbor breakwater. Halfway down both branches and below the industrial sections, there is a dramatic change in land use. The west branch has marinas on both shorelines while the east branch has extensive marinas on its east bank with Koscuiszko Park on the opposite shore.

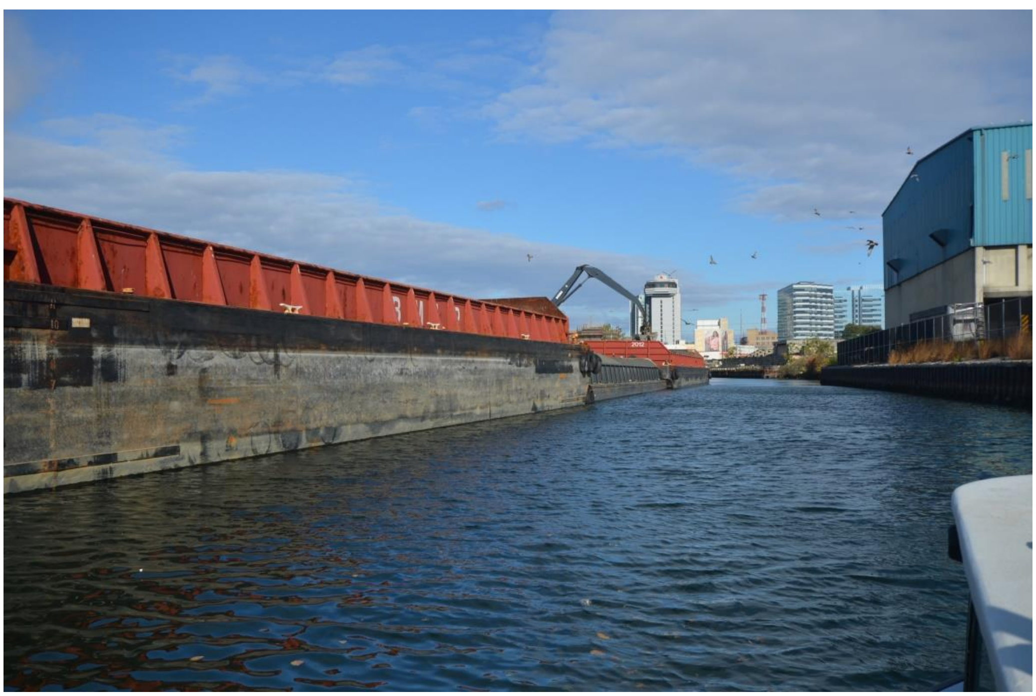


Figure 2.A.1. Industrial development and barge traffic on the east branch of Stamford Harbor.

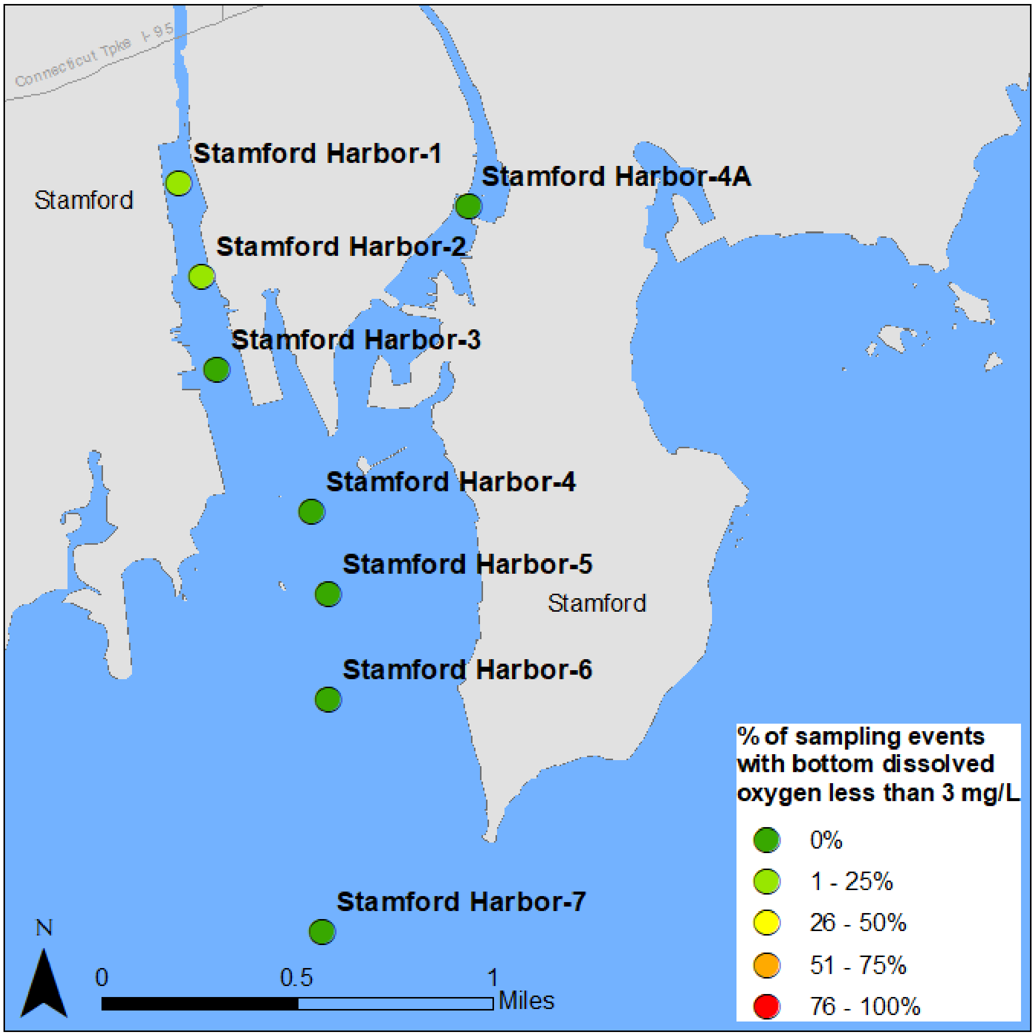


Figure 2.A.2. Map of Stamford Harbor sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 3 mg/L.

Table 2.A.1. Coordinates and descriptions for each sampling station in Stamford Harbor

Site Name	Latitude	Longitude	Description
Stamford Harbor-1	41.041283	-73.545000	Off Sand and Gravel Facility
Stamford Harbor-2	41.037817	-73.543833	Nun Buoy #10
Stamford Harbor-3	41.034350	-73.543083	Can Buoy #7
Stamford Harbor-4	41.029150	-73.538400	Can Buoy #1
Stamford Harbor-4A	41.040500	-73.530850	East branch off Woodland Cemetery
Stamford Harbor-5	41.026100	-73.537550	Can Buoy #9
Stamford Harbor-6	41.022183	-73.537450	Can Buoy #7
Stamford Harbor-7	41.013600	-73.537650	No Wake Buoy

Dissolved Oxygen

Profiles of the water column were taken at 8 sites along the length of the Harbor (Figure 2.A.2, Table 2.A.1). Sampling occurred on 8 days during the monitoring season. Mean dissolved oxygen values in Stamford Harbor ranged from a minimum of 3.81 mg/L on the bottom at Stamford H-1 to a maximum of 7.35 mg/L on the surface at Stamford H-6 (Figure 2.A.3). There were wider differences observed between the surface and bottom dissolved oxygen levels in the upper end of the west channel than the east channel and lower half of the harbor (Figure 2.A.3). Over the course of the monitoring season, there was a general downward trend in dissolved oxygen values at both the surface and the bottom as the summer progressed. Only three individual bottom readings in the upper end of the west channel dropped below 3 mg/L in August on 8/9 and 8/22 (Figure 2.A.4).

Overall, better water quality was observed in 2017 than in 2016. Two factors in particular may have contributed to this change. Differences in rainfall conditions may have increased surface water flow to the east branch as well through the network of existing storm water outfalls (Figure 2.A.6). More freshwater flowing into both channels may have resulted in improved dissolved oxygen levels and lowered salinity. The situation at Stamford H-4A was somewhat different in that the channel always has a circulating system of fresh water based on the continual discharge of treated effluent from the Stamford waste water treatment plant (Figure 2 A.4) of 24 million gallons per day. The second factor may be due to the unseasonably cold weather during late July. Average ambient air temperature dropped 6°C between 7/23 and 7/25 (Appendix 1.1, “Historical Weather”). This weather may have caused cooler surface water temperatures, which then raised the density of the surface layers and increased dissolved oxygen in the water column (Appendix 2.1). In one observed instance, it may have helped to promote downwelling on 7/25 at all 6 of the harbor’s 8 stations (Figure 2.A.4). Harbor waters remained at lower temperature levels for the rest of the summer (Harbor Watch records, data not shown).

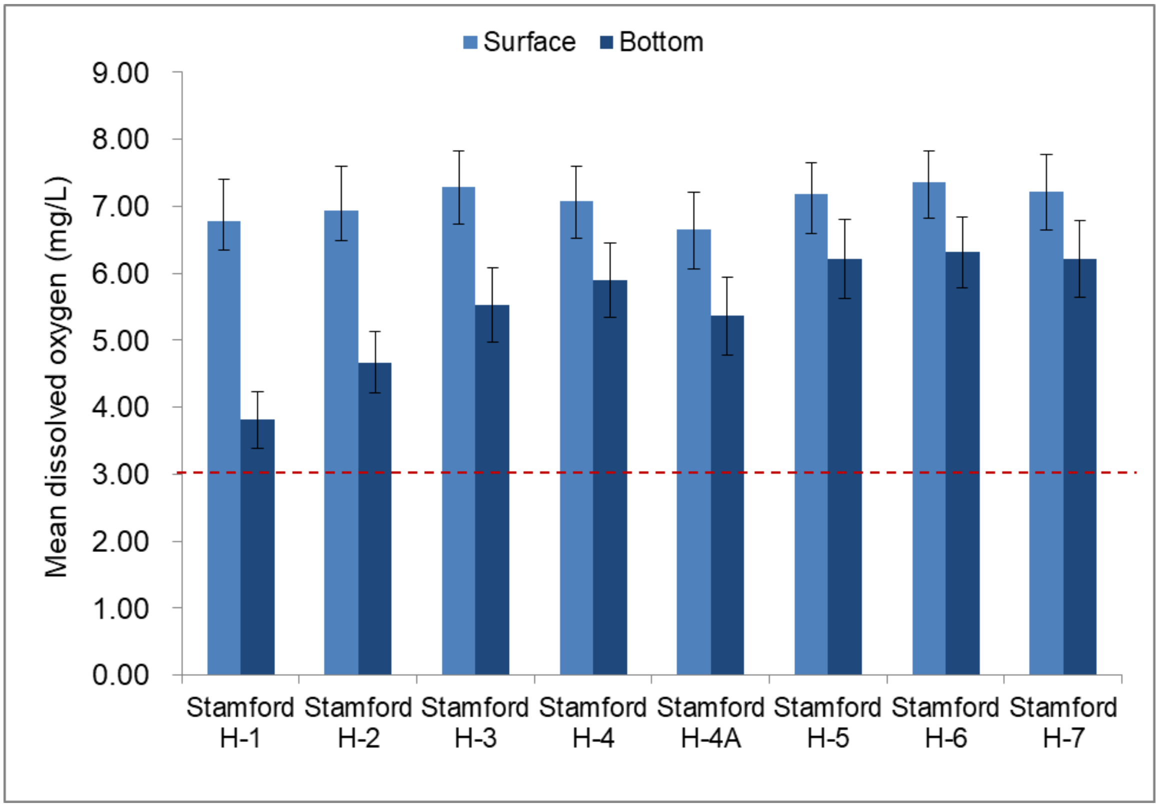


Figure 2.A.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Stamford Harbor. Error bars represent standard error. Dissolved oxygen values below the dashed line indicate hypoxic conditions (less than 3mg/L).

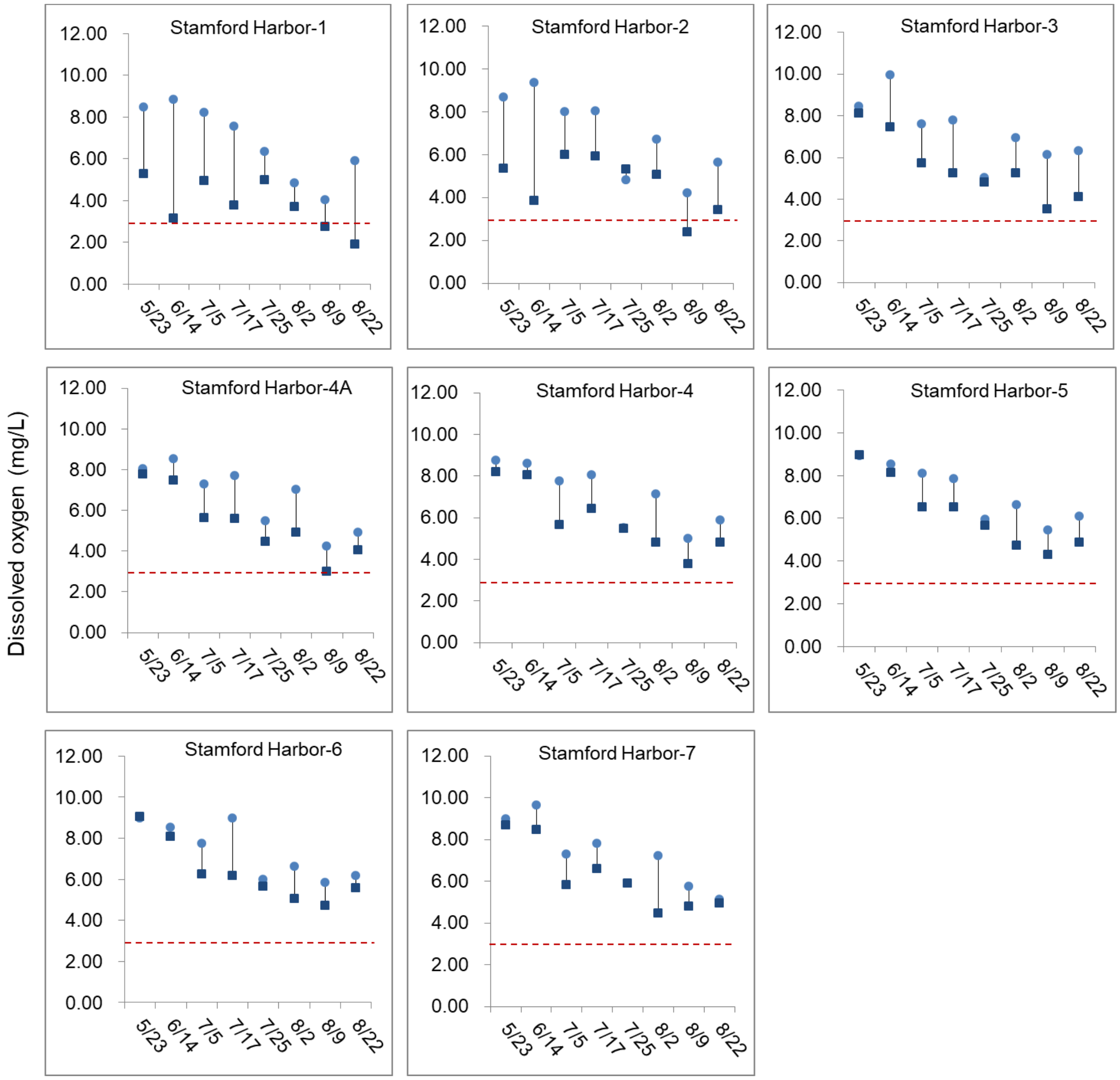


Figure 2.A.4. Surface and bottom dissolved oxygen values at each Stamford Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. The red dashed line represents the threshold for hypoxic conditions (less than 3 mg/L).

Chlorophyll a

Chlorophyll *a* samples were taken on 6/14, 7/5, 7/17 and 8/9. Elevated chlorophyll *a* levels observed on 6/14, 7/5, and 7/17 suggest a large phytoplankton bloom or a sequential series of blooms early in the season, which were observed at Stamford Harbor-I, Stamford Harbor-2, Stamford Harbor-3 and Stamford Harbor-4 (Figure 2.A.5). Elevated levels at these stations may have been caused by a microorganism, *Prorocentrum minas*. This organism was observed on the 6/14 and7/5 monitoring trips with a characteristic dense, smoky color about ½ meter below the surface (R. Harris, personal observations). Dissolved oxygen from photosynthesis may partially account for the elevated dissolved oxygen levels observed in the surface layers of the water column of the northern stations. Based on observations from a total of 8 monitoring days, the harbor would be classified in the highly eutrophic range (> 20 µg/L, ≤ 60 µg/L) for stations Stamford Harbor-1, Stamford Harbor-2 and Stamford Harbor-3 (Figure 2.A.9, Table 2.1). The rest of the harbor stations would fall under the medium eutrophic range (> 5 µg/L, ≤ 20 µg/L; Table 2.1).

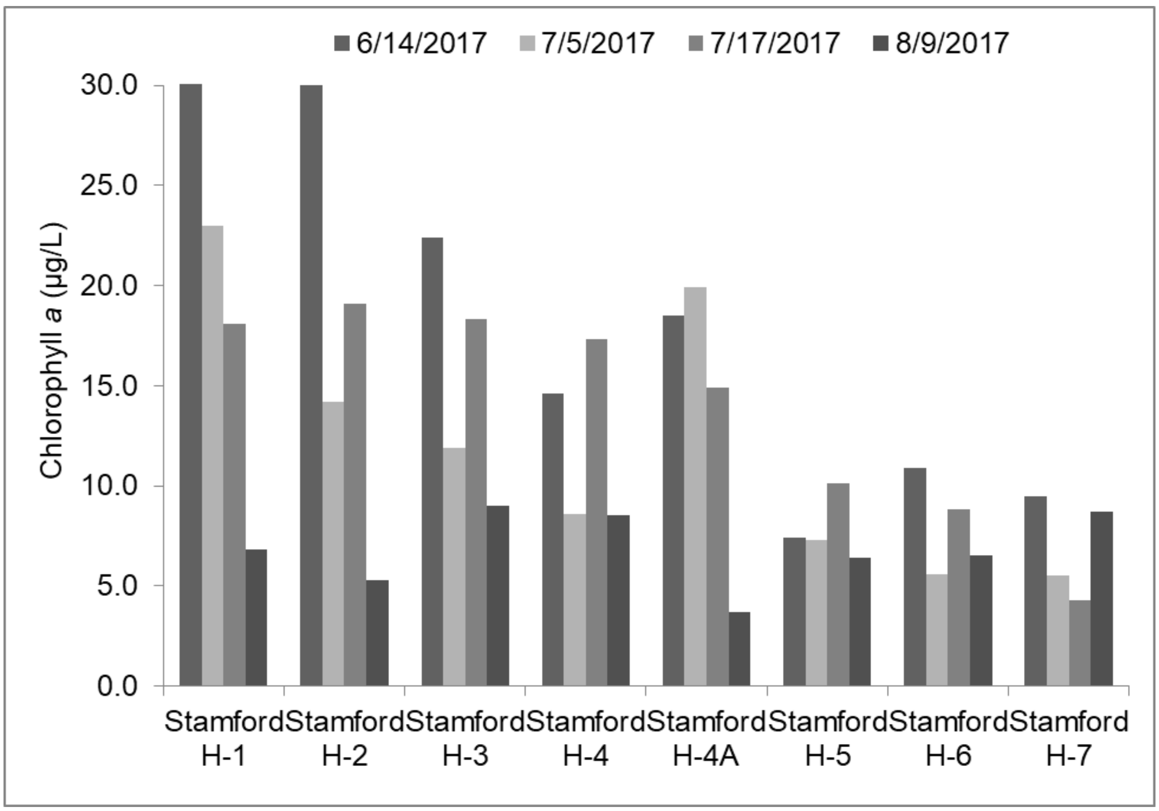


Figure 2.A.5. Average chlorophyll *a* values in Stamford Harbor.

Rippowam River Discharge

The figures below illustrate discharge in cubic feet per second recorded at the United States Geological Survey monitoring station on the Rippowam River in Stamford, CT. Yellow triangles represent the daily median value over the last 20 years, and the blue line represents the recorded discharge for a particular date. In the summer of 2016, discharge was observed to be below historic norms, dipping as low as approximately 1 ft^3/s twice in July and August. For the same time period in 2017, discharge appeared to be closer to historic norms, only dropping to a minimum of approximately 2 ft^3/s at the beginning of September. These figures indicate that flow in the Rippowam River, which discharges to the west branch of the harbor, may have been slightly greater in 2017 than 2016.

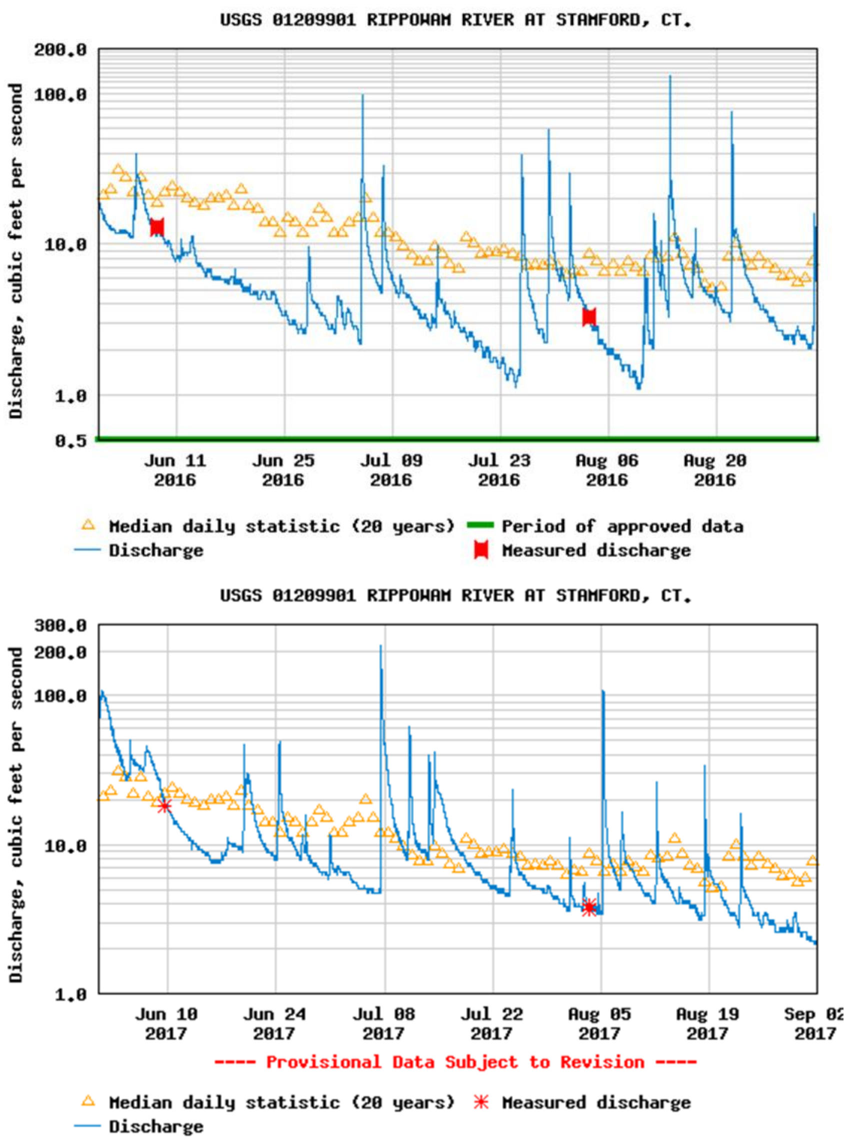


Figure 2.A.6. USGS flow data in $feet^3/s$ for the period of June 1st through August 31st for the 2016 and 2017 respectively for the Rippowam River in Stamford, CT (Graphs courtesy of the U.S. Geological Survey).

B. Five Mile River Harbor

Five Mile River Harbor forms the border between the City of Norwalk and the Town of Darien. It is approximately 2 miles long, and is supplied with fresh water from the Five Mile River with headwaters north of New Canaan, Connecticut. An additional source of fresh water to the estuary is Indian Creek located on the east side of the harbor just north of station FMRH-5 (Figure 2.B.1). Very little salt marsh remains, most of which is located in the Tokeneke cut between stations FMRH-2 and FMRH-1. Land use along the shoreline of the harbor consists primarily of marinas and homes on the Norwalk side with larger single-family homes occupying the Darien side. The east side of the channel has been dredged by the U.S. Coast Guard for slips and moorings up to station FMRH-5, while the west side of the estuary remains too shallow to accommodate most vessels at low tide.

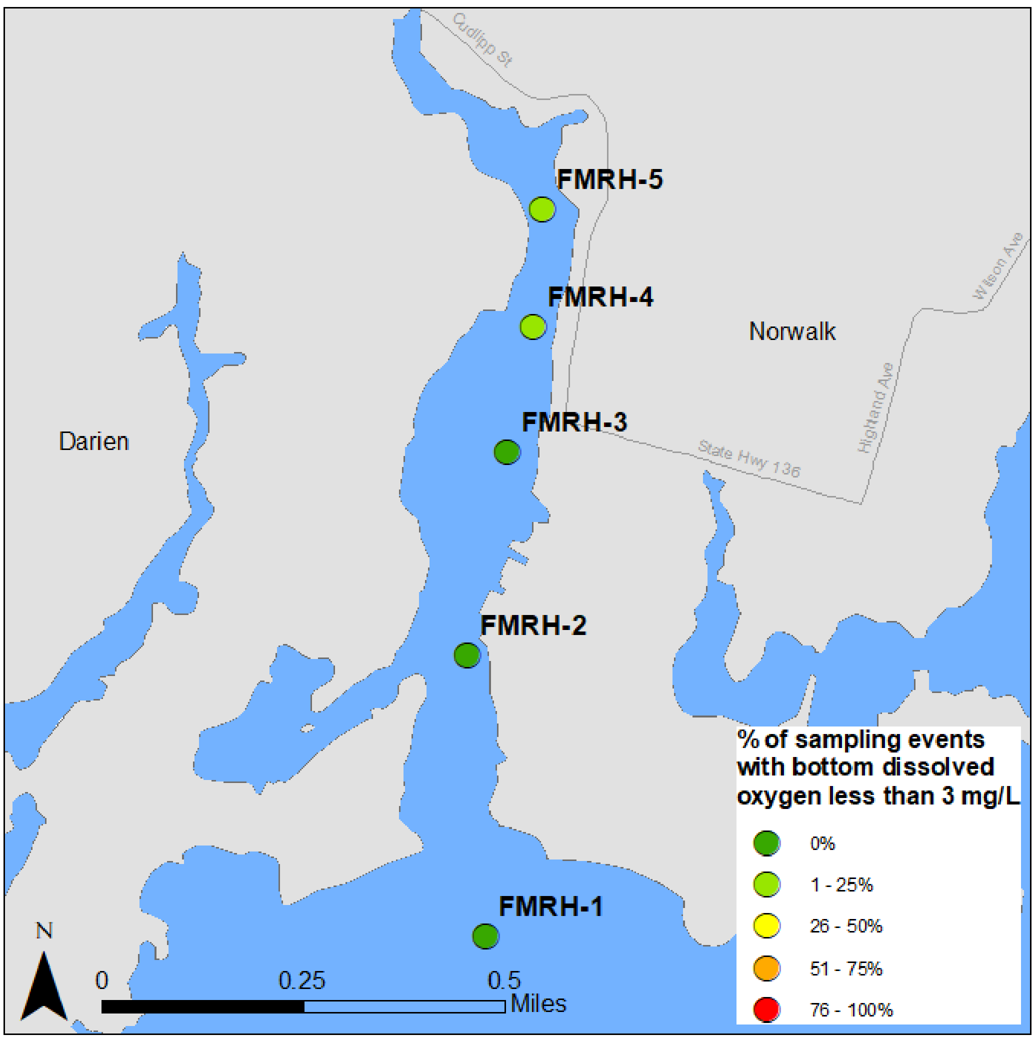


Figure 2.B.1. Map of Five Mile River Harbor sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 3 mg/L.

Table 2.B.1. Coordinates and descriptions for each sampling station in Five Mile River Harbor

Site Name	Latitude	Longitude	Description
FMRH-1	41.056250	-73.445767	Buoy 4
FMRH-2	41.061317	-73.446250	Buoy 6
FMRH-3	41.064967	-73.445317	Five Mile River Works
FMRH-4	41.067233	-73.444733	DownUnder Kayaking dock
FMRH-5	41.069333	-73.444550	Mouth of Indian Creek

Dissolved oxygen

Profiles of the water column were taken at 5 sites along the length of the Harbor (Figure 2.B.1, Table 2.B.1). Monitoring occurred on 8 days during the monitoring season. Surface and bottom dissolved oxygen concentrations at all sites had mean values above 6 mg/L (Figure 2.B.2). For comparison, during the 2016 season the observed dissolved oxygen mean for station FMRH-5 was 4.6 mg/L at the bottom and 5.3 mg/L at the surface (Figure 2.B.4). The average dissolved oxygen at the other four stations ranged from 5.2 mg/L to 5.8 mg/L in 2016 at the bottom. The average surface dissolved oxygen in 2016 at stations FMRH-4 to FMRH-2 exceeded 6 mg/L with only station FMR-1 exceeding 7 mg/L (Crosby et al., 2017a).

One factor contributing to improved dissolved oxygen levels in 2017 could be an increase of fresh water flow from the Five Mile River based on stream gauge heights (Figure 2.B.6). A second factor could be atypically cool weather conditions. Ambient air temperatures dropped as much as 6 °C in late July (Appendix 1.1, "Historical Weather"). Water temperature at the 5 stations from July to August had lower temperatures relative to similar sampling dates in 2016 and consequently more dissolved oxygen could have mixed into the surface layers (Figure 2.B.2, Figure 2.B.3, Appendix 2.2). Nevertheless, dissolved oxygen concentrations decreased from June to August (Figure 2.B.3). Sampling of this harbor was not conducted in September, but dissolved oxygen concentrations increased with the cooler weather in Norwalk and Saugatuck Harbors which had longer survey periods (Section C and D of this report).

On 5/19 and 7/31, at all 5 stations the lowest dissolved oxygen concentrations were observed at the surface of the water column while the highest dissolved oxygen values were found at the bottom, which is opposite of the typical pattern in the water column (Figure 2.B.3). This may have been due to unusual changes in the air temperature which rose from 20.6 °C on 5/14 to 31.7 °C on the test date of 5/19 and 21.1 °C on 7/25 to 28.3 °C on the test date of 7/31 (Appendix 1.1, "Historical Weather"). This could have resulted if the river water entering the harbor was warmer and thus had less dissolved oxygen. Over the course of the monitoring season, there was a general downward trend in dissolved oxygen concentrations at both the surface and the bottom as the summer progressed. Only two individual bottom readings in the upper end of the harbor dropped below 3 mg/L on 8/21 (Figure 2.B.3).

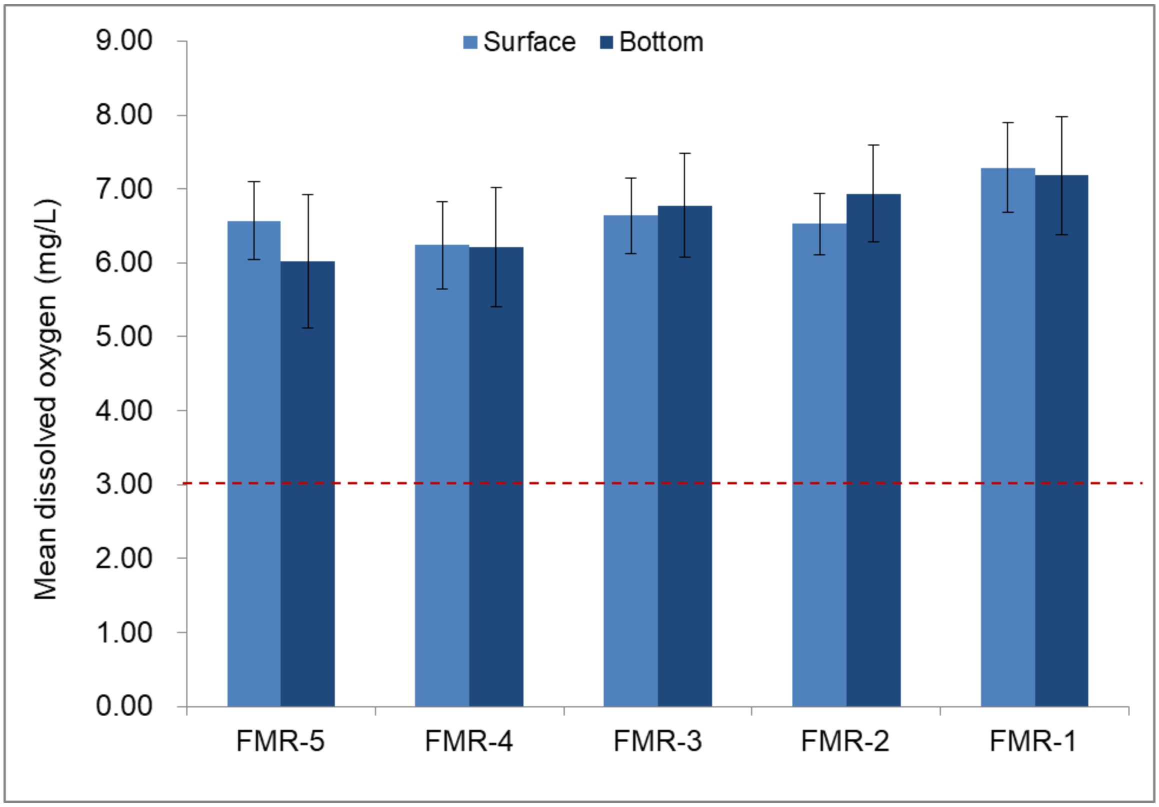


Figure 2.B.2. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Five Mile River Harbor. Error bars represent standard error. Values below the red dashed line indicate hypoxic conditions (less than 3mg/L).

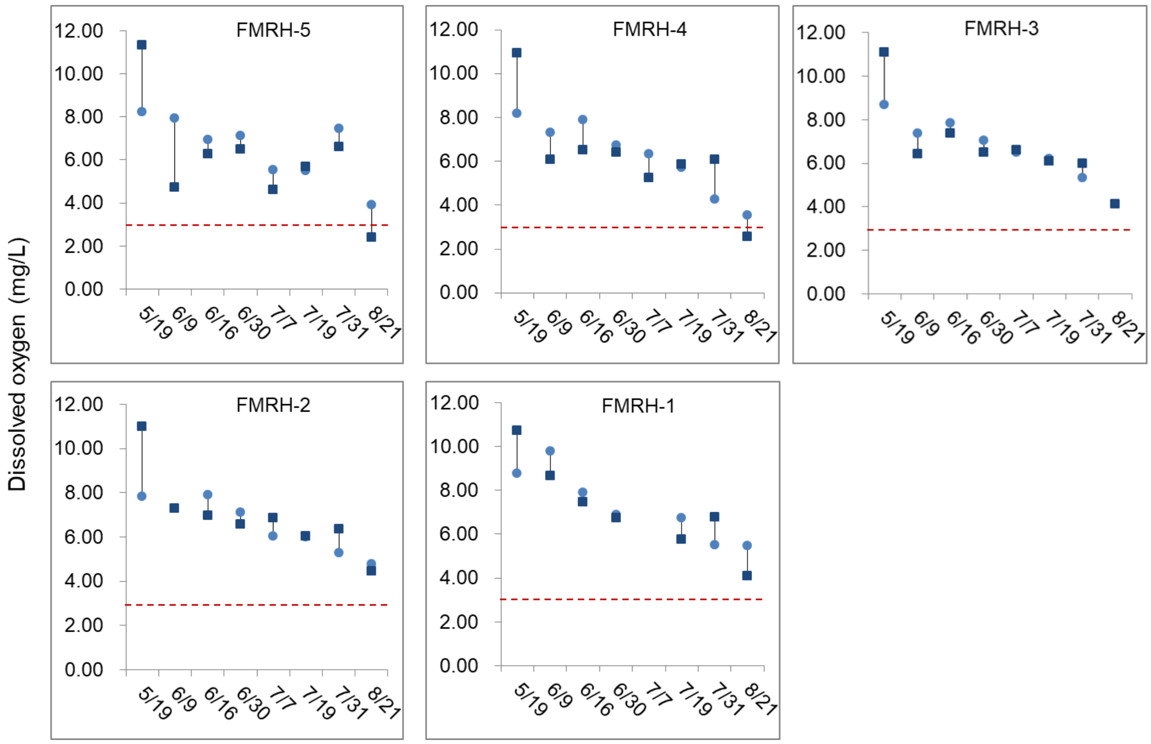


Figure 2.B.3. Surface and bottom dissolved oxygen values at each Five Mile River Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. The red dashed line represents 3 mg/L where hypoxia begins.

Chlorophyll a

Chlorophyll *a* samples were taken on 7/7, 7/19, 7/31 and 8/31. Four dates of testing show that all monitoring stations had chlorophyll *a* concentrations within the medium euphotic range (> 5 µg/L, ≤ 20 µg/L; Figure 2.B.4, Table 2.1). One exception is 8/31 where a phytoplankton bloom observed at station FMRH-5 appeared to have impacted stations downstream, with the station FMRH-2 sample having an atypically high value of 28 µg/L. This one chlorophyll *a* value temporarily raised the classification to highly eutrophic for station FMRH-2 (> 20 µg/L, ≤ 60 µg/L; Table 2.1). Rainfall of 0.22 inches fell 2 days prior to testing on 8/31 which may have added nutrients to the harbor waters and accelerated the bloom ("Norwalk Health Department Raingauge"). Results from the 2017 study were similar to those observed during the 2016 season (Crosby et al., 2017a).

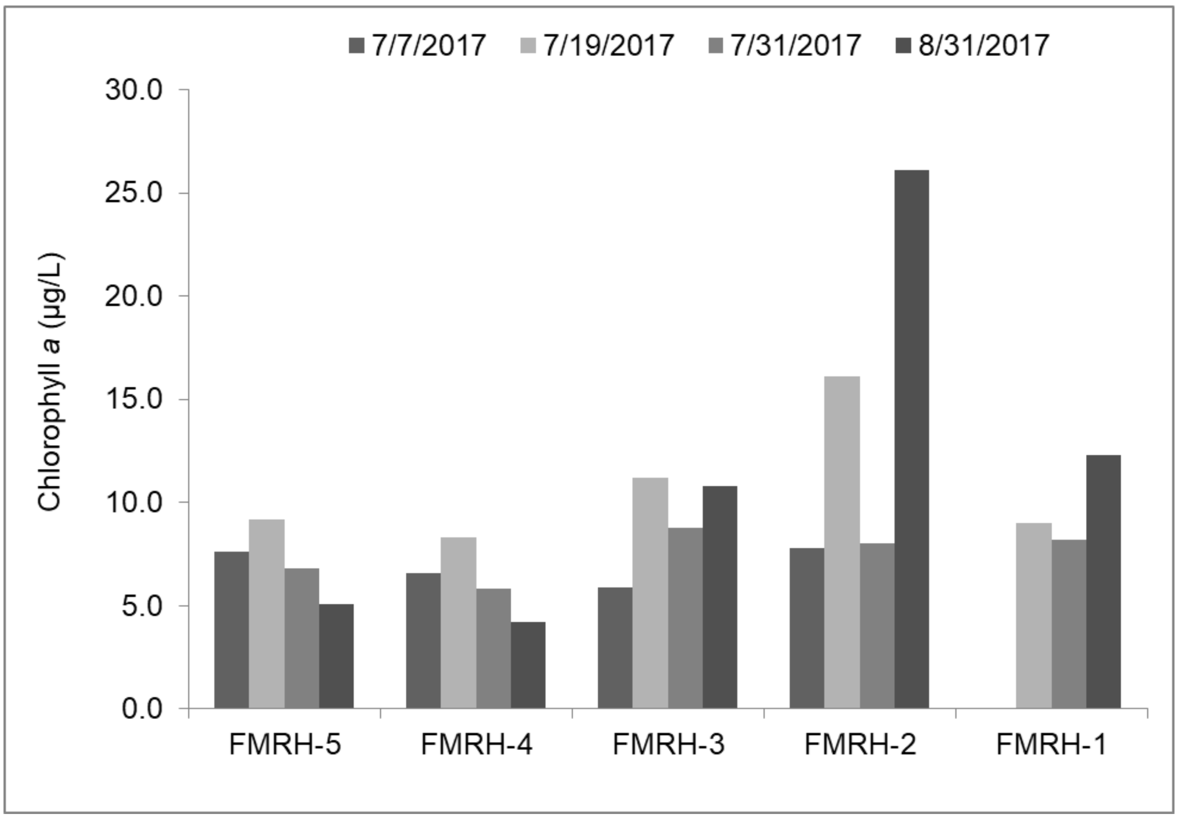


Figure 2.B.4. Average chlorophyll *a* values in Five Mile River Harbor. Data from FMRH-1 on 7/7 was not available.

Stream Gauge Height in Five Mile River

The figures below illustrate stream gauge height in feet recorded at the United States Geological Survey monitoring station on the Five Mile River in New Canaan, CT. The blue line represents the recorded gauge height. In 2016, gauge height reached a maximum of approximately 2.3 ft in early May while in 2017 the gauge reached peaks above 2.5 on multiple occasions through the end of June. Towards the end of the monitoring season, both years had gauge heights drop to around 1.8 ft. These figures indicate that flow in the Five Mile River may have been slightly greater in 2017 than 2016. This may be due to increased rainfall in the watershed in 2017.

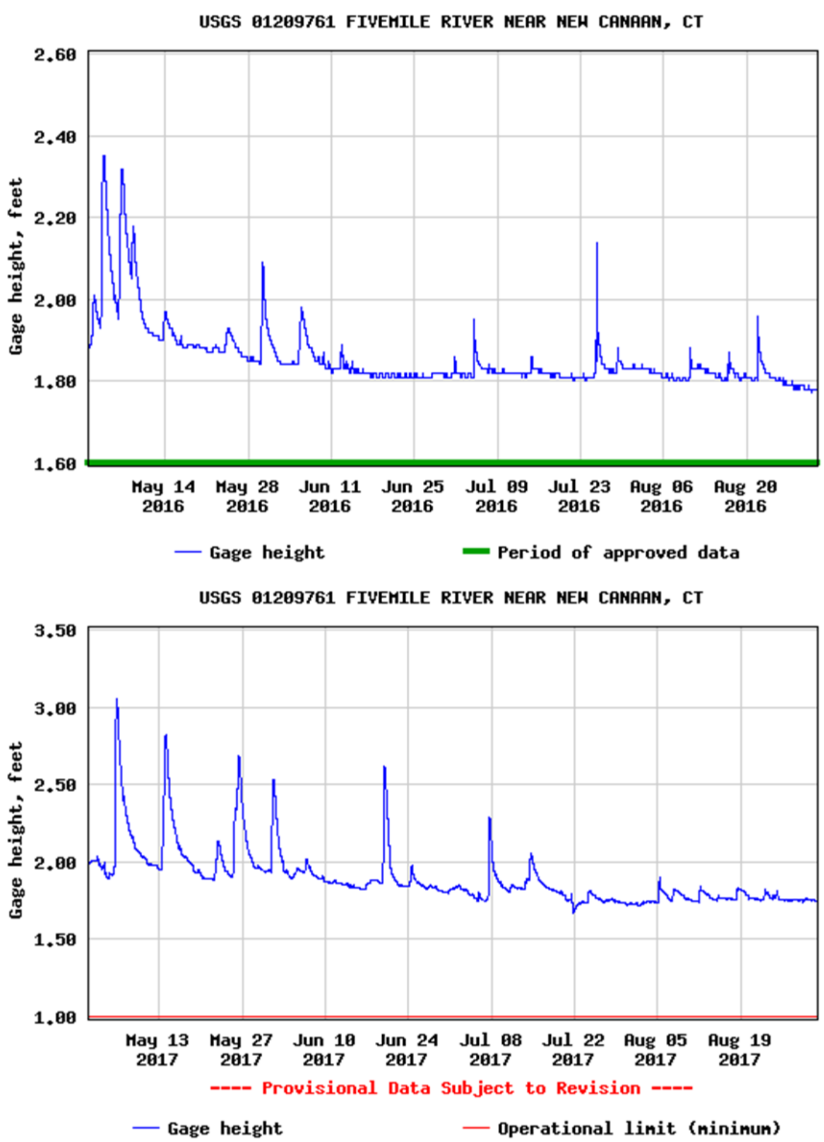


Figure 2.B.5. USGS stream gauge height for the period of May 1st through August 31st for the 2016 and 2017 respectively for the Five Mile River in New Canaan, CT (Graphs courtesy of the U.S. Geological Survey).

C. Norwalk Harbor

Norwalk Harbor, located in Norwalk, CT, is fed with freshwater from the Norwalk River. The harbor once had extensive acres of wetlands on both shorelines (Figure 2.C.1) which have now been filled in or removed and replaced with hardened shoreline to accommodate shipping for the many industrial and commercial businesses located along the shores. Land use around the edges of the harbor include landfills, marinas, and housing developments ranging from high density apartments to medium sized single-family homes.

Two sections of the harbor will be discussed. The inner harbor, which includes the length of the estuary (Figure 2.C.2) from Wall Street to the Norwalk Islands, included 8 monitoring stations. The outer harbor (Figure 2.C.2) had 8 additional monitoring stations that covered the area from just outside the mouth of Five Mile River Harbor east along the apron of Norwalk Harbor to a point just south of the Norwalk Islands off of Westport.

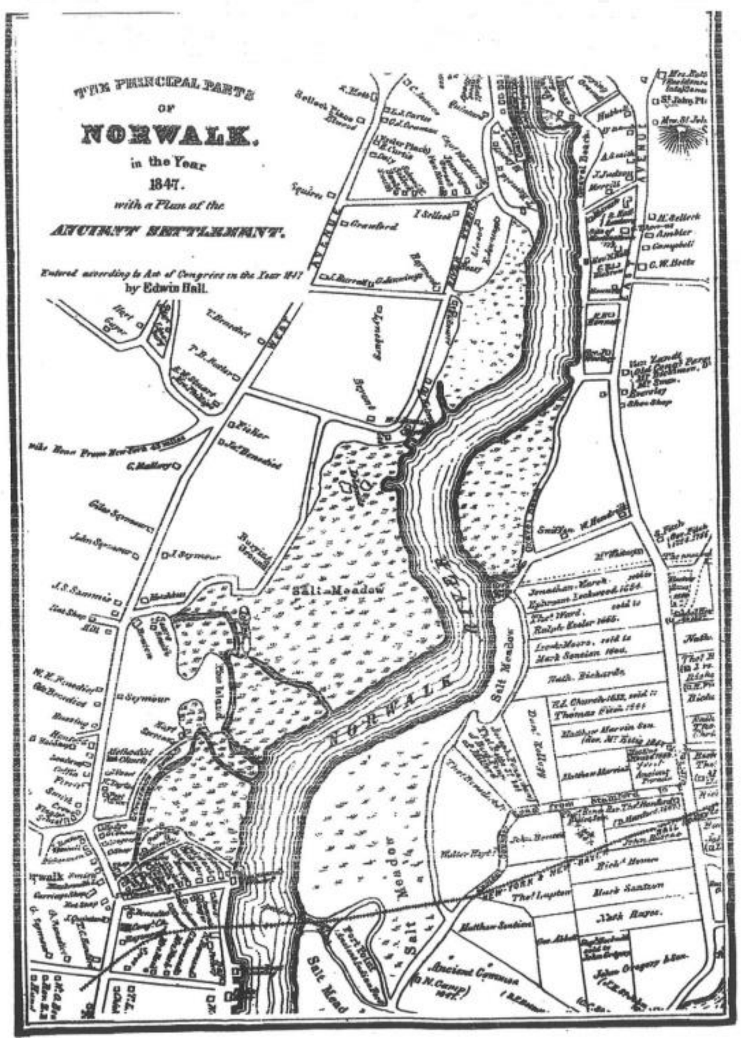


Figure 2.C.1. Norwalk Harbor estuary in 1847. Extensive wetlands once dominated both shorelines. Image credit: Norwalk Historical Society.

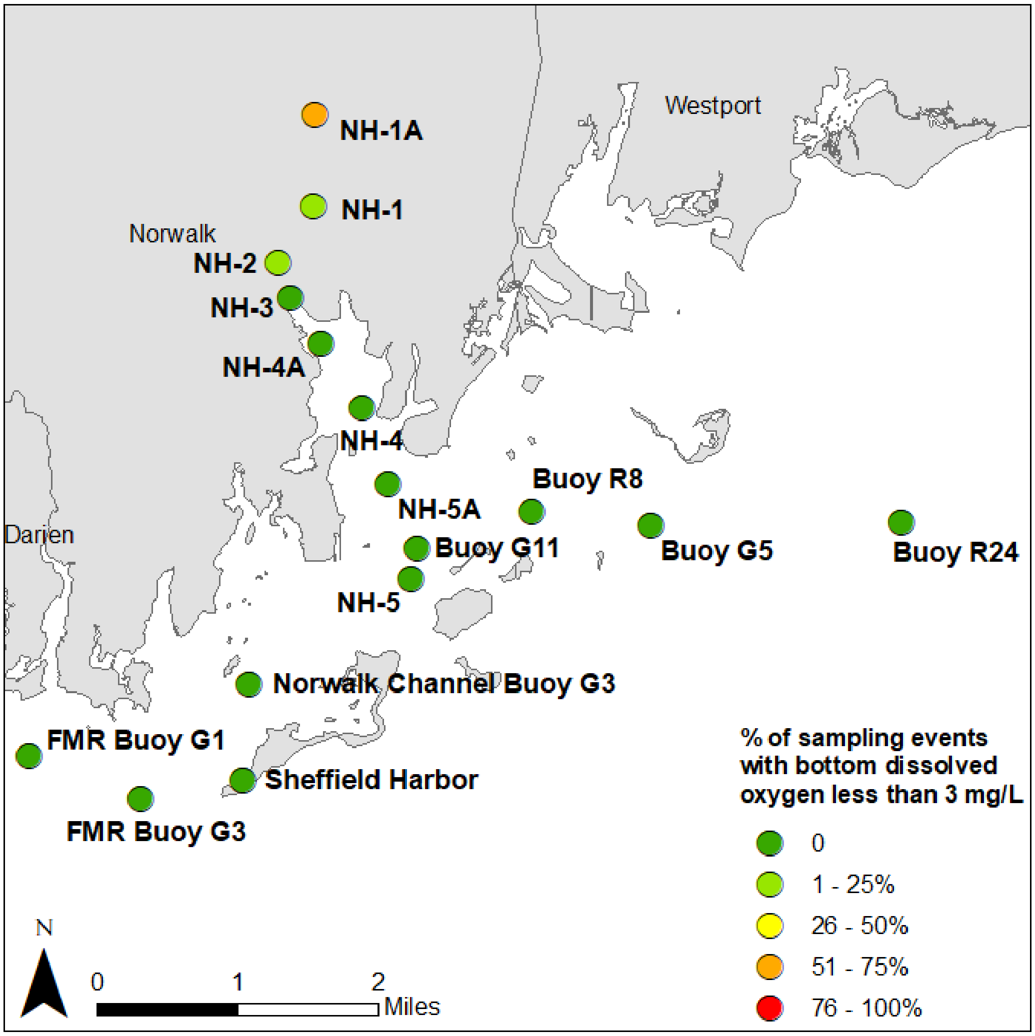


Figure 2.C.2. Map of Norwalk Harbor sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 3 mg/L.

Table 2.C.1. Coordinates and descriptions for each sampling station in Norwalk Harbor

Site Name	Latitude	Longitude	Description
NH-1A	41.117389	-73.411056	Wall Street
NH-1	41.108000	-73.411167	I-95 Bridge
NH-2	41.102056	-73.416000	Maritime Aquarium dock
NH-3	41.098472	-73.414194	Public boat launch
NH-4A	41.093861	-73.410028	Ischoda Yacht Club moorings
NH-4	41.087278	-73.404250	Buoy 19
NH-5A	41.079402	-73.400727	Buoy 15
NH-5	41.069611	-73.397472	Oyster stakes off Shae Island
Buoy G11	41.0728	-73.396617	Buoy G11
Buoy R8	41.07665	-73.38115	Buoy R8
Buoy G5	41.075233	-73.364867	Buoy G5
Buoy R24	41.075733	-73.33065	Buoy R24
Norwalk Channel Buoy G3	41.058583	-73.419433	Norwalk Channel Buoy G3
Sheffield Harbor	41.04875	-73.420217	Sheffield Harbor
FMR Buoy G3	41.046667	-73.434083	FMR Buoy G3
FMR Buoy G1	41.051083	-73.449417	FMR Buoy G1

Inner Harbor Dissolved oxygen

Profiles were taken in the inner harbor at 8 sampling stations. Sampling occurred 20 times between May and October 2017. Mean dissolved oxygen concentrations ranged from a minimum of 2.92 mg/L at the bottom at station NH-1A to a maximum of 7.27 mg/L at the surface at station NH-4 (Figure 2.C.3). Wide ranges in dissolved oxygen concentrations at the surface and bottom were observed in most of the upstream sampling locations (Figure 2.C.3, Figure 2.C.4). In the sampling locations further seaward in the harbor, the difference in concentrations was lower, presumably from the wider area of the harbor and increased mixing reducing stratification. The upper 3 stations, NH-1A, NH-1 and NH-2 likely had a highly stratified water column throughout the season driven by a steady flow of fresh water entering the harbor from the Norwalk River (Figure 2.C.8). This stratification led to station NH-1A consistently being the site with the most impaired water in the harbor for dissolved oxygen. As the fresh water moved seaward, mixing increased, in particular near station NH-2 with 18 million gallons per day of treated effluent being discharged from the Norwalk waste water treatment plant (Figure 2.C.2, WPCA Norwalk). The 3 upper harbor sites have historically experienced prolonged periods of hypoxia because they have limited flushing and are often exposed to a variety of inputs from storm drain networks and anthropogenic waste on the harbor bottom. Water columns at stations south of NH-4A exhibited less stratification as the fresh water became increasingly diluted. Typically, dissolved oxygen concentrations tend to decrease when air temperatures rise as the summer progresses. This year, however, unseasonably cooler weather occurred in late summer, which may have increased surface water cooling especially at night (Appendix 1.1, “Historical Weather”, Appendix 2.3). Cooler surface water can sink and create downwelling circulation, which could have aided in adding dissolved oxygen to the water column (Figure 2.C.4).

Throughout the monitoring season, dissolved oxygen values decreased as the summer progressed (Figure 2.C.4). Exceptions to this were 6/16 and 9/19 where both surface and bottom temperatures were elevated, possibly due to photosynthetic activity. A dinoflagellate bloom, *Prorocentrum micans*, occurred in June for approximately two weeks and was visible as large brown clouds in the harbor waters. Samples confirming the species present were collected by Richard Harris and identified by Dr. Gary Wikfors at the NOAA laboratory in Milford, CT. The second observed event was a bloom of an unidentified species which only persisted for several days in early September.

The 2017 summer season showed some improvement in water quality as evidenced by mean dissolved oxygen values that exceeded 2016 values by up to 1 mg/L at most of the 8 monitoring stations (Crosby et al., 2017a). Although station NH-1A remains as the most impaired site in the estuary due to the impact of variable flow from the Norwalk River and the proximity of known pollution sources, an observed mean dissolved value of 2.92 mg/L at the bottom water column was an improvement over recent years (Figure 2.C.3, Figure 2.C.4). As a testament to the improved water quality at station NH-1A, a school of hundreds of menhaden was observed congregating at the station for several weeks at the end of August without any apparent adverse effect. Fish kills have been a routine occurrence during the summer in the Norwalk estuary, though fewer have been observed since 2005 (R. Harris, personal observation).

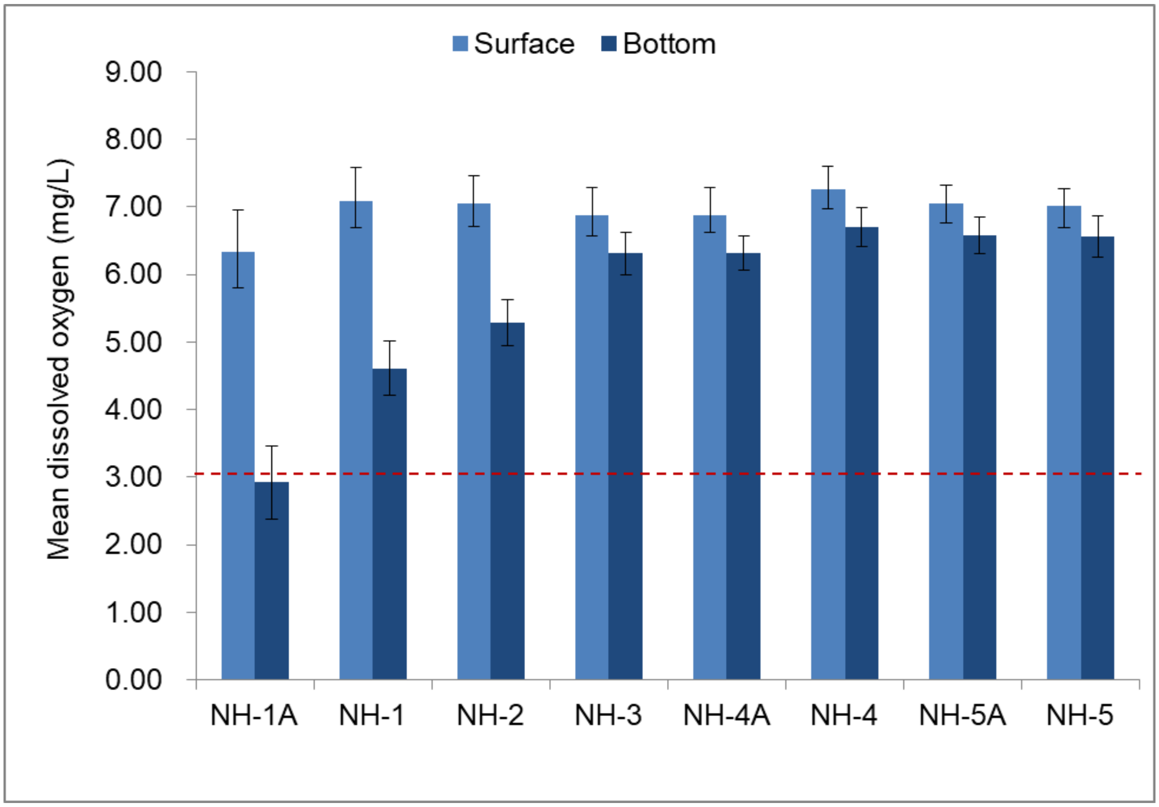


Figure 2.C.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Norwalk Harbor. Error bars represent standard error. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

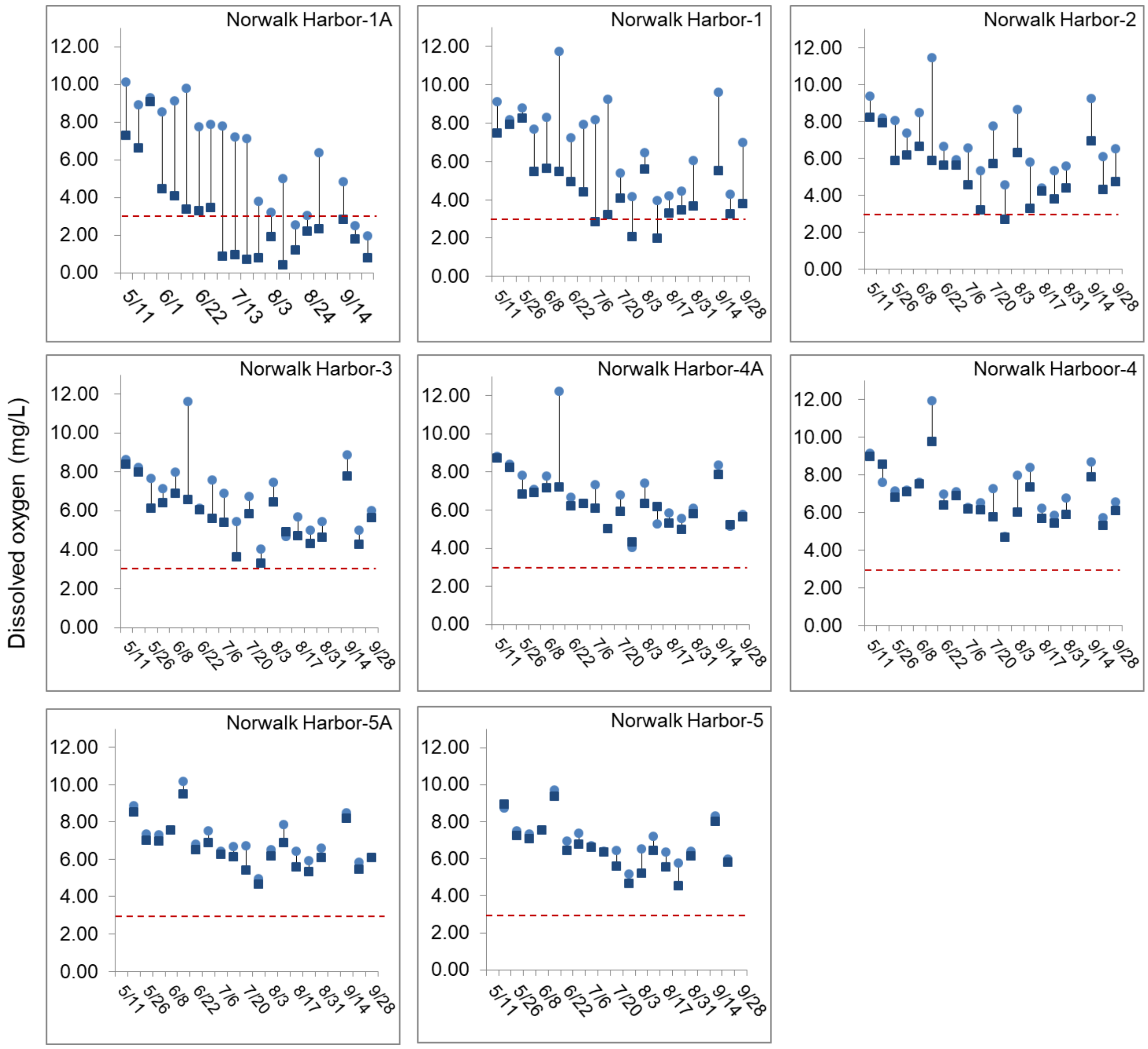


Figure 2.C.4. Surface and bottom dissolved oxygen values at each Norwalk Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

Outer Harbor Dissolved Oxygen

Profiles in the outer harbor were conducted on 7 days at a subset of 8 sampling locations each day by Coast Guard Flotilla 72 members. Dissolved oxygen levels observed in this area can be indicative of whether dissolved oxygen-impaired water may enter the harbor from the east or west between the Norwalk Islands and the mainland. It is important to note that the data collected for the outer harbor sites was collected in the evenings rather than the early morning. Mean bottom dissolved oxygen values at all stations except station R24 exceeded 6.0 mg/L. All mean surface dissolved oxygen values with the with the exception of station Buoy G5 met or exceeded 7 mg/L (Figure 2.C.5, Figure 2.C.6). Results were similar to what was observed at these same stations in 2016. Water quality in this area remained good during the monitoring period with only a slight decline in dissolved oxygen into August (Figure 2.C.6). All dissolved oxygen concentrations were observed to be above 3 mg/L on each sampling day. This may have been the result of the fact that, as mentioned above, the outer harbor sampling was conducted in the evening when dissolved oxygen concentrations tend to be at their highest due to a full day of activity by photosynthetic organisms in the water column.

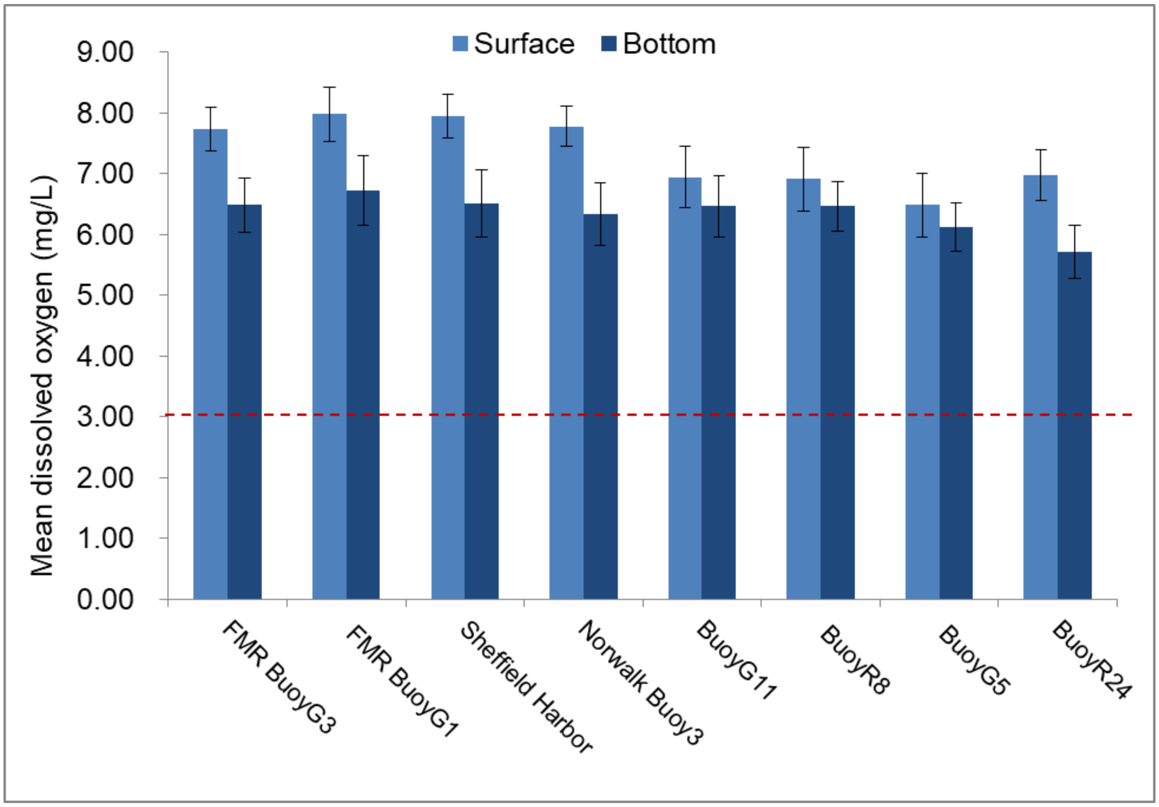


Figure 2.C.5. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in the Outer Norwalk Harbor with sampling conducted during the evening. Error bars represent standard error. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

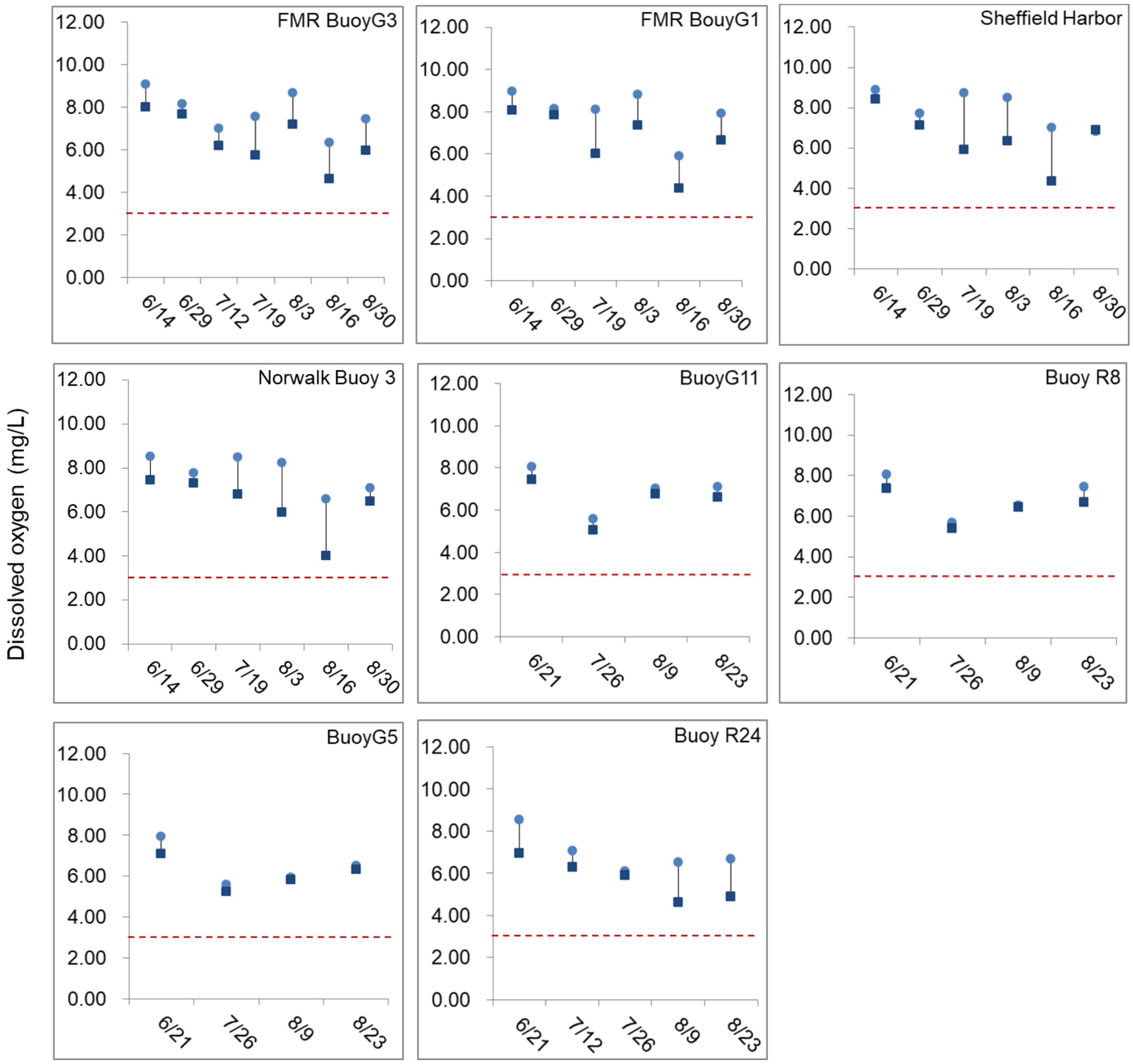


Figure 2.C.6. Surface and bottom dissolved oxygen values at each outer Norwalk Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

Chlorophyll a

Water samples for chlorophyll *a* monitoring were collected during 4 monitoring events on 6/8, 6/15, 7/13 and 8/3 at each of the inner harbor stations. On all 4 dates, dissolved oxygen levels were observed to increase in the surface layers of the water column, likely due to the release of dissolved oxygen during photosynthesis (Figure 2.C.4). The increase was substantial on 6/15 at the time *Prorocentrum micans* was identified in the harbor waters (G. Wikfors, personal communication). This dinoflagellate was observed in the harbor during same time period in the 2016 season. It appeared as patches of black clouds just below the surface and lasted for about 2 weeks. This dinoflagellate may have a toxic form during some phase of its development but no adverse effects were observed in Norwalk Harbor (G. Wikfors, personal communication). There were possibly additional phytoplankton blooms on 7/13, 8/3 and 8/31 from unidentified species. The harbor was classified as medium eutrophic (> 5 µg/L, ≤ 20 µg/L) according to the Bricker scale with one documented excursion into the high eutrophic category (> 20 µg/L, ≤ 60 µg/L) observed at stations NH-1 and NH-2 on 8/3/17 (Figure 2.1).

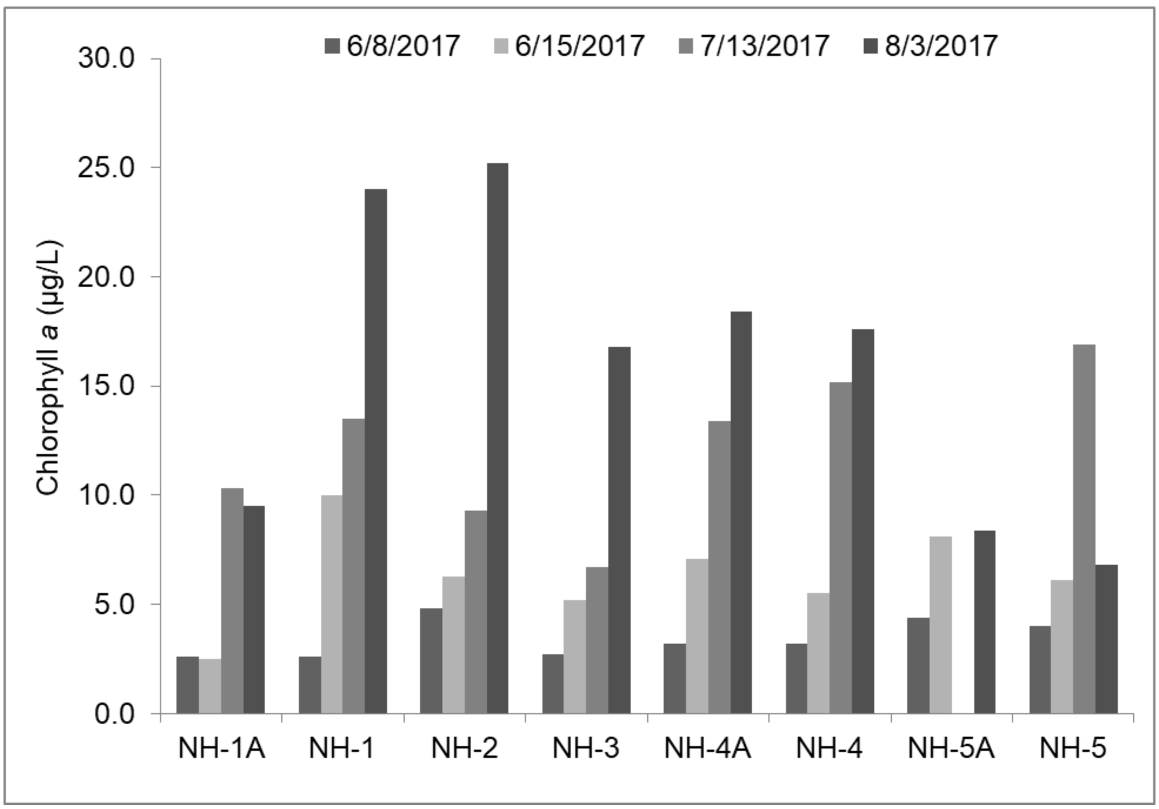


Figure 2.C.7. Average chlorophyll *a* values in Norwalk Harbor.

Norwalk River Discharge

The figures below illustrate discharge in cubic feet per second recorded at the United States Geological Survey monitoring station on the Norwalk River in South Wilton, CT. Yellow triangles represent the daily median value over the last 54 years, and the blue line represents the recorded discharge for a particular date. In the summer of 2016, discharge was observed to be below the historic norm into July, dipping as low as approximately 4 ft^3/s. For the same time period in 2017, discharge appeared to be closer to historic norms, dropping to approximately 4 ft^3/s at the beginning of August, a about month later than 2016 records. These figures suggest that flow in the Norwalk River may have been slightly greater in 2017 than 2016. This increase in flow may be related to the increase in rainfall totals over 2016.

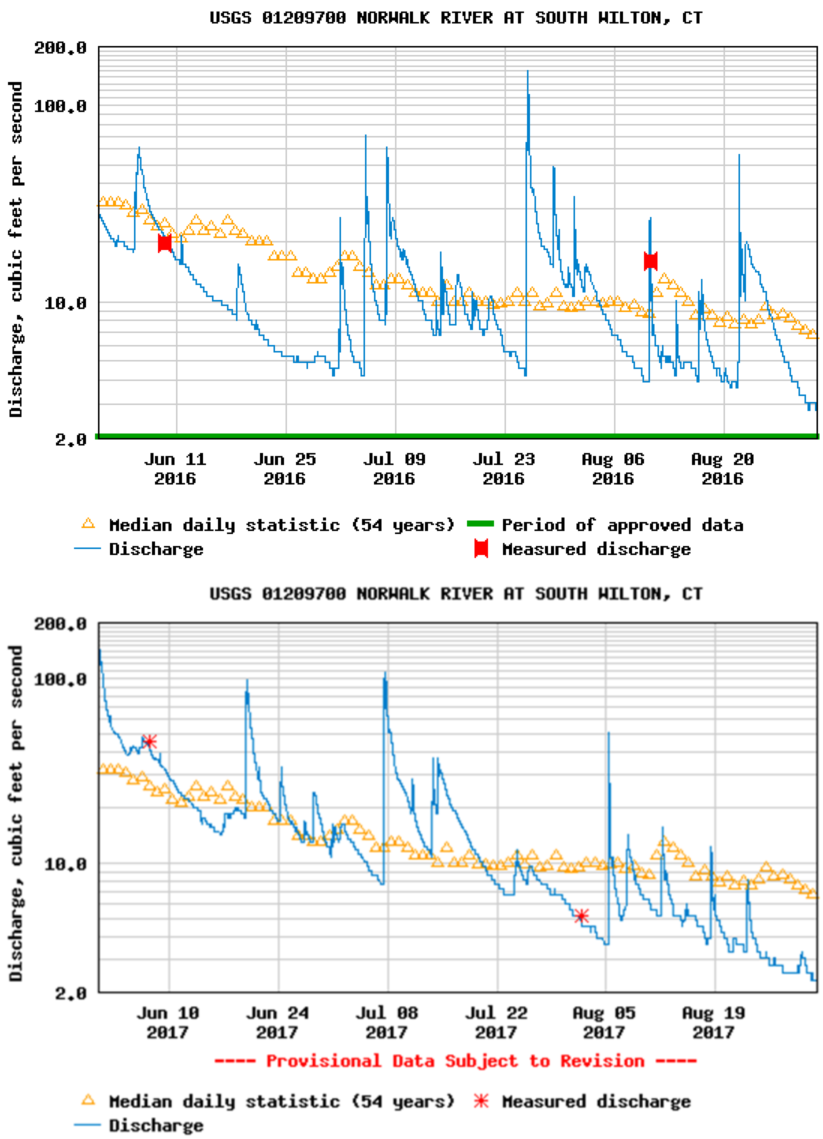


Figure 2.C.6. USGS flow data in $feet^3/s$ for the period of June 1st through August 31st for the 2016 and 2017 respectively for the Norwalk River in South Wilton, CT (Graphs courtesy of the U.S. Geological Survey).

D. Saugatuck Harbor

Fed by the Saugatuck River, Saugatuck Harbor is approximately three miles long and relatively narrow with the exception of two basins. The first of these is a large basin located approximately ¼ of a mile below the Route 1 bridge (Figure 2.D.1). The second smaller basin is located just to the north side of the I-95 bridge (Figure 2.D.2). The estuary then broadens into a large but shallow harbor ¼ mile downstream from the Metro North railroad bridge (Figure 2.D.1). The land area on both sides of the upper estuary and the main harbor is almost fully developed. The commercial area of the Town of Westport borders the northeastern side of the harbor above the Route 1 bridge. From this point moving southward the east bank of the harbor is developed with large single-family homes that continue to the Longshore Country Club area and to the Compo Boat Basin Marina. The west bank of the harbor is developed with a mixture of commercial businesses including a rowing club and a few small marinas. The Saugatuck Shores area on the western bank of Saugatuck Harbor is developed with large single-family homes and two yacht clubs. Some salt marshes are present along the harbor margins south of the Canal Street bridge and just to the north of the I-95 bridge. Much of the shoreline has been filled for development but several large strip marshes are also still present along the western bank as the harbor opens into a larger basin near the mouth (Figure 2.D.2).

Figure 2.D.1. Looking upstream at the first basin the harbor from the uppermost station, SH-6.

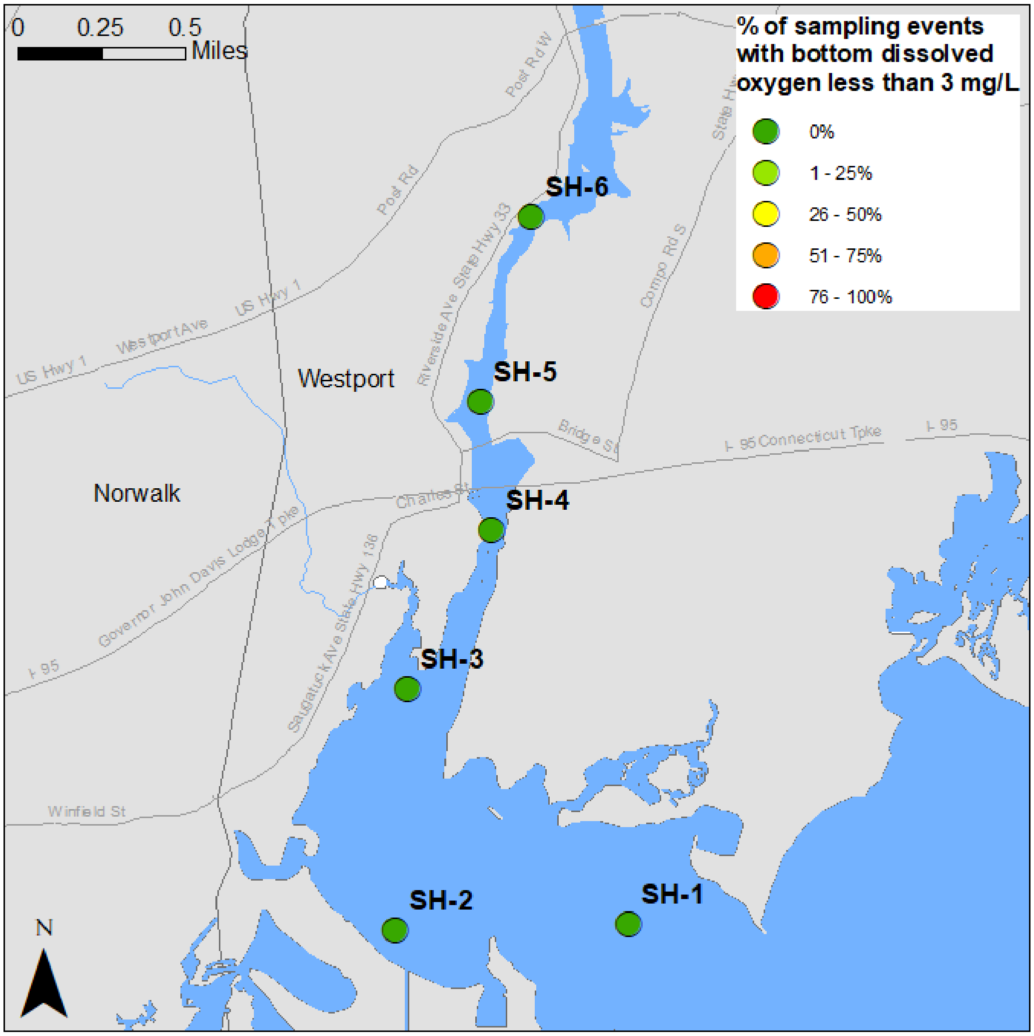


Figure 2.D.2. Map of Saugatuck Harbor sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 3 mg/L.

Table 2.D.1. Coordinates and descriptions for each sampling station in Saugatuck Harbor

Site Name	Latitude	Longitude	Description
SH-1	41.102050	-73.360533	Buoy 9
SH-2	41.101733	-73.373833	Buoy 18
SH-3	41.112167	-73.373317	Buoy 27
SH-4	41.119067	-73.368517	Railroad bridge
SH-5	41.124617	-73.369233	VFM marina (in the channel)
SH-6	41.132683	-73.366383	Sunoco (in the channel)

Dissolved Oxygen

Profiles were taken at 6 stations on 8 sampling days from June to September 2017. Mean dissolved oxygen levels ranged between 6.13 mg/L at the bottom of station SH-2 to 7.70 mg/L at the surface of station SH-6 (Figure 2.D.3). All individual readings at each station were recorded to be above 3 mg/L (Figure 2.D.4). Water quality observed during 2017 in Saugatuck Harbor was improved relative to 2016 (Crosby et al., 2017a). Improvement in the Saugatuck water quality may be related to greater rainfall in the Saugatuck River's watershed in 2017, which could have resulted in greater freshwater volume flowing in the Saugatuck River and ultimately flowing into the estuary where it may have served to increase and aid flushing efficiency. Unseasonably cool weather during late summer may also have promoted better water quality by driving downwelling in cooler surface waters and allowing more dissolved oxygen to enter the surface waters (Figure 2.D.4). Rainfall amounts for 2017 were marginally higher than 2016 as recorded at the Norwalk Health Department for the period of May through September ("Norwalk Health Department Raingauge").

Increased river flow in the whole watershed could have helped improve flushing efficiency at stations SH-6 and SH-5 by adding to the flow during ebb tide associated with the large basin just to the north of station SH-6 (Figure 2.D.2, Figure 2.D.6). The increased intensity and volume of flow might have helped to mix the water column and raise the dissolved oxygen levels on 7/28 and 8/4 at station SH-6 and, to a lesser degree, at downstream stations SH-5 and SH-4 (Figure 2.D.4). The decline in water quality observed on 7/12 may have been due to a large storm on 7/11 that resulted in 0.82 inches of precipitation ("Norwalk Health Department Raingauge"). The storm run-off may have temporarily added pollutants to station SH-6 from the first flush of the storm.

Lower water temperatures during 2017 were likely the result of a decline in ambient air temperature in late summer (Appendix 1.2, "Historical Weather", Appendix 2.4). The effect of an extended air temperature decline was seen on 8/25 as apparent downwelling and upwelling was observed at 3 of the 6 stations in the Saugatuck estuary due to rapid cooling and subsequent increased density of the surface waters (Figure 2.D.4, Appendix 2.4). This process likely resulted in vertical mixing of the water column as the dense surface layers sank and caused the bottom water to be displaced upward. Similar dissolved oxygen values observed at all levels of a water column can generally be a sign that some vertical mixing has occurred due either to density-driven downwelling or mechanical mixing (Figure 2.D.4). Located at the outlet of the large flushing basin, station SH-6 in particular was likely subjected to both natural forces. The decrease in water temperatures and rapid increase in dissolved oxygen levels throughout the harbor as noted on monitoring dates 9/1 and 9/13 may have been related to unseasonably low ambient air temperatures for the period 9/1 through 9/4 and again on 9/6 through 9/14 (Appendix 1.2, "Historical Weather", Appendix 2.4)).

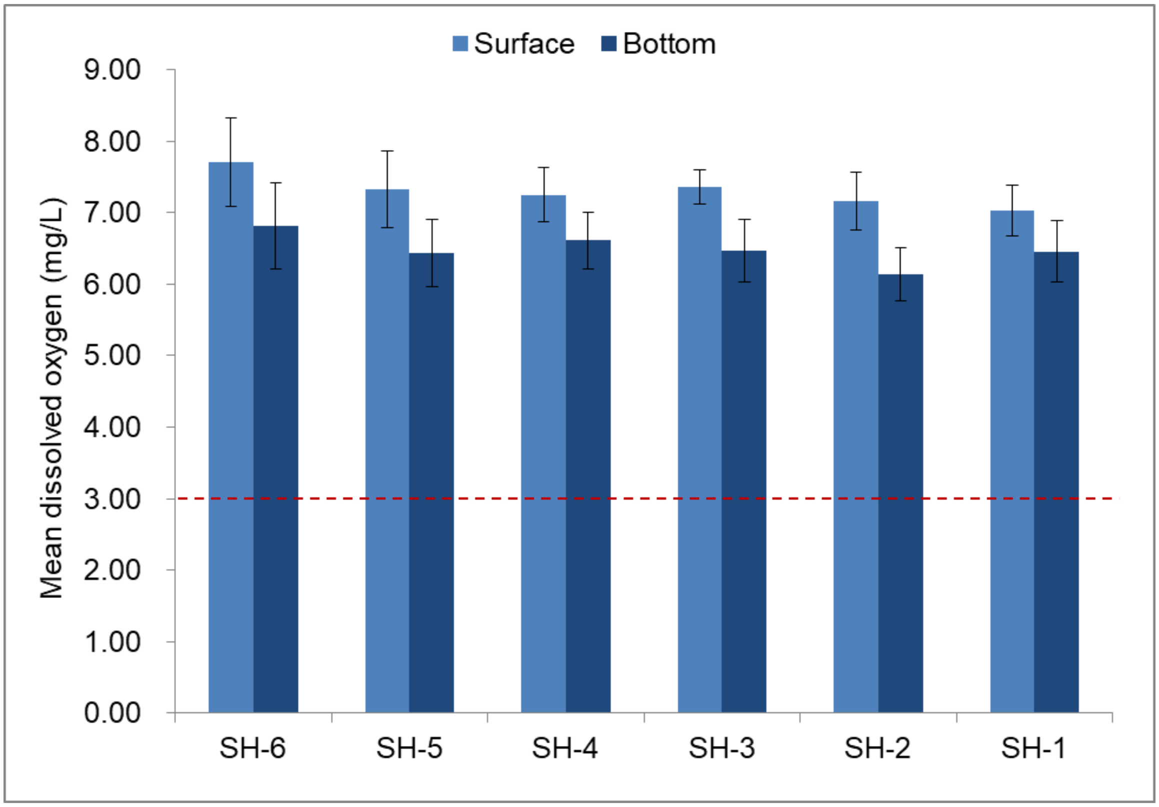


Figure 2.D.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Saugatuck Harbor. Error bars represent standard error. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

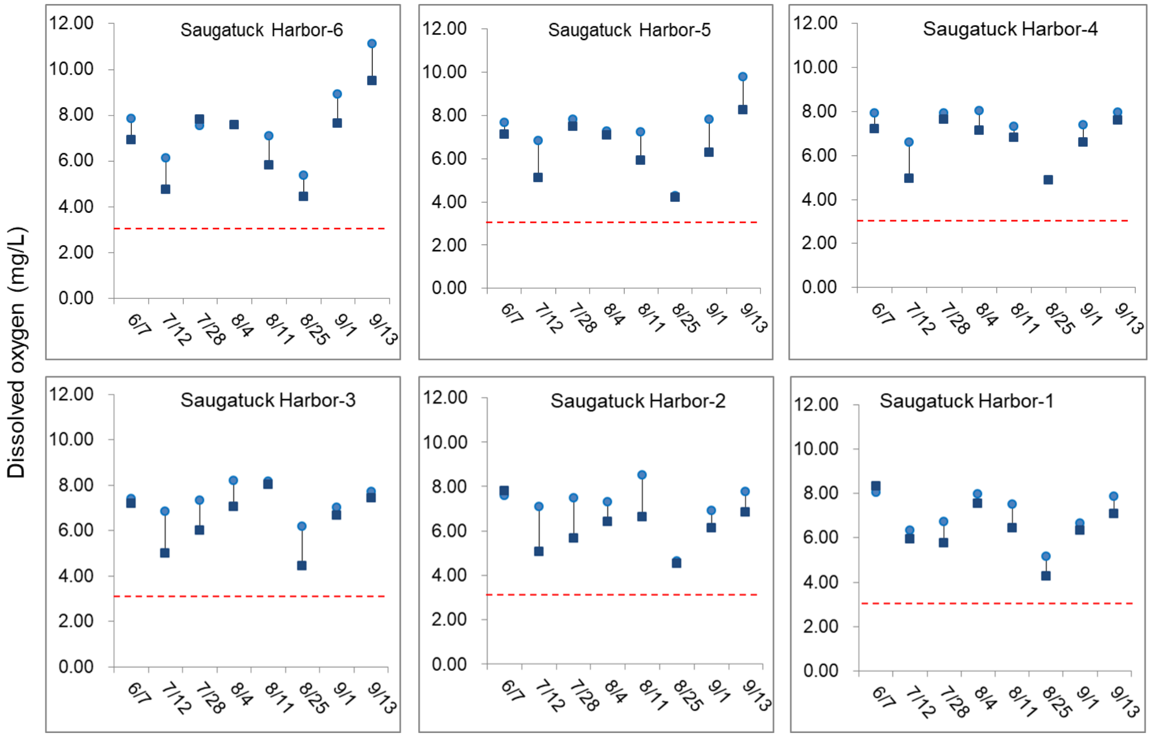


Figure 2.D.4. Surface and bottom dissolved oxygen values at each Saugatuck Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

Chlorophyll a

Chlorophyll *a* sampling was conducted during 5 monitoring events on 6/13, 7/12, 8/4, 8/11, and 8/25. A large amount of microalgae was observed in particular at stations SH-6, SH-5, and SH-4 (Figure 2.D.5). The river's fresh water input and storm drain outfalls served as likely sources of nutrients in close proximity to these three sites in particular, likely facilitating the high productivity observed. Two large blooms encompassing the area around these top three stations occurred on 7/12 and 8/25 (Figure 2.D.5). The first of these blooms was observed immediately after a rainfall event of 0.87 inches which may have accelerated the bloom by flushing a renewed supply of nutrients into the estuary ("Norwalk Health Department Raingauge"). The second major bloom on 8/25 was observed 2 days after a rainfall event of 1.28 inches with a similar result. A third bloom was also observed only at station SH-4 on 8/11, but was not coupled with a rain event as the others had been (Figure 2.D.5). Overall, the chlorophyll *a* data for the 2017 season was similar to what was observed during the 2016 monitoring season (Crosby et al., 2017a). This harbor can thus be classified as highly eutrophic (> 20 µg/L, ≤ 60 µg/L) for the 3 northern stations and medium eutrophic (> 5 µg/L, ≤ 20 µg/L) for the lower 3 stations based on the Bricker classification system (Table 2.1, Figure 2.D.5).

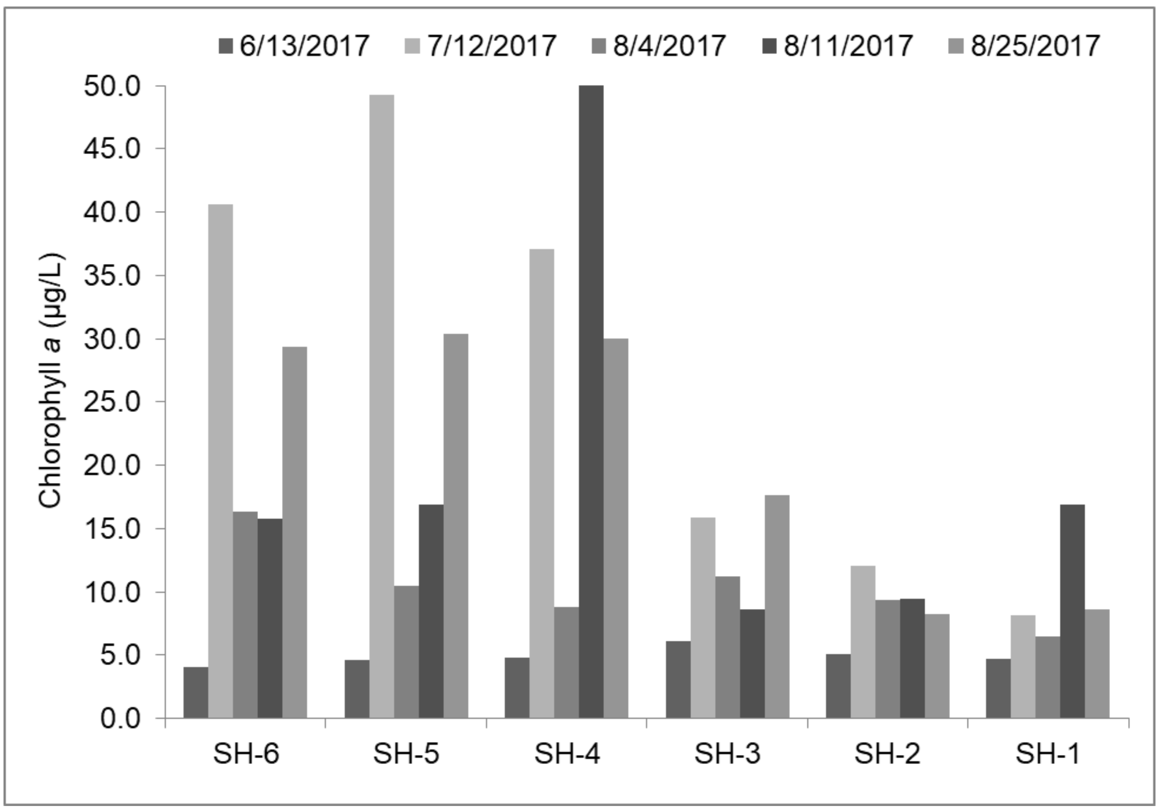
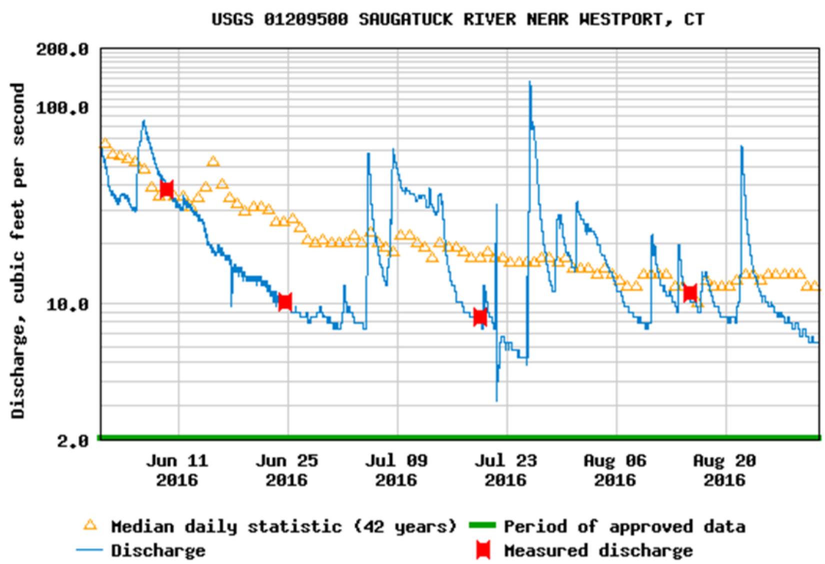


Figure 2.D.5. Average chlorophyll *a* values in Saugatuck Harbor.

Saugatuck River Discharge

The figures below illustrate discharge in cubic feet per second recorded at the United States Geological Survey monitoring station on the Saugatuck River near Westport, CT. Yellow triangles represent the daily median value over the last 42 years, and the blue line represents the recorded discharge for a particular date. In the summer of 2016, discharge was observed to be predominantly below historic norms whereas for the same time period in 2017, discharge was recorded above the historic norms for most of the season. These figures indicate that flow in the Saugatuck River, may have been slightly greater in 2017 than 2016. This increase in flow may be related to the increase in rainfall totals over 2016.



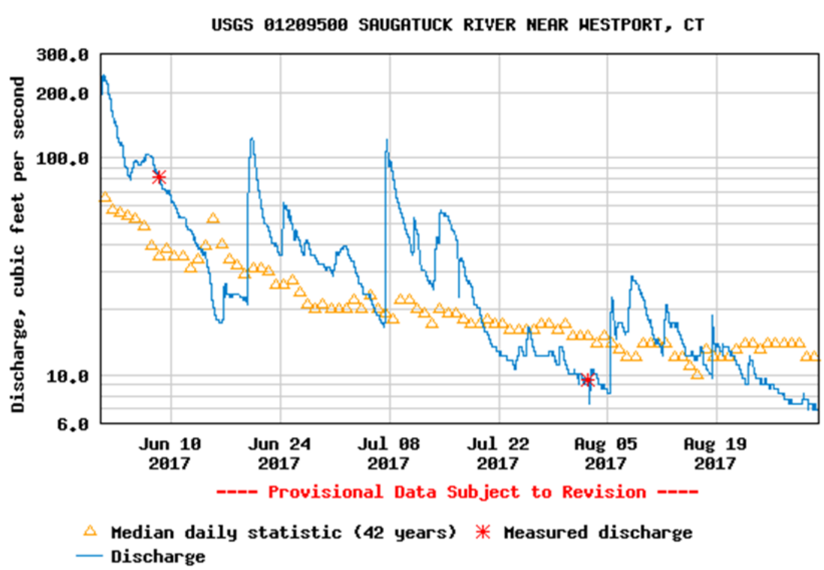


Figure 2.D.6. USGS flow data in feet^3/s for the period of June 1st through August 31st for the 2016 and 2017 respectively for the Saugatuck River near Westport, CT (Graphs courtesy of the U.S. Geological Survey).

E. Johnson's Creek and Lewis Gut

Lewis Gut is a large, marine extension of Bridgeport Harbor that extends 2 miles to the east behind a barrier beach known as Pleasure Beach on its western end and Long Beach on its eastern extremity. The barrier beach and the waters of Lewis Gut have been spared the impact of man-made development over time because a fire destroyed the only bridge that connected the barrier beach to the mainland. A noteworthy environmental feature of Lewis Gut is the extensive *Spartina alterniflora* salt marsh which flanks the northern edge and eastern end of Lewis Gut.

Johnson's Creek is a short ¼ mile channel that starts at the western end of Lewis Gut and extends northward passing a series of petroleum storage tanks and 2 marinas on the east bank up to the I-95 off-ramp. This creek is the terminus of a small stream, Bruce Brook. Johnson's Creek is included in this survey because its waters mix with those of the Gut during tidal cycles (Figure 2.E.1). The 2 water bodies present a significant contrast in terms of water quality (Figure 2.E.2). On the one hand, Lewis Gut possesses all the features of an environmentally sound embayment that is surrounded by a natural shoreline. As an added benefit, the bordering extensive wetlands serve as a system to improve water quality. On the other hand, Johnson's Creek is commercially developed and has all the elements of an industrially overcrowded shoreline which receives the discharge from a badly polluted brook (Figure 2.E.3).

Figure 2.E.1. Looking down Johnson's Creek, which has many commercial land uses on its borders –the swing bridge is in the background where Johnson's Creek meets Lewis Gut.

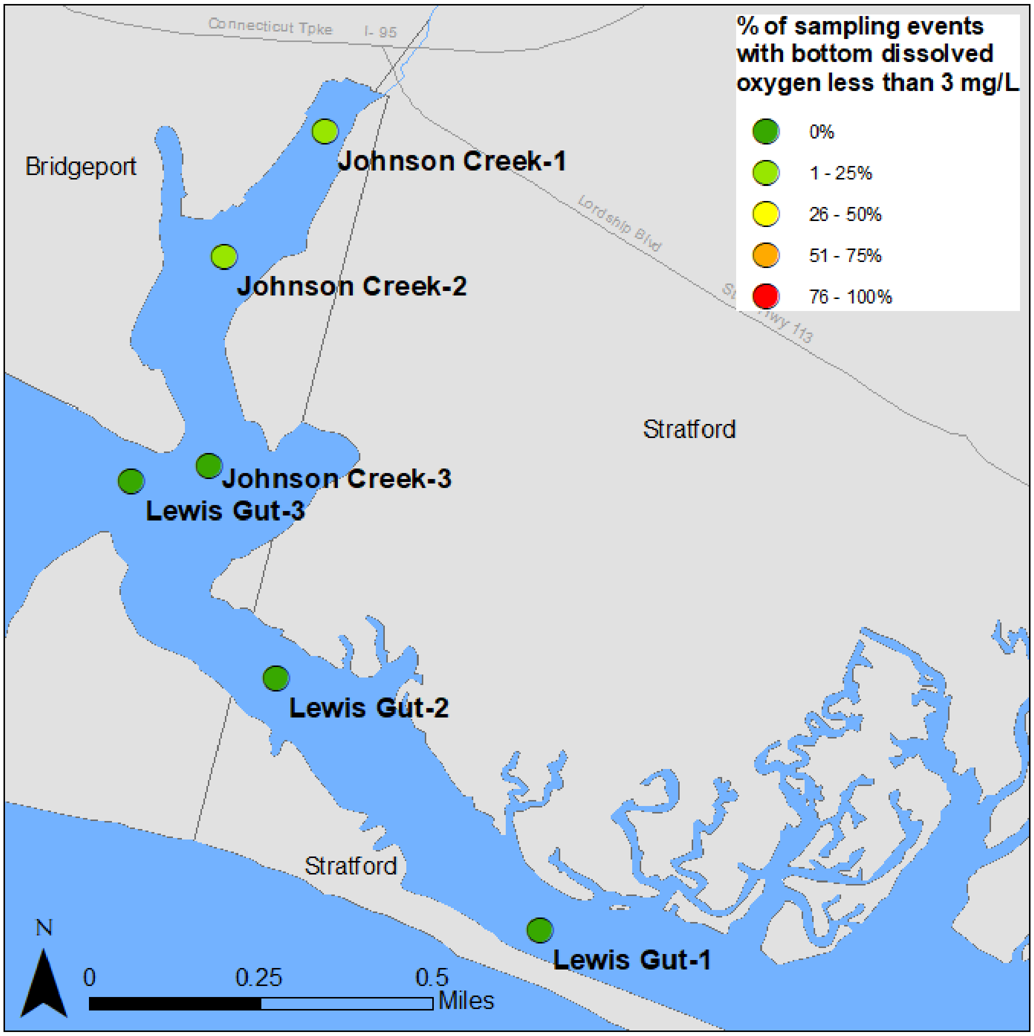


Figure 2.E.2. Map of Johnson's Creek and Lewis Gut sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 3 mg/L.

Table 2.E.1. Coordinates and descriptions for each sampling station in Johnson's Creek and Lewis Gut

Site Name	Latitude	Longitude	Description
Johnson Creek-1	41.172900	-73.160583	Off of East End Yacht Club
Johnson Creekt-2	41.170250	-73.163367	Mid-channel off PC Metals
Johnson Creek-3	41.165833	-73.163750	Nun Buoy #4
Lewis Gut-1	41.156083	-73.154467	Lewis Gut-east end
Lewis Gut-2	41.161383	-73.161867	Lewis Gut
Lewis Gut-3	41.165517	-73.165917	Swing Bridge east side

Figure 2.E.3. An aerial view of a highly industrialized Johnson's Creek in contrast to the natural setting around Lewis Gut (photo source: Google Maps).

Dissolved Oxygen

Mean dissolved oxygen levels were observed to be slightly higher in Lewis Gut than in Johnson's Creek (Figure 2.E.3). All sites had mean dissolved oxygen levels above 3 mg/L (Figure 2.E.3). August 8th had the lowest observed oxygen values at each site. Individual readings fell below 3 mg/L on this date at the 2 upper stations in Johnson's creek, JC-1 and JC-2. Ambient air temperatures dropped August, but a corresponding decrease in water temperatures was not observed (Figure 2.E.4, Appendix 1.2, "Historical Weather", Appendix 2.5). Salinity in Johnson's Creek showed a very weak gradient in the water column (Harbor Watch records, data not shown). It should be mentioned that the west side of Johnson's Creek has very large storm water outfalls. These can discharge large amounts of fresh water to the waterway during storms which seemed to drive periodic stratification at JC-2 and JC-3. Lewis Gut, on the other hand, showed little evidence of a fresh water discharge because it is flanked by tidal wetlands which help to maintain water quality. There was no observable salinity gradient in Lewis Gut. This lack of stratification plays a part in why the difference in top and bottom dissolved oxygen levels was not as wide at each sampling station as observed in other harbors (Figure 2.E.4). Dissolved oxygen concentrations in 2017 were slightly lower than those observed during the 2016 monitoring season (Crosby et al., 2017a). This entire area is heavily impacted by sewage pollution (and the resultant nutrient inputs) from Bruce Brook (Crosby et al., 2017b), without which the dissolved oxygen conditions might have been higher than what was observed.

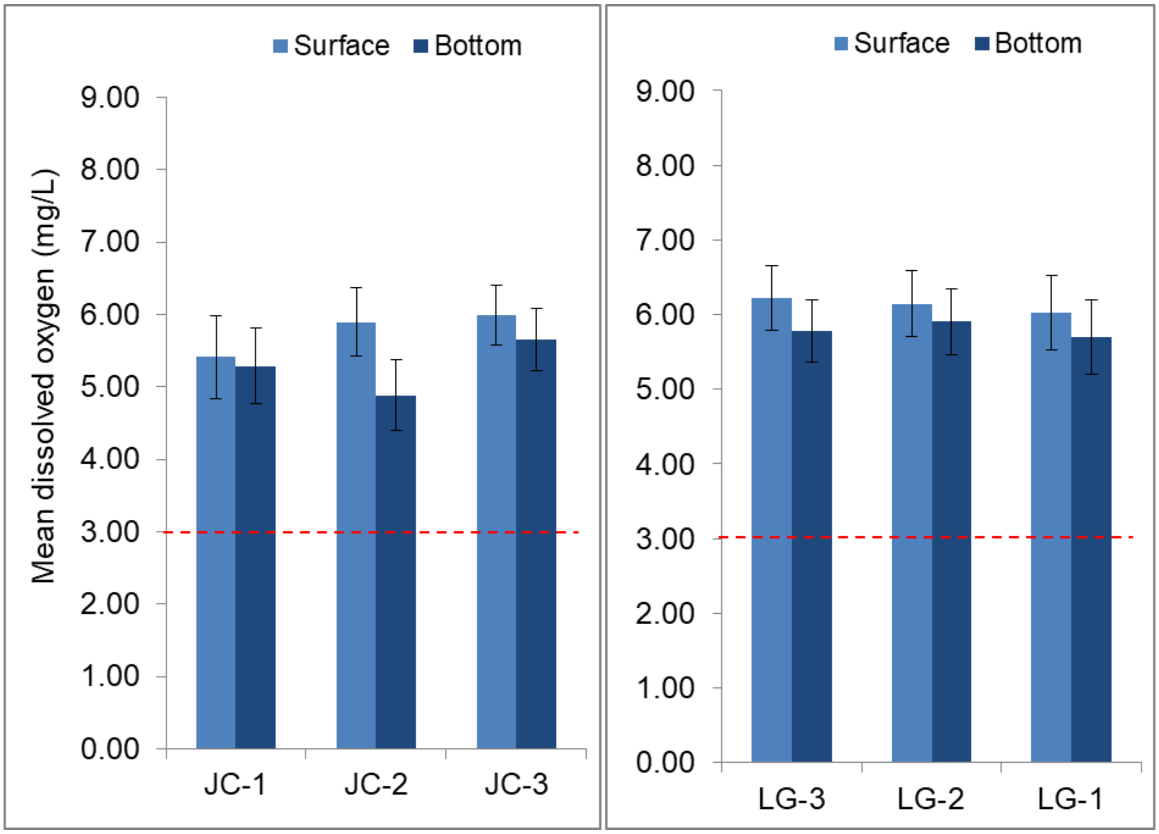


Figure 2.E.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Johnson's Creek and Lewis Gut Harbor. Error bars represent standard error. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

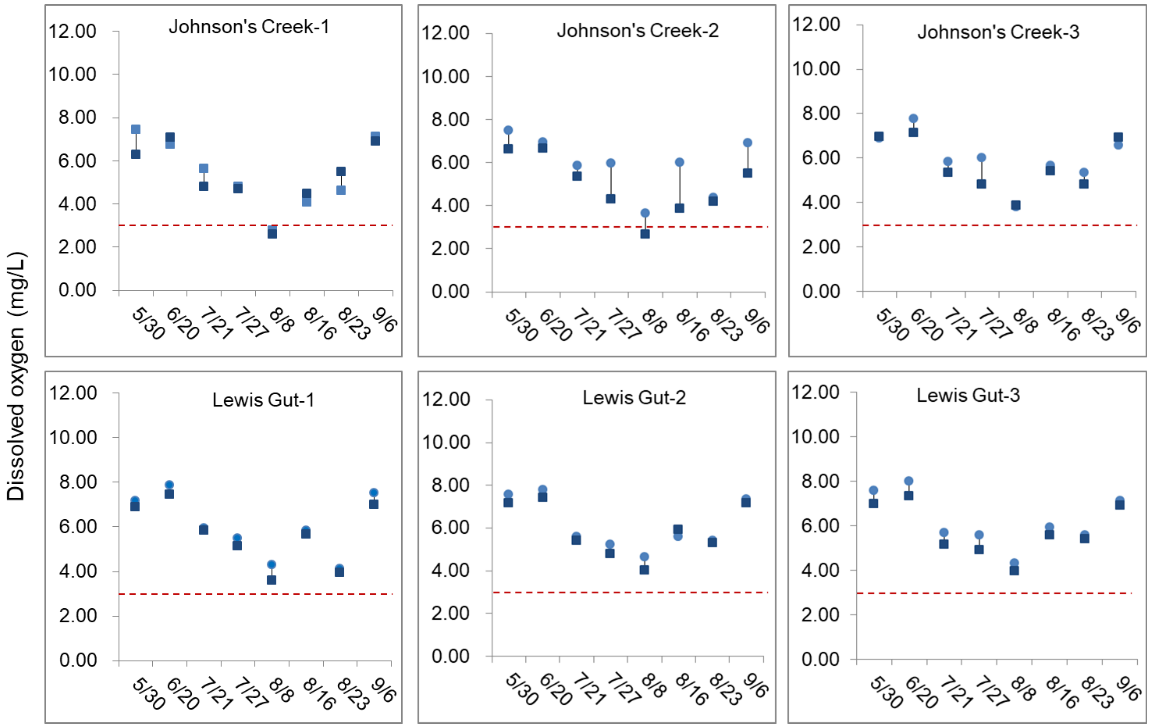


Figure 2.E.4. Surface and bottom dissolved oxygen values at each Johnson's Creek and Lewis Gut Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

Chlorophyll a

Chlorophyll *a* samples were taken 5 times during the 2017 monitoring season in Johnson's Creek and Lewis Gut on 5/30, 7/21, 8/8, 8,16 and 9/6 (Figure 2.E.5). Johnson's Creek production of microalgae was more prolific, likely due to its industrial setting, fresh water input from Bruce Brook, and the discharge from storm drain outfalls serving as sources of nitrogen. Discharge from Bruce Brook is typically relatively low and provides limited flushing assistance to Johnson's Creek except when heavy rains turn the brook into a robust flow. Lewis Gut has no major source of fresh water and the surrounding area includes a large *Spartina alterniflora* salt marsh to the north and an extensive sandy beach to the south. The only flushing source is rainfall and what runs off from the wetlands on ebb tide. The net result is a more uniform distribution of phytoplankton and slightly lower productivity in Lewis Gut (Figure 2.F.5). Both Lewis Gut and Johnson's Creek can be classified as having medium eutrophic characteristics (> 5 µg/L, ≤ 20 µg/L; Table 2.1).

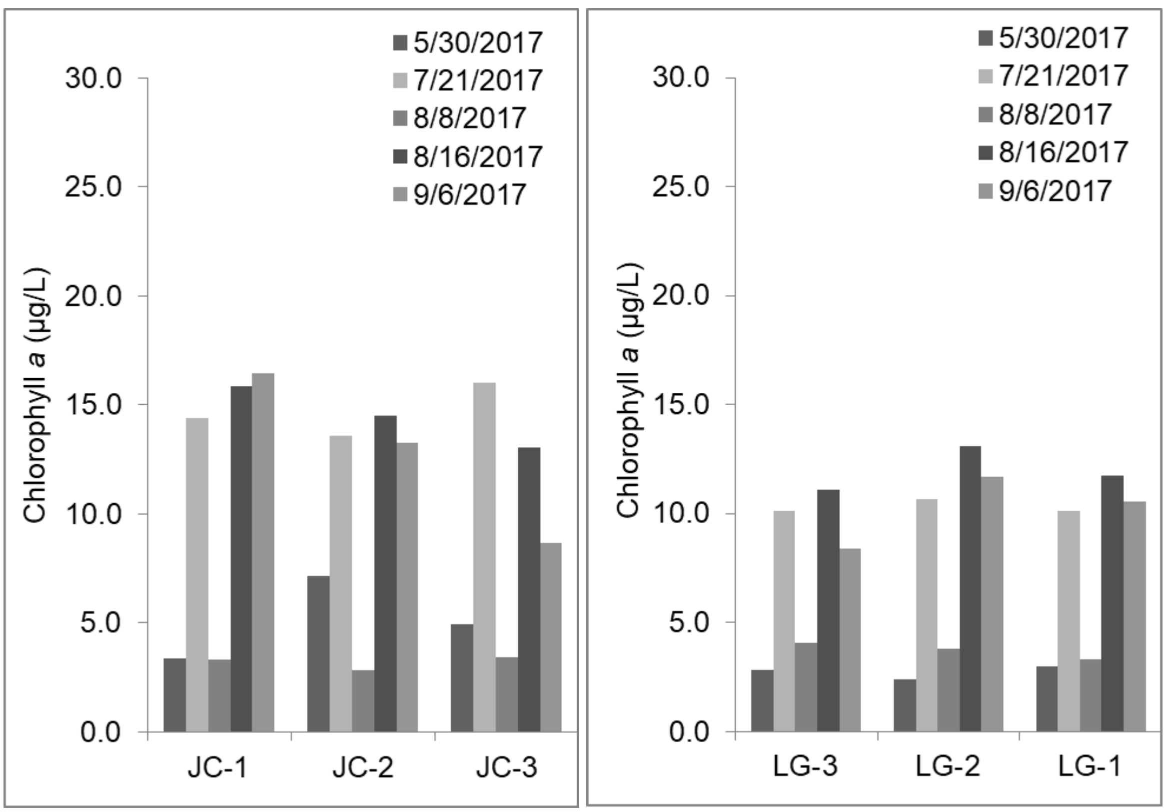


Figure 2.E.5. Average chlorophyll *a* values in Johnson's Creek and Lewis Gut.

F. Quinnipiac Harbor

The Quinnipiac Harbor is an important estuary for the shellfish industry because it is a spawning ground for oysters. The Quinnipiac River supplies the fresh water flow at the northern end of the estuary near the I-91 bridge. The southern end of the estuary widens to a broad but shallow harbor south of the Ferry Street Bridge. The area between the Ferry Street bridge and the I-91 bridge is the upper portion of the estuary and is the area designated for this water quality survey. Approximately 1.5 miles long by 0.25 miles wide, this portion of the estuary is a semi-enclosed basin. A protected wetland, the 35 acre Quinnipiac Meadows - Eugene B. Fargeorge Preserve, is located on the eastern shoreline along the upper portion of the estuary (Figure 2.F.1). The lower portion, south of the Grand Avenue Bridge, is occupied by Copps Island Oysters harvesting facility and a barge refurbishing company. The land use on the western shore is defined by having a marina and residential housing. The area south of the Grand Avenue Bridge is navigable by large vessels while the area north of the bridge becomes very shallow at low tide and is navigable only by small boats.

Figure 2.F.1. View of the large flushing basin in Quinnipiac Harbor with extensive wetlands on the eastern shore.

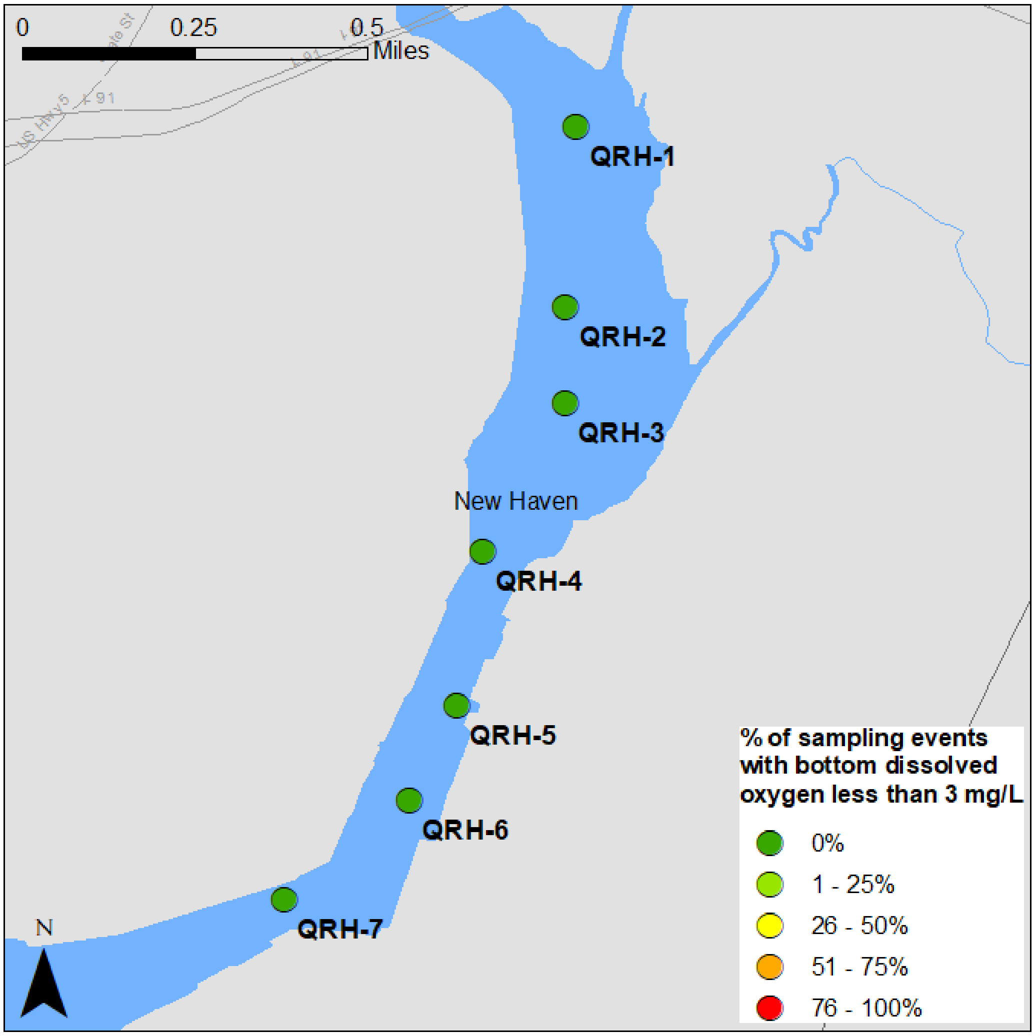


Figure 2.F.2. Map of Quinnipiac Harbor sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 3 mg/L.

Table 2.F.1. Coordinates and descriptions for each sampling station in Quinnipiac Harbor

Site Name	Latitude	Longitude	Description
QRH-1	41.318350	-72.885483	Mid-channel just north of Quinnipiac Meadows
QRH-2	41.314550	-72.885783	Off of the Anastasio's Boathouse Cafe
QRH-3	41.312550	-72.885800	Mid-channel south of Waucoma Yacht Club
QRH-4	41.309409	-72.888093	Upstream from the Grand Ave Bridge
QRH-5	41.306167	-72.888817	South end of the shell pile on Quinnipiac Ave
QRH-6	41.304167	-72.890133	Four pilings
QRH-7	41.302067	-72.893617	Ferry Street Bridge

Dissolved Oxygen

Seven stations were monitored in Quinnipiac harbor over 6 days from June through August. Water monitoring during this season was difficult and some of the harbor monitoring had to be modified or incompletely sampled on some of the scheduled research dates. Reasons for missing data include occasional mechanical problems with the research boat's outboard engine, dangerous currents on ebb tide, and very shallow water that could only be accessed during mid to high tides. Water quality with respect to dissolved oxygen was improved during the 2017 season relative to the 2016 season in that there were no observed instances of hypoxia or individual dissolved oxygen concentrations at 3 mg/L or below (Figure 2.F.3, Figure 2.F.4). All bottom dissolved oxygen readings exceeded 4 mg/L and all surface dissolved oxygen surface readings exceeded 5 mg/L (Figure 2.F.3).

The summer season for 2017 differed from the 2016 season in two important ways. Inland rainfall amounts may have been greater on the Quinnipiac's 50 mi^2 watershed than what was observed at the shore based on discharge data (Figure 2.F.5). Higher flow rates can aid in greater flushing efficiency for an estuary. More fresh water arriving at station QRH-1 could have caused more of the underlying salt water wedge to be entrained in the overlying fresh water and moved seaward. This extra force at station QRH-1 may have ultimately resulted in more water entering the salt water wedge at the mouth of the harbor (Figure 2.F.1). The large basin just south of I-91 holds a large amount of water and can provide robust flushing power during ebb tide irrespective of the river input. Flushing and mixing may be further enhanced by both sets of bridge abutments as the water moves downstream through these constricted areas of the estuary bed. When adding the higher force of river water created during storm events to that which already exist at ebb tide, strong currents were often produced.

Other positive conditions that served to promote better water quality in the Quinnipiac Harbor were periods of unseasonably cooler weather that occurred in July and August. Rapid temperature declines on 7/14, 7/25, 7/30, 8/8, and 8/24 could have reduced water temperatures by as much as 2 °C versus what was observed during 2016 during approximately the same monitoring period (Appendix 1.3, "Historical Weather", Appendix 2.6). Although the data showed dissolved oxygen levels on the bottom above 3 mg/L, we anticipated that dissolved oxygen concentrations would be higher due to the significant beneficial natural features in the upper harbor, the unusually cool weather, and the fact that the Quinnipiac River flow appeared normal relative to historical medians (Appendix 1.2, Figure 2.F.5).

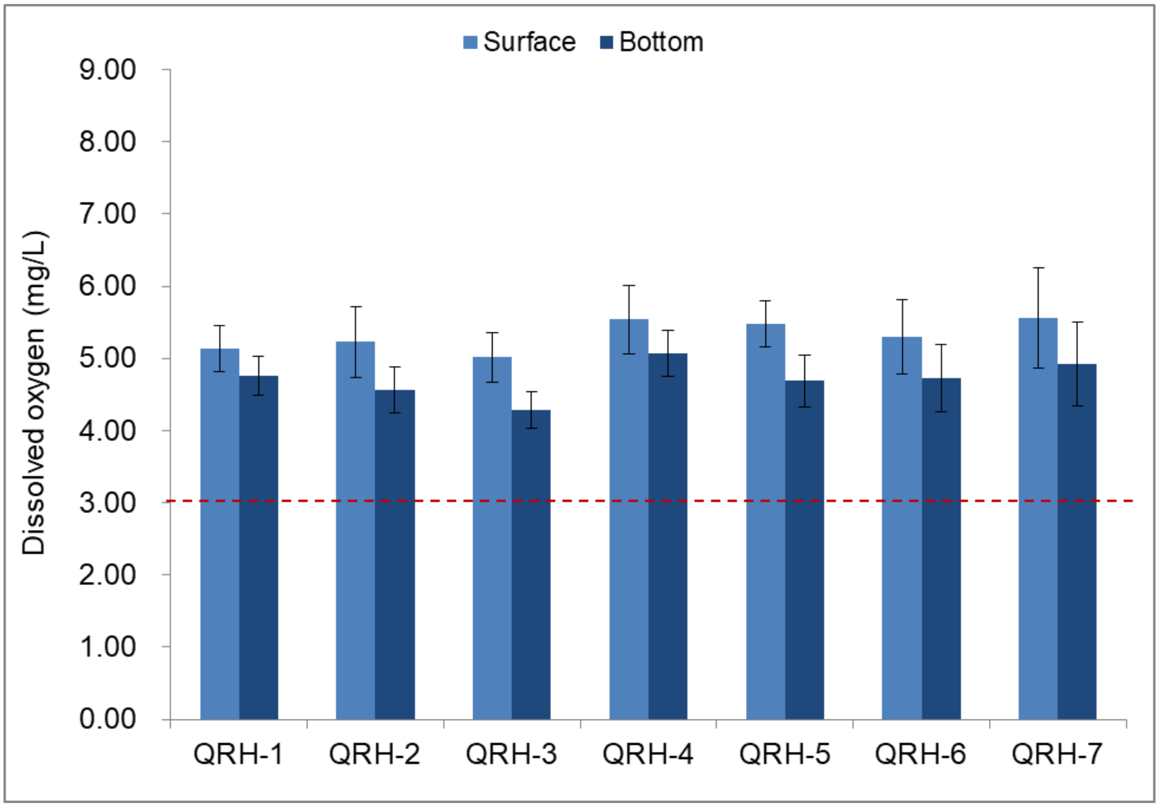


Figure 2.F.2. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Quinnipiac River Harbor. Error bars represent standard error. Values below the red dashed line represent hypoxic conditions (less than 3 mg/L).

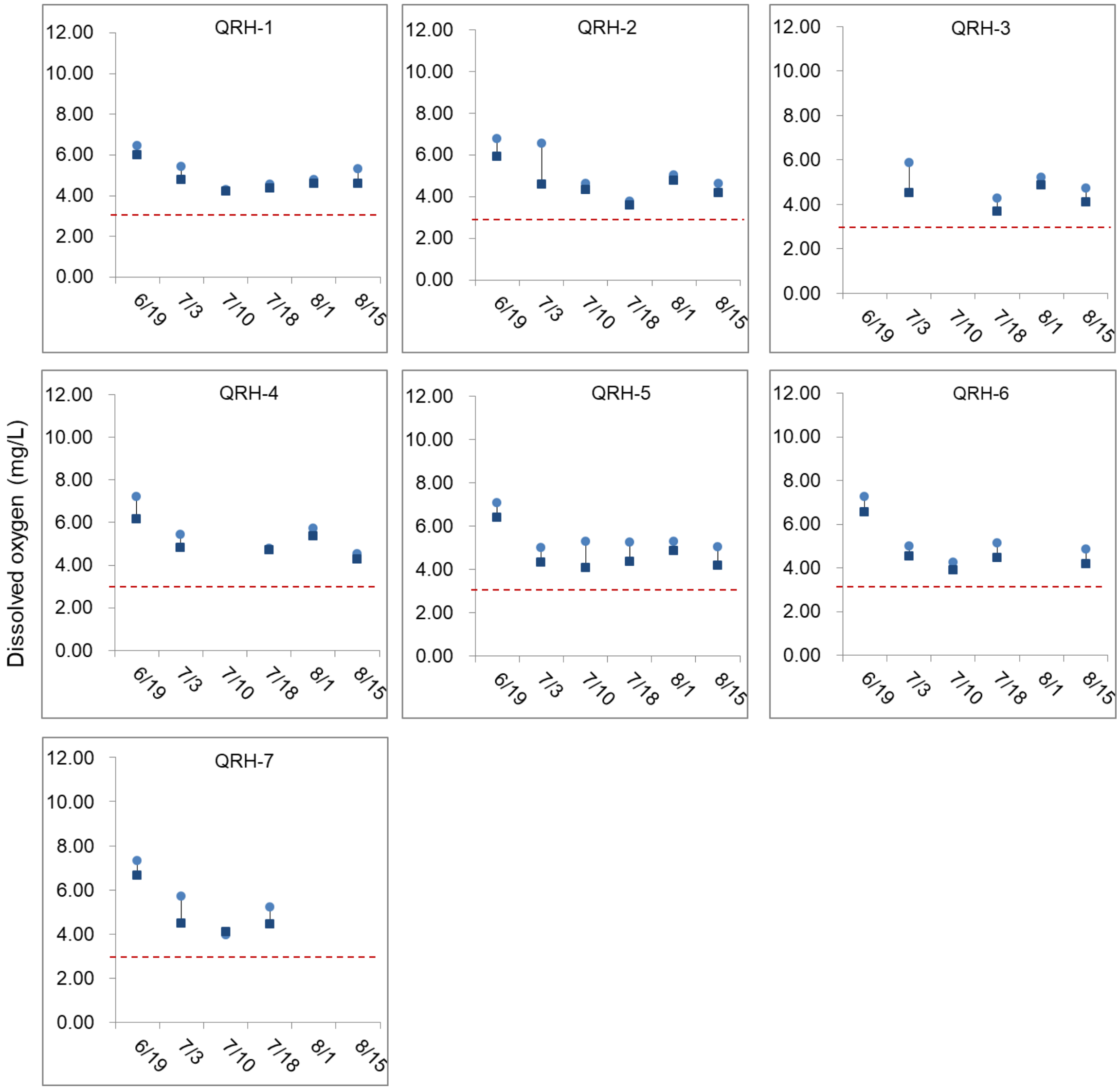


Figure 2.F.3. Surface and bottom dissolved oxygen values at each Quinnipiac River Harbor sampling station on each monitoring date during the 2017 season. Circles represent surface dissolved oxygen values and squares represent bottom dissolved oxygen values. The red dashed line represents 3 mg/L where hypoxia begins.

Chlorophyll a

Samples were obtained during 4 monitoring events on 6/19, 7/10, 8/1 and 8/15 (Figure 2.F.4). Difficulty was encountered in completing chlorophyll *a* tests at stations QRH-5, QRH-6 and QRH-7 due to shallow water and extreme currents encountered at low tide. Quinnipiac Harbor can be characterized as medium eutrophic (> 5 µg/L, ≤ 20 µg/L; Table 2.1). Phytoplankton growth appeared to be distributed across the estuary in a fairly even pattern. This was due in part to the efficient flushing cycle on ebb tide provided by the large expanse of water at the northern end of the waterway.

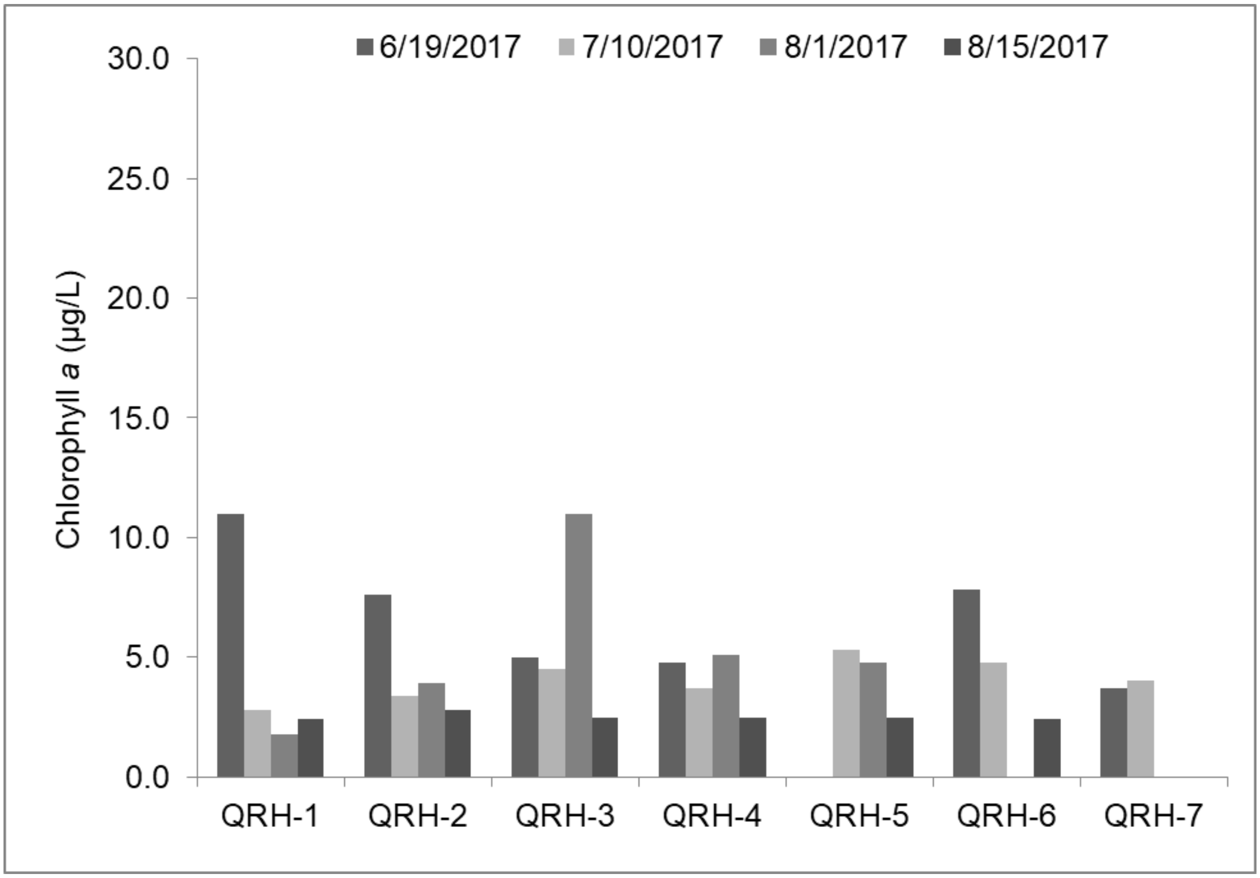
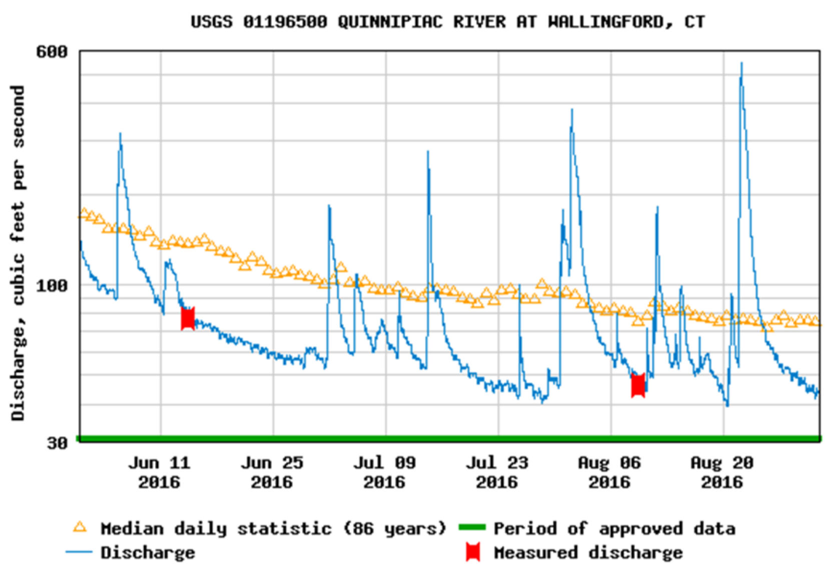


Figure 2.F.4. Average chlorophyll *a* values in Quinnipiac River Harbor.

Quinnipiac River Discharge

The figures below illustrate discharge in cubic feet per second recorded at the United States Geological Survey monitoring station on the Quinnipiac River in Wallingford, CT. Yellow triangles represent the daily median value over the last 86 years, and the blue line represents the recorded discharge for a particular date. During 2016, discharge rates were well below historic norms with occasional large peaks above the historic norm. In 2017, discharge was predominantly observed over historic norms. These figures indicate that flow in the Quinnipiac River, may have been greater in 2017 than 2016. This increase in flow may be related to the increase in rainfall over 2016.



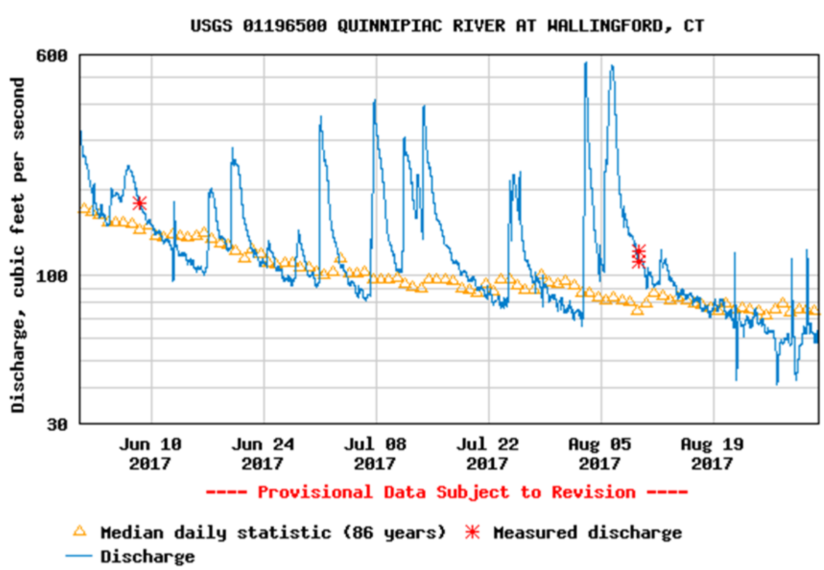


Figure 2.F.5. USGS flow data in $feet^3/s$ for the period of June 1st through August 31st for the 2016 and 2017 respectively for the Quinnipiac River in Wallingford, CT (Graphs courtesy of the U.S. Geological Survey).

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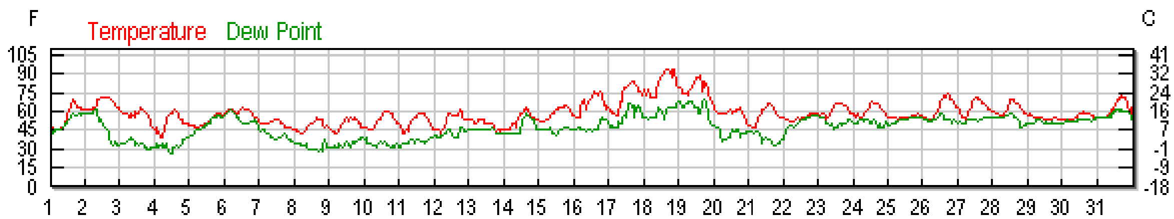
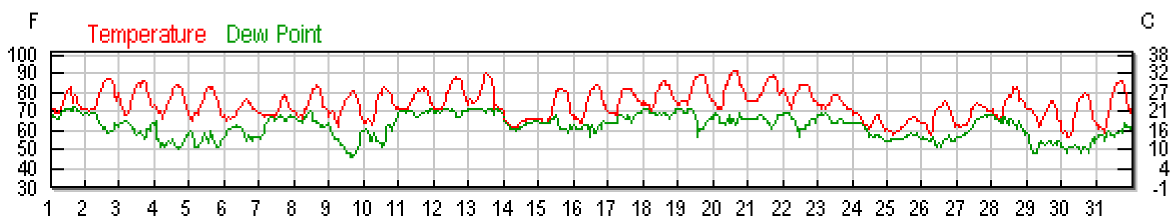
Appendix 1

Historical temperature data for each harbor were retrieved from Weather Underground, which uses the nearest airport for historic data sets ("Historical Weather"). For Stamford Harbor, Five Mile Harbor, and Norwalk Harbor temperature data used was recorded at Westchester County Airport in White Plains, NY. For Saugatuck Harbor, Lewis Gut and Johnson's Creek temperature data used was recorded at Sikorsky Airport in Bridgeport, CT. And lastly, temperature data used for Quinnipiac Harbor was recorded at Tweed Airport in New Haven, CT.

a.



b.



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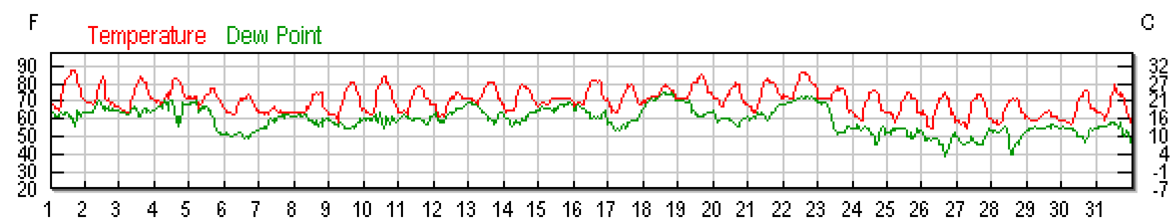
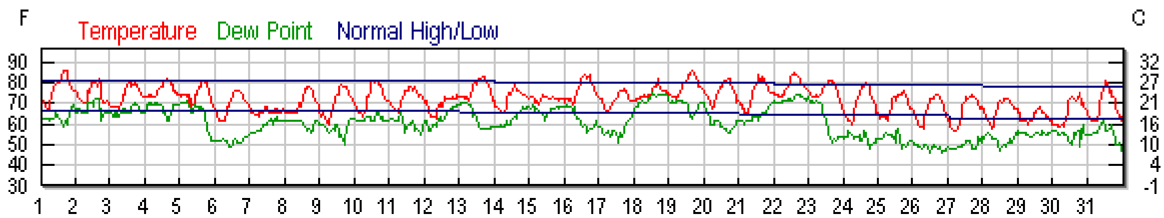


Appendix 1.1. Daily air temperature at Westchester County Airport in (a) May 2017, (b) July 2017, and (c) August 2017.

a.



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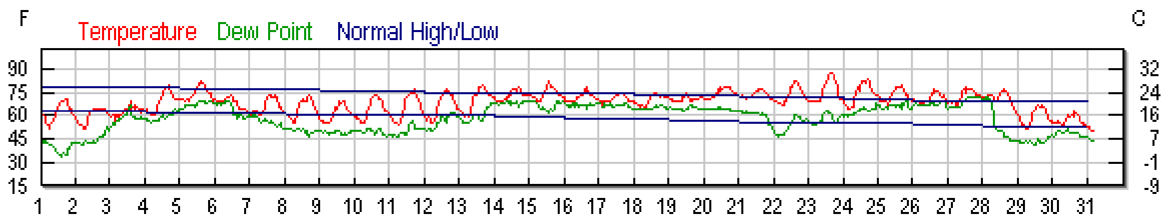
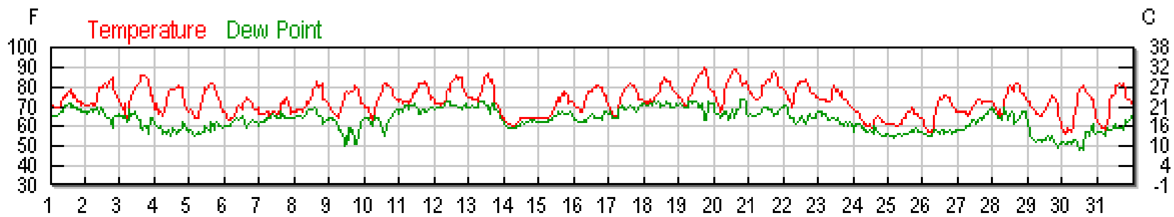
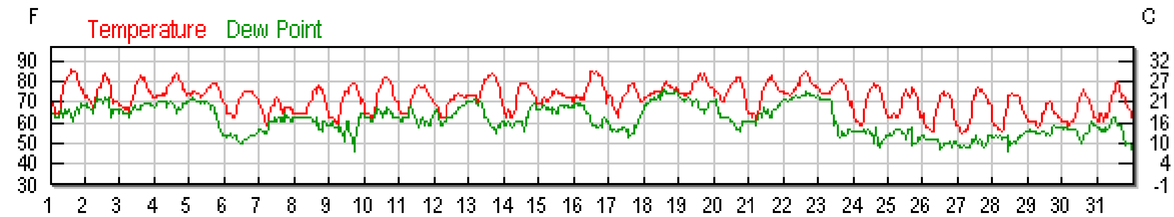


Appendix 1.2. Daily air temperature at Sikorsky Airport in (a) August 2017 and (b) September 2017.

a.



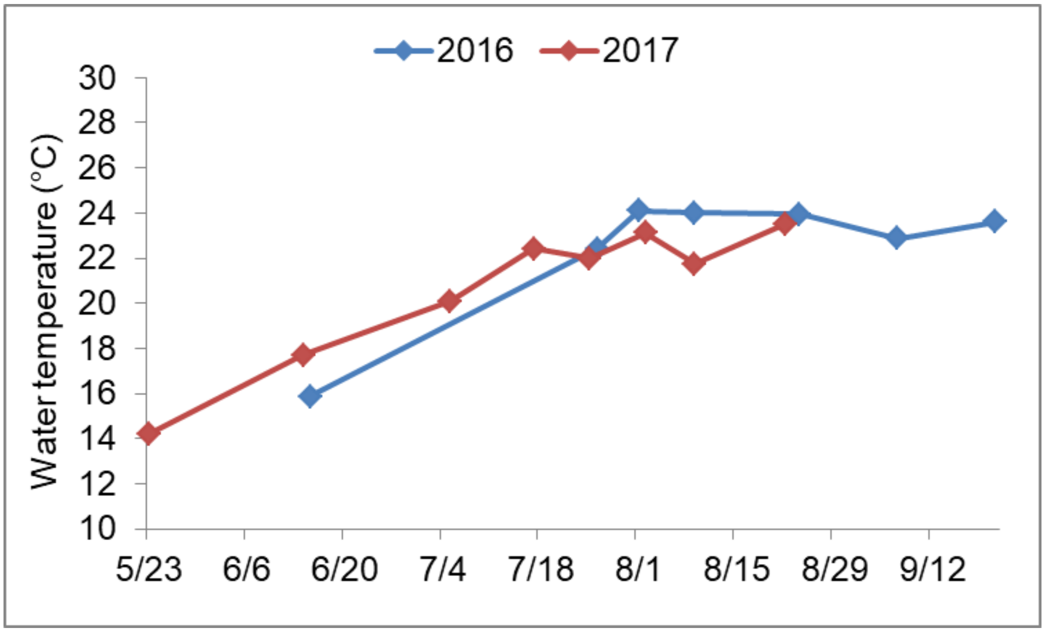
b.



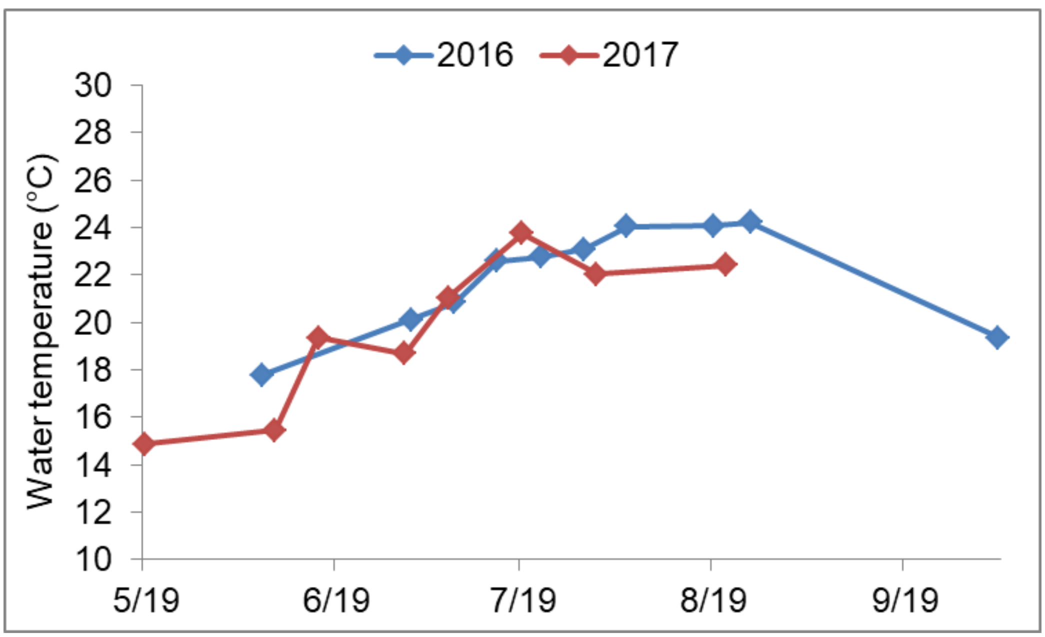
Appendix 1.3. Daily air temperature at Tweed Airport in (a) July 2017 and (b) August 2017.

Appendix 2

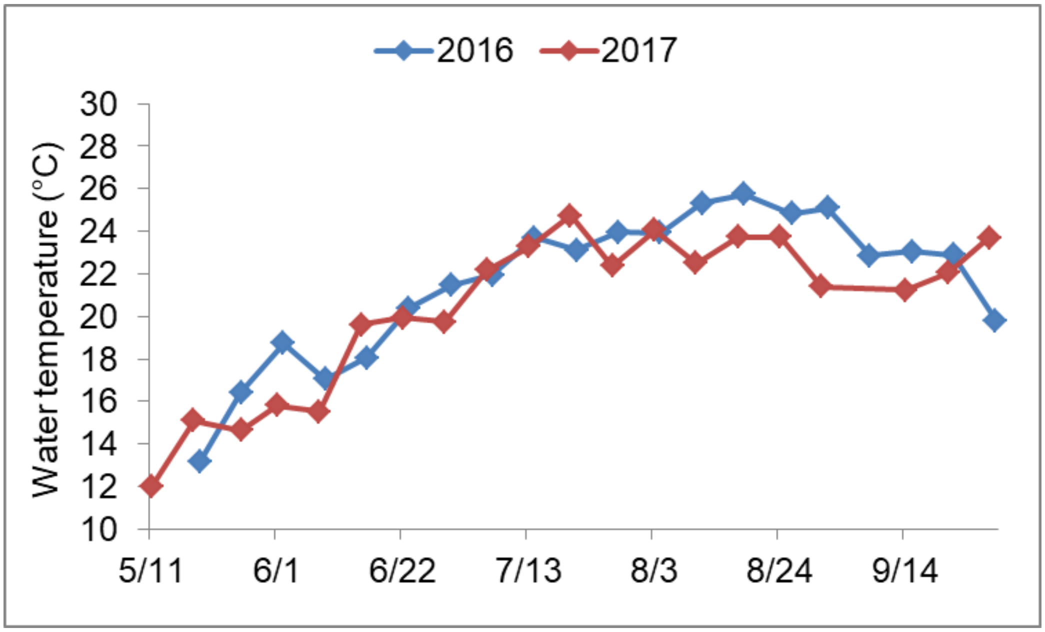
The following graphs illustrate average water temperatures across all sites and all depths for each harbor on each monitoring date in 2016 and 2017. This comparison indicates that slightly cooler water temperatures were observed in late July and August 2017 compared to 2016.



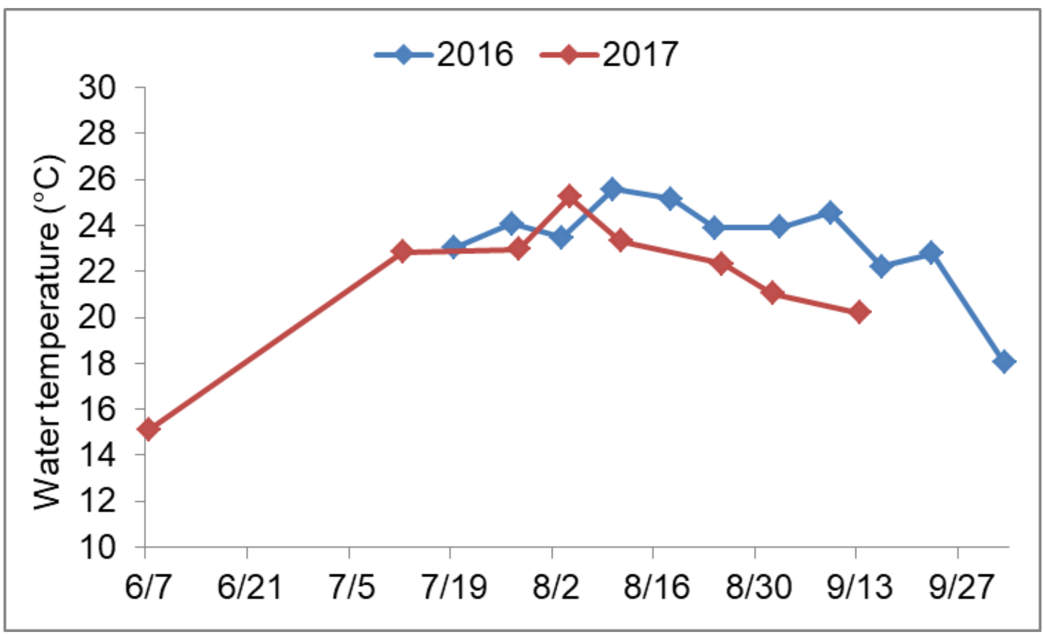
Appendix 2.1. Average water temperatures across all sites and all depths in Stamford Harbor for all 2016 and 2017 monitoring events.



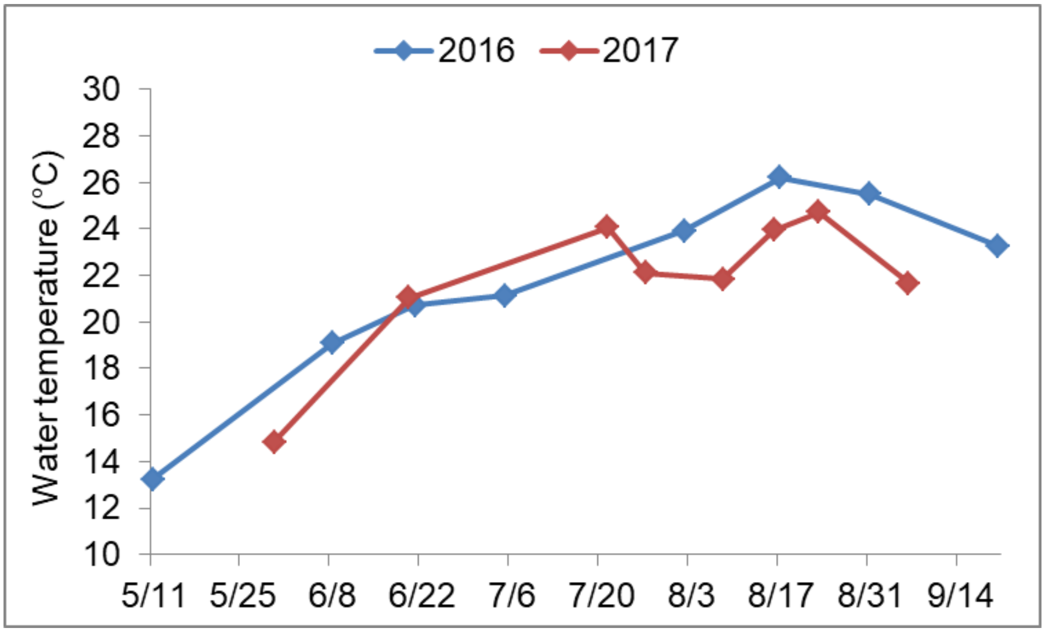
Appendix 2.2. Average water temperatures across all sites and all depths in Five Mile River Harbor for all 2016 and 2017 monitoring events.



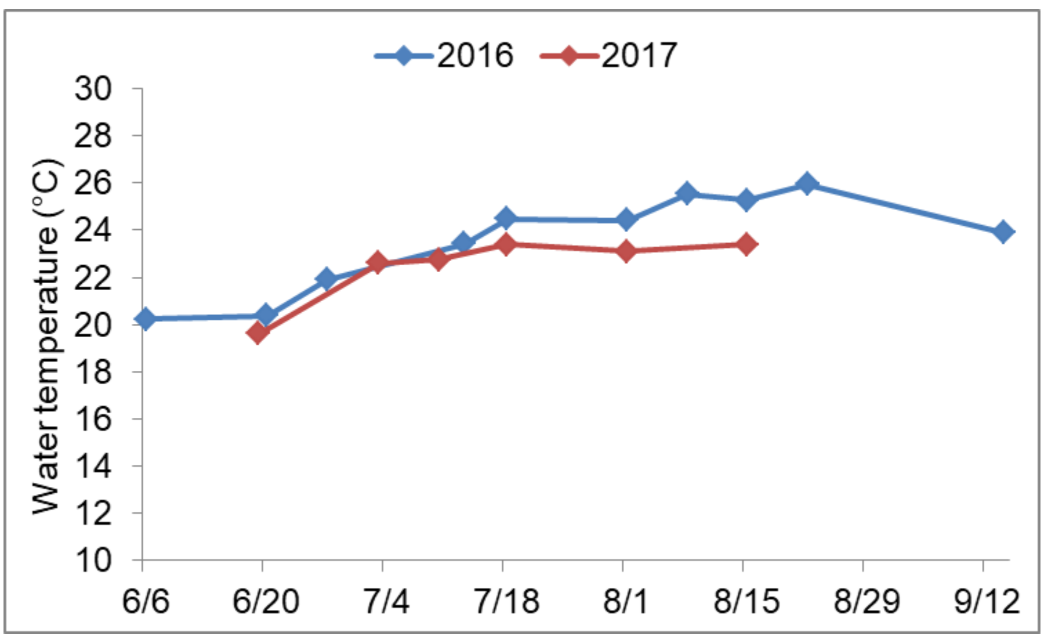
Appendix 2.3. Average water temperatures across all sites and all depths in Norwalk Harbor for all 2016 and 2017 monitoring events.



Appendix 2.4. Average water temperatures across all sites and all depths in Saugatuck Harbor for all 2016 and 2017 monitoring events.



Appendix 2.5. Average water temperatures across all sites and all depths in Lewis Gut and Johnson's Creek for all 2016 and 2017 monitoring events.



Appendix 2.6. Average water temperatures across all sites and all depths in Quinnipiac for all 2016 and 2017 monitoring events.