HARBOR HEALTH STUDY

Harbor Watch | 2018

Harbor Health Study: 2018

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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, Bridgeport Harbor (Johnson's Creek and Lewis Gut sections), and New Haven Harbor (Quinnipiac River section)

Acknowledgements

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Introduction

Harbor Watch is a water quality research and education program based out of Earthplace in Westport, CT. Our mission is to improve water quality and ecosystem health in Connecticut. In this report, we present research conducted in 2018 on the fish community in Norwalk Harbor, Connecticut, as well as water quality conditions in six harbors along the Connecticut coast. The Harbor Monitoring effort was led by our partner at Copps Island Oysters, Richard Harris.

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 2018, water quality data were collected in six harbors (Stamford, Five Mile, Norwalk, Saugatuck, Bridgeport Harbor (Johnson's Creek and Lewis Gut sections), and New Haven Harbor (Quinnipiac River section), 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 national 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 the effects of 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 28 years of studying fish in the harbor, there has been a notable increase in development along the harbor banks. As a result of 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. Numbers (catch per trawl) have declined dramatically for this species during recent years (Crosby et al. 2018b).

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 annually 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 1.4).

Please see our recent paper in* Estuaries and Coasts *for a more in-depth analysis:
Crosby SC, Cantatore NL, Smith LM, Cooper JR, Fraboni PJ, & Harris RB (2018) Three Decades of Change in Demersal Fish and Water Quality in a Long Island Sound Embayment. *Estuaries and Coasts*, 1-11.

Methods

Trawling was conducted from the R.V. Annie, a 26' converted oyster scow equipped with a pot hauler 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 staff and/or 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, typically a minimum of 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 positioned within the selected 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 the pot hauler. 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 28 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.

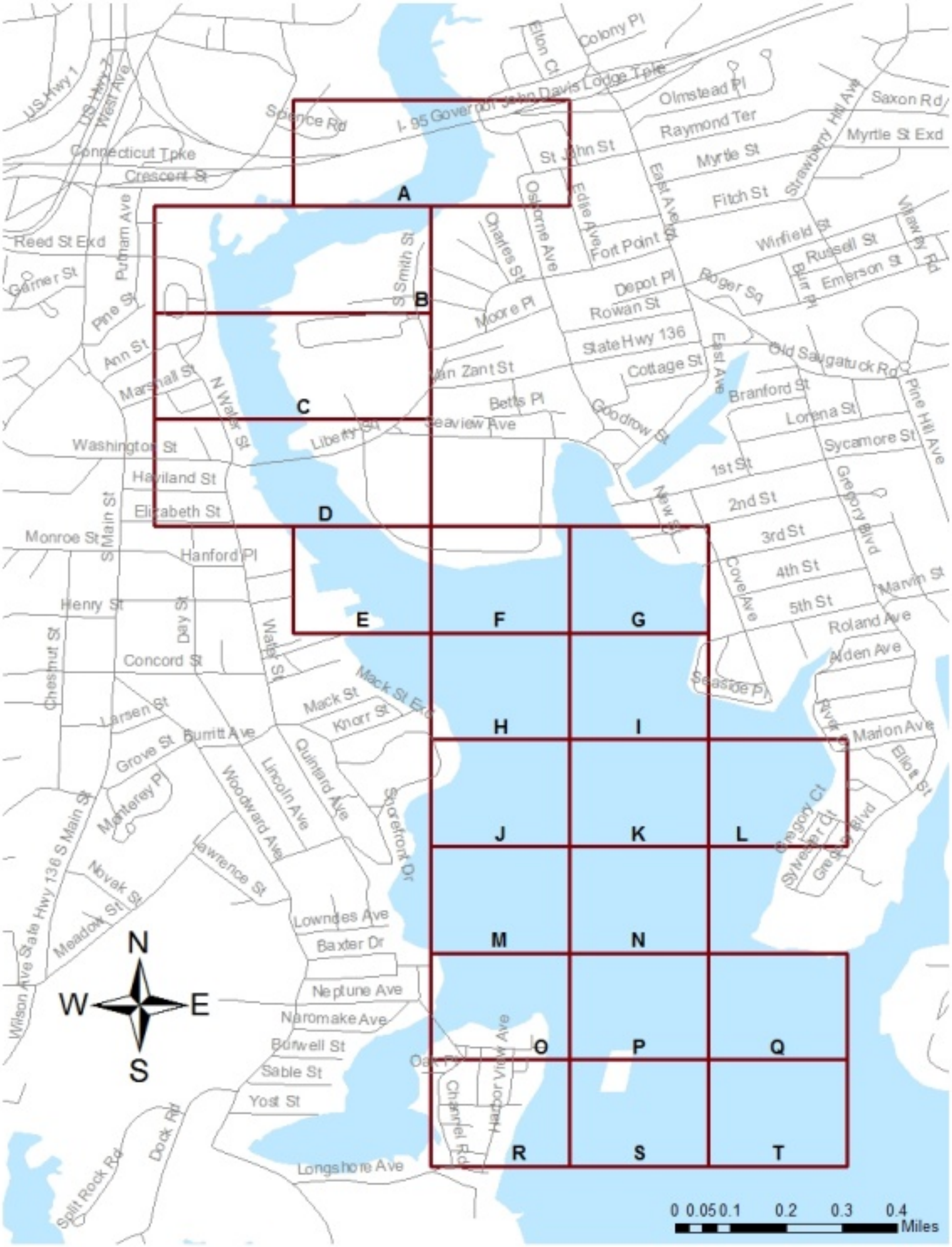

Figure 1.1. Location of trawl sampling areas or "boxes" within Norwalk Harbor.

Results and Discussion

Fish

During the 2018 sampling season, 148 individual fish from 14 different species were caught in Norwalk Harbor. The 3 most abundant species caught in 2018 were cunner (*Tautogolabrus adspersus*), northern searobin (*Prionotus carolinus*), and northern pipefish (*Syngnathus fuscus*), making up over 63% of the total number of individuals (Figure 1.2). Fish were observed in all 19 of the boxes sampled. Boxes “N” and “S” had the greatest number of fish per trawl during 2018, with 3.5 fish per trawl (total number of individuals over whole season divided by number of trawls in that box; Figure 1.3). While sampling was typically 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 (by becoming mud flats; Table 1.1). Eight individuals of an unknown species were collected in one trawl. These fish were believed to be Striped Bass but a more thorough confirmation of that identification was not conducted so they are reported as “unknown” species in this report. Despite bunker being present at the mouths of the harbors, there was a lack of bunker observed in the inner Norwalk Harbor, which tend to deplete dissolved oxygen resources when they are present (personal observations, R. Harris).

Table 1.1. Total number of trawls per box, May through October 2018

Box	# Trawls
A	5
B	4
C	5
E	3
F	4
G	3
H	4
I	4
J	3
K	5
L	5
M	5
N	2
O	3
P	3
Q	4
R	5
S	2
T	6
Total	**75**

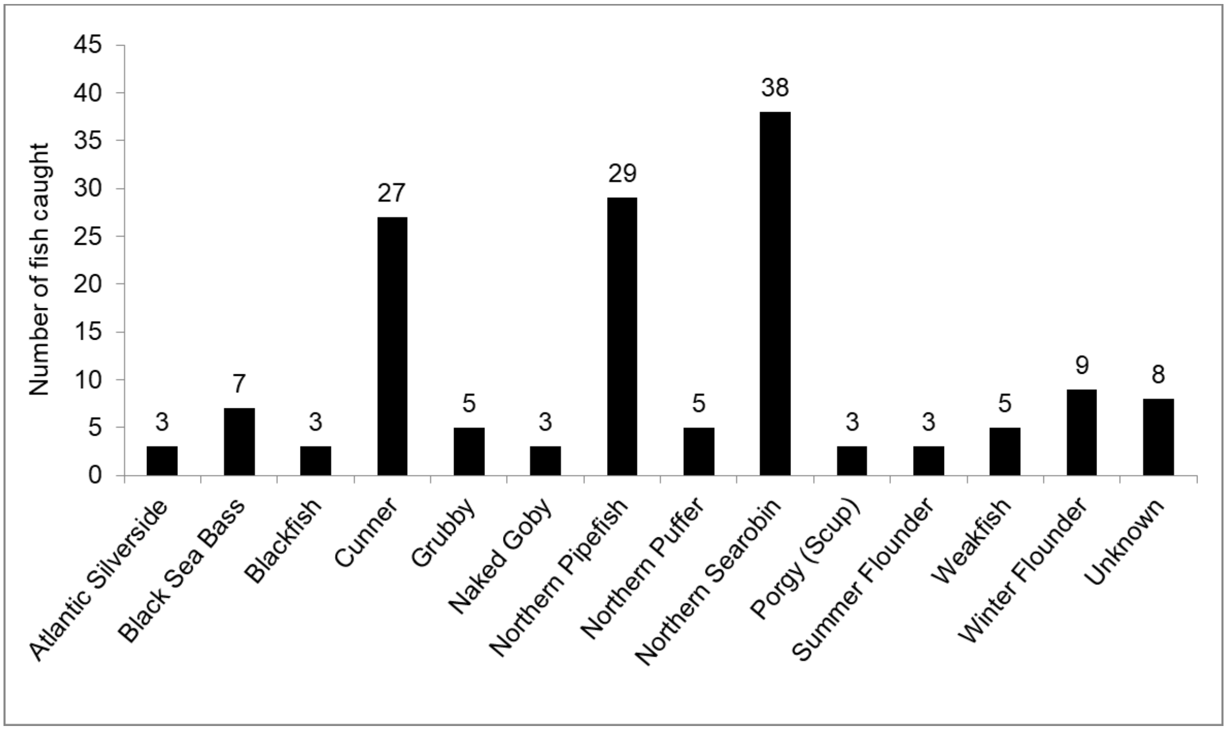

Figure 1.2. Total number of individuals caught for each species observed in Norwalk Harbor, May through October 2018.

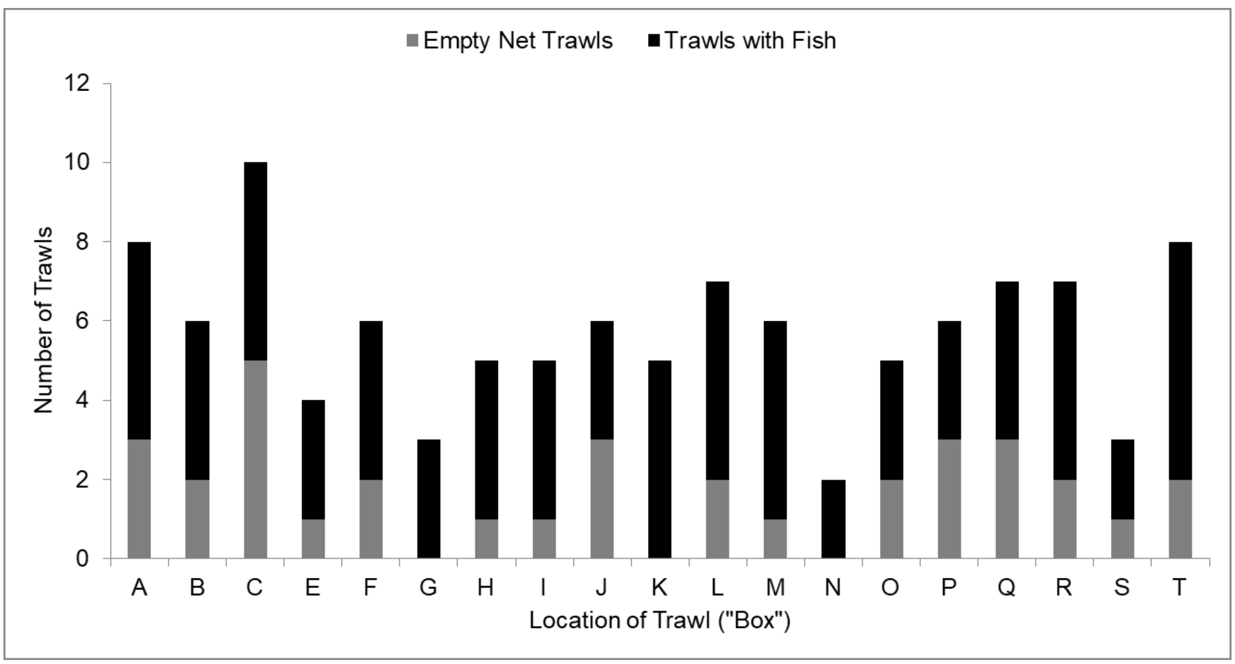

Figure 1.3. Number of trawls with fish or without fish in each "box" in Norwalk Harbor from May through October 2018.

The overall number of fish per trawl in 2018 was 1.97 fish. This was a slight increase from 2017 (Table 1.2, Figure 1.4). Potential drivers of the apparent decline in catch over time 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 2019.

The 2018 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. Only 9 winter flounder were caught in 2018.

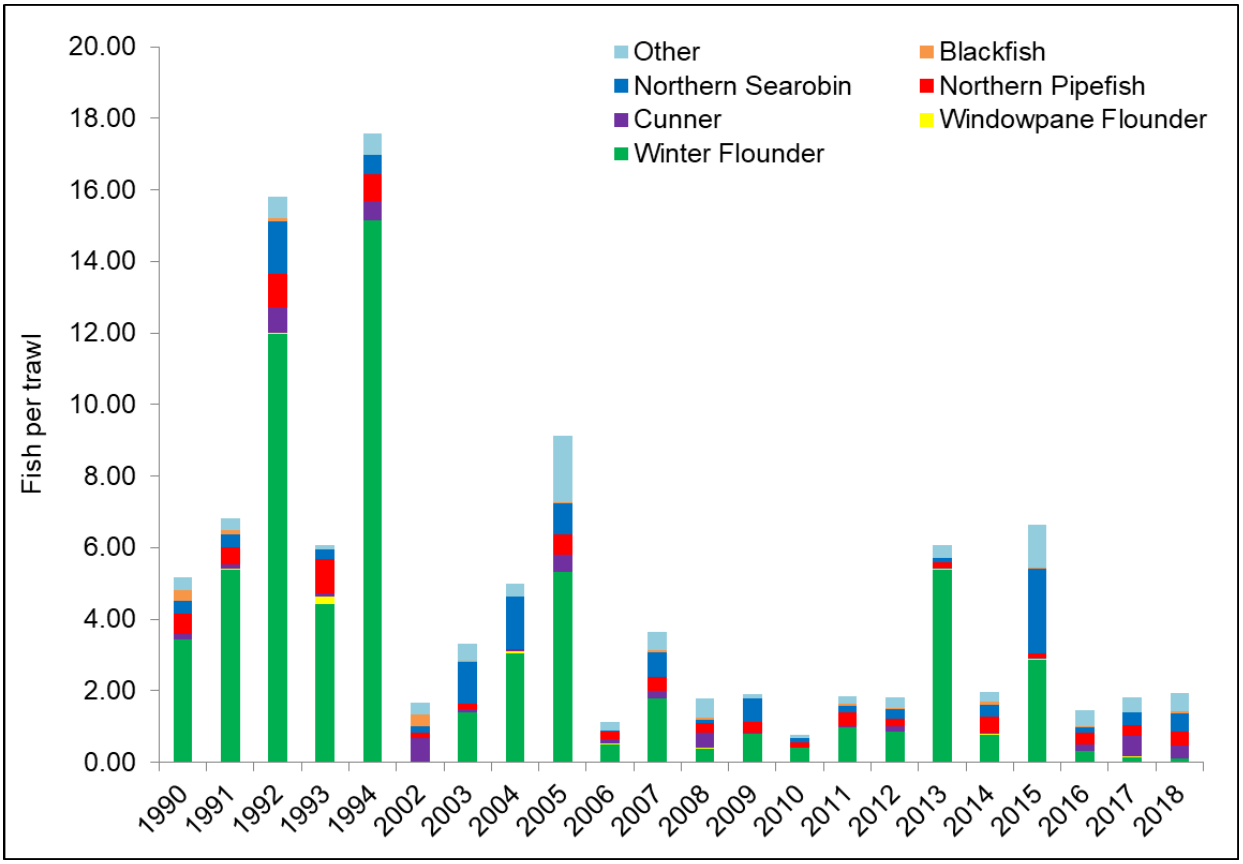

Figure 1.4. Number of fish caught per trawl (total number of individuals divided by total number of trawls) of species of interest from 1990 to 2018 in Norwalk Harbor.

Table 1.2 Catch per trawl for select species of interest from 1990 to 2018 in Norwalk Harbor

	Blackfish	Cunner	Winter Flounder	Windowpane Flounder	Northern Pipefish	Northern Searobin	Other	Total
1990	0.30	0.14	3.44	0.00	0.58	0.35	0.37	5.19
1991	0.12	0.12	5.38	0.03	0.48	0.36	0.33	6.83
1992	0.10	0.70	11.97	0.05	0.93	1.47	0.58	15.80
1993	0.01	0.07	4.42	0.23	0.96	0.26	0.12	6.07
1994	0.00	0.55	15.14	0.00	0.76	0.52	0.62	17.59
2002	0.33	0.67	0.00	0.00	0.17	0.17	0.33	1.67
2003	0.02	0.09	1.39	0.00	0.17	1.15	0.50	3.33
2004	0.00	0.03	3.05	0.05	0.03	1.48	0.34	4.98
2005	0.04	0.48	5.33	0.00	0.56	0.85	1.85	9.13
2006	0.00	0.12	0.51	0.03	0.20	0.03	0.25	1.13
2007	0.04	0.22	1.78	0.00	0.39	0.70	0.52	3.65
2008	0.06	0.44	0.38	0.02	0.26	0.10	0.54	1.80
2009	0.00	0.03	0.79	0.00	0.29	0.66	0.12	1.90
2010	0.00	0.00	0.41	0.00	0.16	0.12	0.07	0.75
2011	0.05	0.05	0.97	0.00	0.38	0.18	0.20	1.84
2012	0.03	0.13	0.87	0.00	0.22	0.28	0.29	1.82
2013	0.00	0.02	5.37	0.03	0.16	0.12	0.35	6.06
2014	0.10	0.01	0.76	0.05	0.47	0.32	0.27	1.97
2015	0.03	0.03	2.88	0.01	0.13	2.36	1.21	6.65
2016	0.02	0.20	0.32	0.00	0.33	0.15	0.44	1.45
2017	0.01	0.58	0.14	0.01	0.32	0.34	0.41	1.82
2018	0.04	0.36	0.12	0.00	0.39	0.51	0.52	1.97

Crustaceans

3,449 individual crustaceans representing 12 species were observed in 2018. The catch was dominated by shore shrimp, black fingered mud crabs, and long clawed hermit crabs, with those three species accounting for approximately 91% of the total (Figure 1.5).

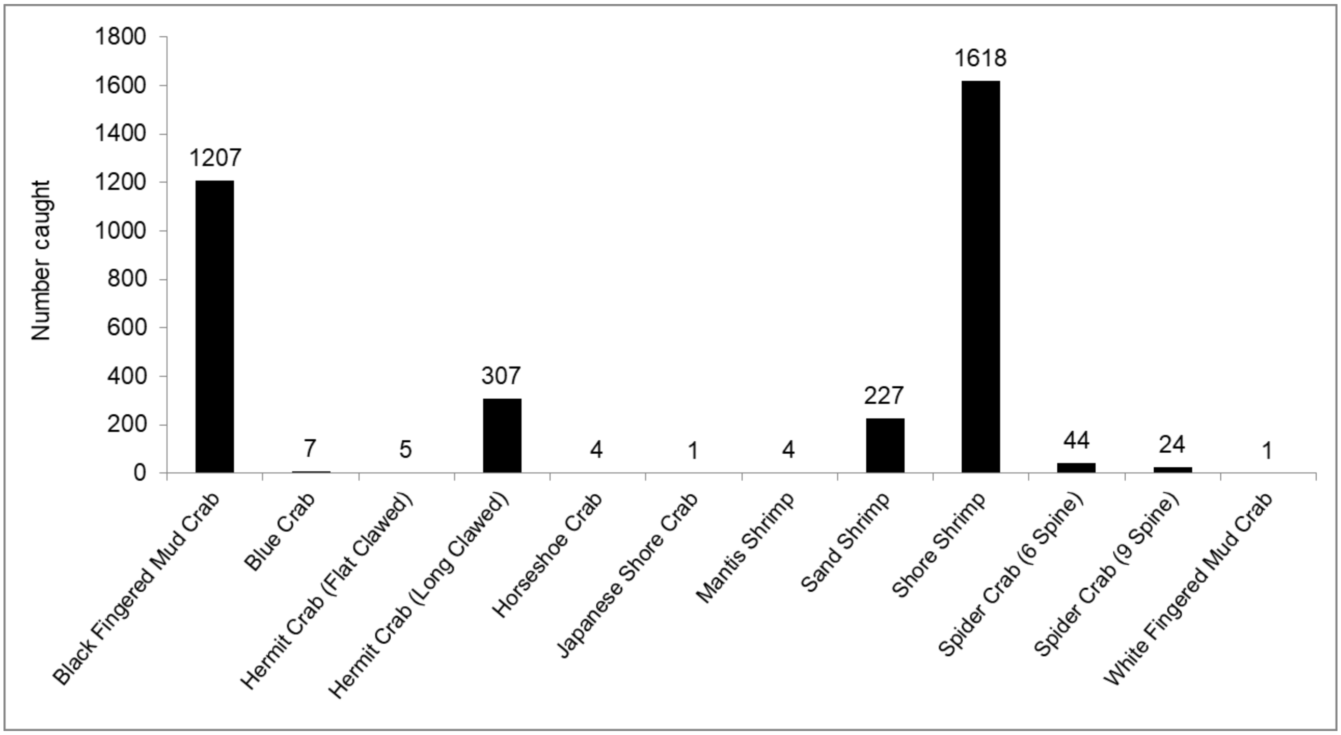

Figure 1.5. Total number of crustaceans caught by species in Norwalk Harbor from May through October 2018.

2. Dissolved Oxygen Surveys

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Norwalk Harbor, Saugatuck Harbor, Five Mile Harbor, Stamford Harbor, Bridgeport Harbor (Johnson's Creek and Lewis Gut sections), and New Haven Harbor (Quinnipiac River section) were studied in 2018. 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 2018, 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 when exposed to oxygen demanding (reducing) bottom sediments and poor flushing. 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.

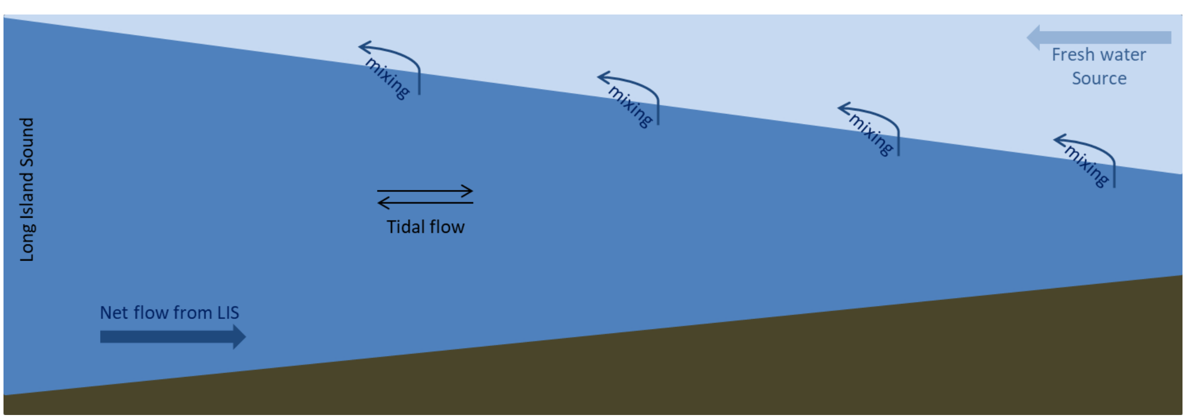


Figure 2.1. Sketch of estuary tidal wedge, water flow, and water column mixing.

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 filled in for shoreline development and are replaced with man-made bulk-heading. Two harbors monitored in this study where large marshes are present and contribute to flushing efficiency are New Haven Harbor (Quinnipiac River section) and Lewis Gut. In many harbors throughout New England, the majority of historic salt marshes have been lost (Bromberg and Bertness 2005).

Two natural forces that can affect flushing in a 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 (upwelling and downwelling). This movement of water can help to increase oxygen concentrations at the bottom.

Rainfall can have negative or 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 decreased dissolved oxygen conditions.

Rainfall totals varied along the coast. The largest amount of rainfall fell during September averaging 9.52 inches of rain with the smallest accumulation in May averaging 3.11 inches based on data from four rain gauges across the coast (Figure 2.2, Weather Underground Historical Weather, Norwalk Health Department Raingauge). Rainfall totals were highest in the Norwalk area, totaling 32.31 inches from May through September (Weather Underground Historical Weather, Norwalk Health Department Raingauge), nearly 12 inches more than the year prior (Figure 2.3). In 2017, there was a general downward trend during the monitoring season with more rainfall occurring in May, while in 2018 rainfall was highest in all harbors in September. Although rainfall in the harbor area is important, rainfall inland can greatly increase river flow into an estuary. During 2018, rivers feeding the six estuaries were substantially higher at the end of the summer than in 2017; Norwalk River is a good example (Figure 2.C.9).

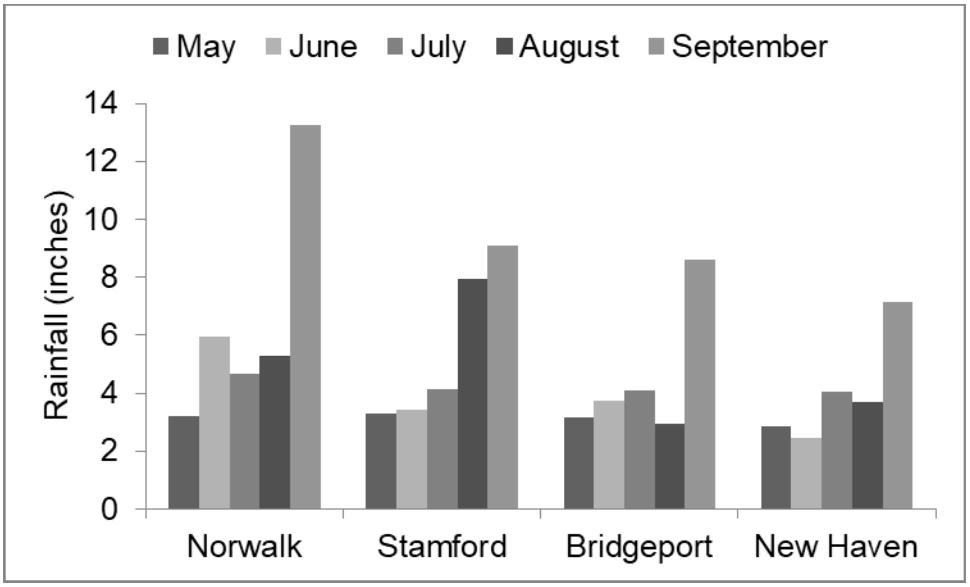


Figure 2.2. Rainfall totals for each geographical area monitored. Stamford, Bridgeport and New Haven precipitation data was collected from Wunderground.com while Norwalk precipitation data was collected from the Norwalk Health Department rain gauge.

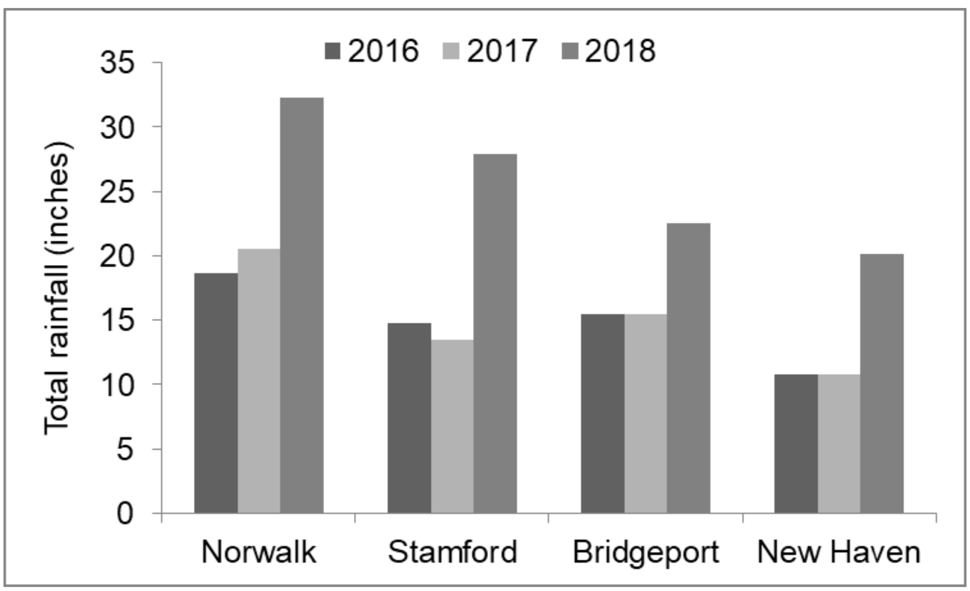


Figure 2.3. May through September rainfall totals in 2016, 2017, and 2018 for each geographical area monitored. Stamford, Bridgeport and New Haven precipitation data were collected from Wunderground.com, while Norwalk precipitation data were collected from the Norwalk Health Department rain gauge.

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 sampling (May to September). Additional year-round studies will be needed to fully assess the productivity status of these 6 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 (Crosby et al. 2018b). In 2018, conditions overall had improved, with 93% of the observed dissolved oxygen levels being above 3 mg/L. Norwalk Harbor and Stamford Harbor had the greatest percentage of observations below 3 mg/L, at 13% (Figure 2.4). Norwalk Harbor has a history of poor flushing and extended periods of hypoxia in the upper reaches of the harbor. Hypoxia (defined as values < 3 mg/L) was not observed in New Haven Harbor during this sampling; however it had the greatest percentage of sampling events with observed concentrations of dissolved oxygen less than 5 mg/L. In the following pages, a detailed analysis of each harbor will be discussed.

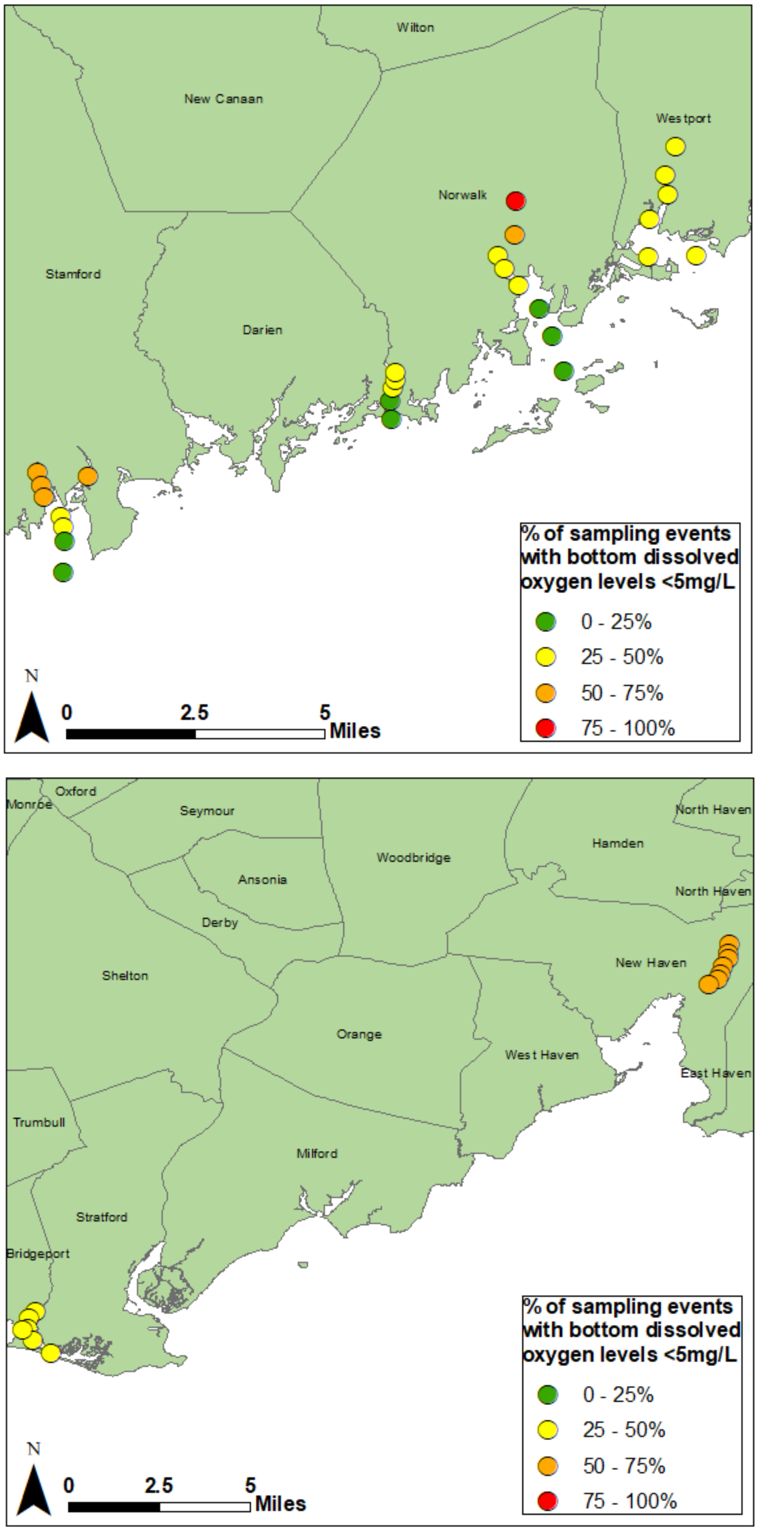


Figure 2.4. Percentage of sampling days where bottom dissolved oxygen values fell below 5 mg/L in 2018 in the western harbors (top) and the eastern harbors (bottom).

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 5 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 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 Fisherbrand 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 one of two labs used for analysis: (1) the National Oceanic and Atmospheric Administration laboratory in Milford, CT where they were analyzed for chlorophyll *a* concentrations by Dr. Julie Rose, or (2) the Harbor Watch laboratory in Westport, CT where they were analyzed by Nicole Spiller. 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). Filtered samples processed by Harbor Watch used the same method but on a Turner Trilogy fluorometer. 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 (Weather Underground 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 (City of Stamford Website: “The Plant”). With the exception of differences in freshwater 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. Commercial sand and gravel and industrial facilities are located near the 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 to the south. 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.

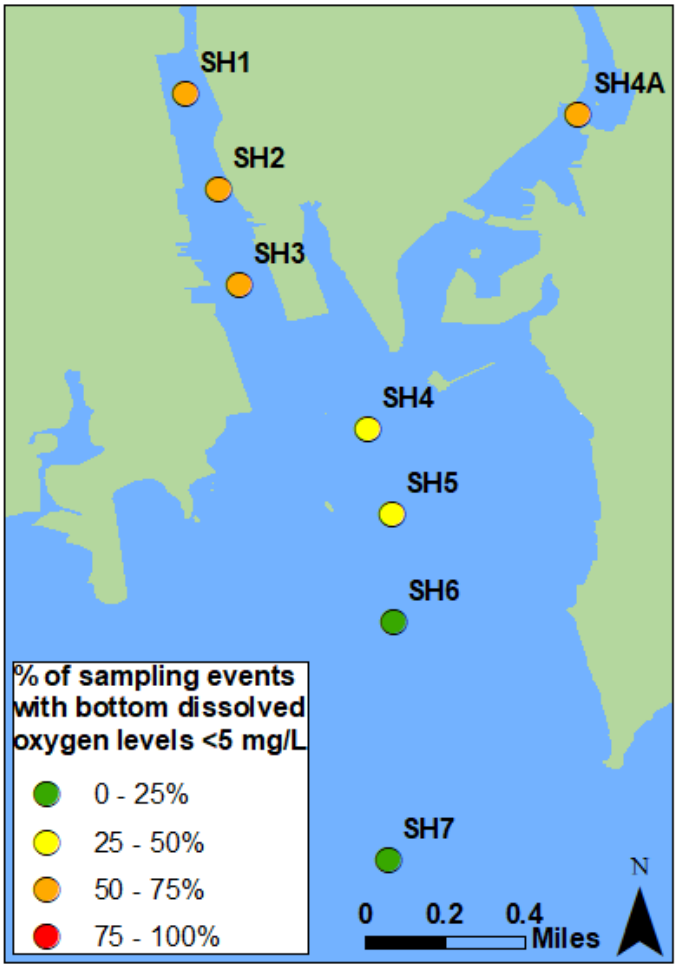


Figure 2.A.2. Map of Stamford Harbor sampling stations for 2018. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 5 mg/L.

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

Site Name	Latitude	Longitude	Description
SH-1	41.041283	-73.545000	Off Sand and Gravel Facility
SH-2	41.037817	-73.543833	Nun Buoy #10
SH-3	41.034350	-73.543083	Can Buoy #7
SH-4	41.029150	-73.538400	Can Buoy #1
SH-4A	41.040500	-73.530850	East branch off Woodland Cemetery
SH-5	41.026100	-73.537550	Can Buoy #9
SH-6	41.022183	-73.537450	Can Buoy #7
SH-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 7 days during the monitoring season. Mean dissolved oxygen values in Stamford Harbor ranged from a minimum of 4.09 mg/L on the bottom at SH-1 to a mean dissolved oxygen of 7.4 mg/L on the surface at SH-5 (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 seasonal downward trend in dissolved oxygen values at both the surface and the bottom as the summer progressed, but a recovery of dissolved oxygen levels began in late August with the seasonal cooling for surface waters (Figure 2.A.4). Forty two percent of the dissolved oxygen concentrations observed were less than 5 mg/L, and 13% were less than 3 mg/L. During early August, a seasonal recovery in dissolved oxygen values was observed at stations SH-1 through SH-4 (Figure 2.A.4).

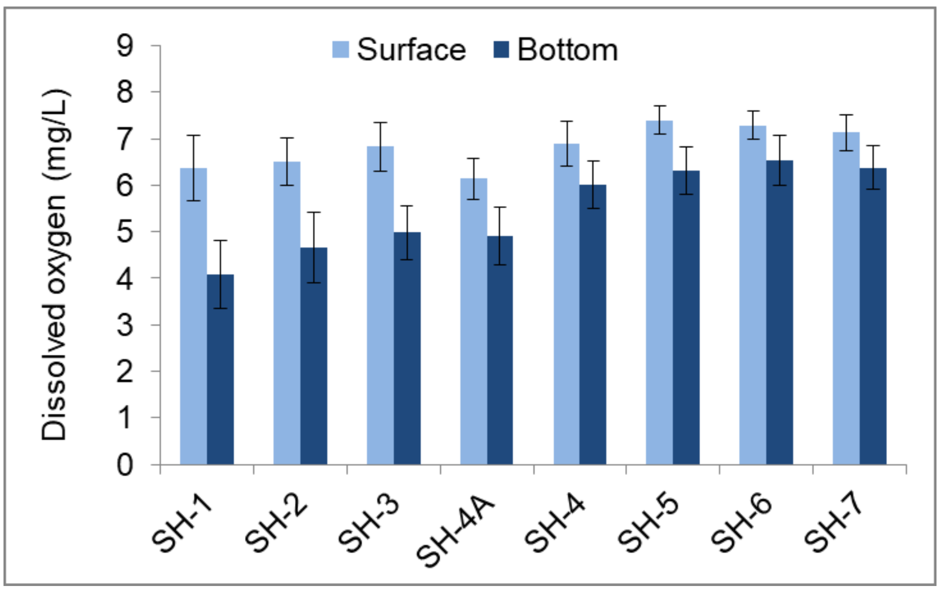


Figure 2.A.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Stamford Harbor in 2018. Error bars represent standard error.

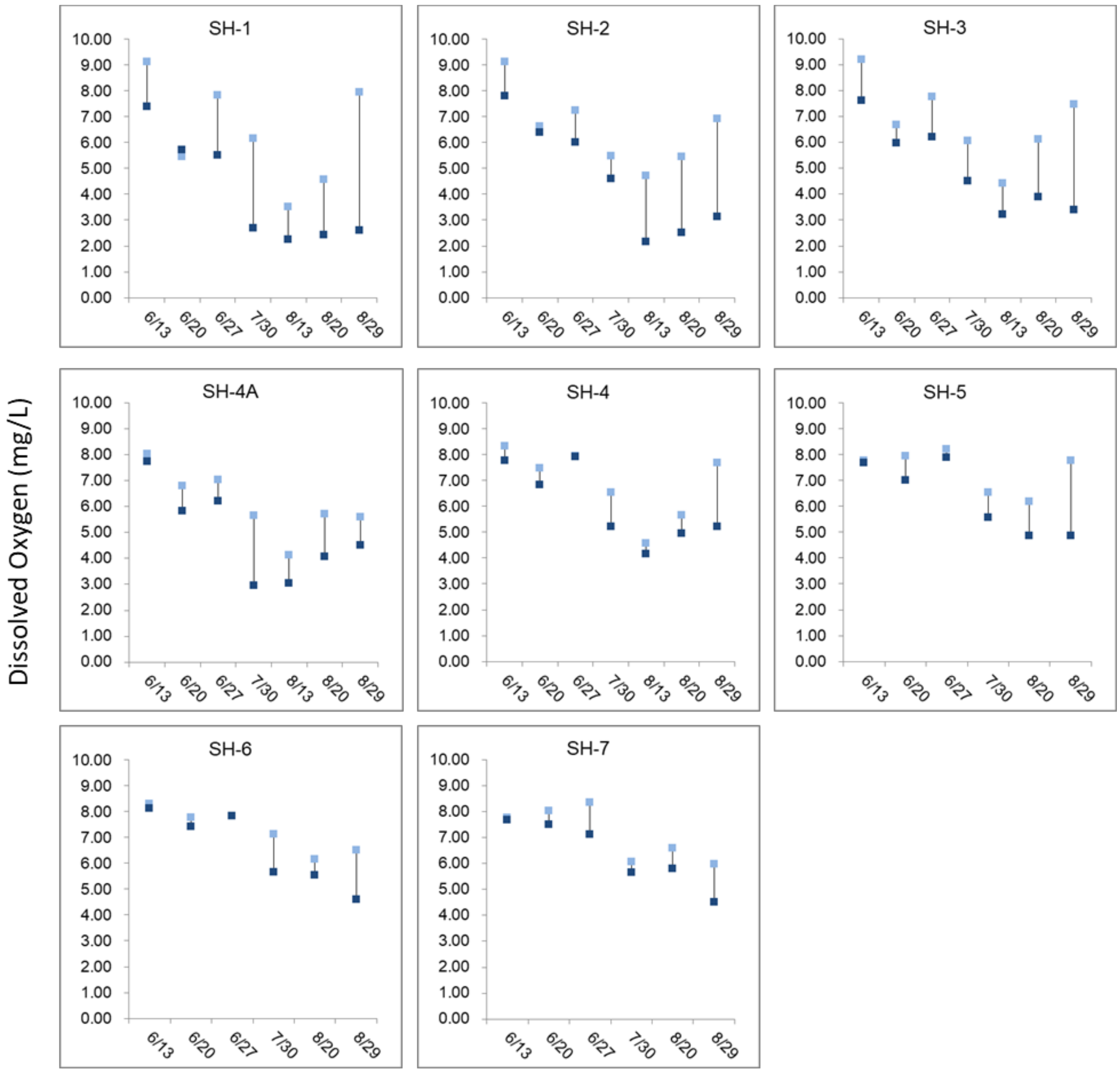


Figure 2.A.4. Surface and bottom dissolved oxygen values at each Stamford Harbor sampling station on each monitoring date during the 2018 season. Light blue squares represent surface dissolved oxygen values and dark blue squares represent bottom dissolved oxygen values.

Chlorophyll a

Chlorophyll *a* samples were taken on 4/12, 5/22, 6/13, and 7/19/2018. While the harbor was classified in the medium eutrophic or highly eutrophic range in 2017, the concentrations observed in 2018 were generally much lower (Table 2.1) at the northern end of the west branch, allowing for a medium eutrophic classification for the Stamford estuary.

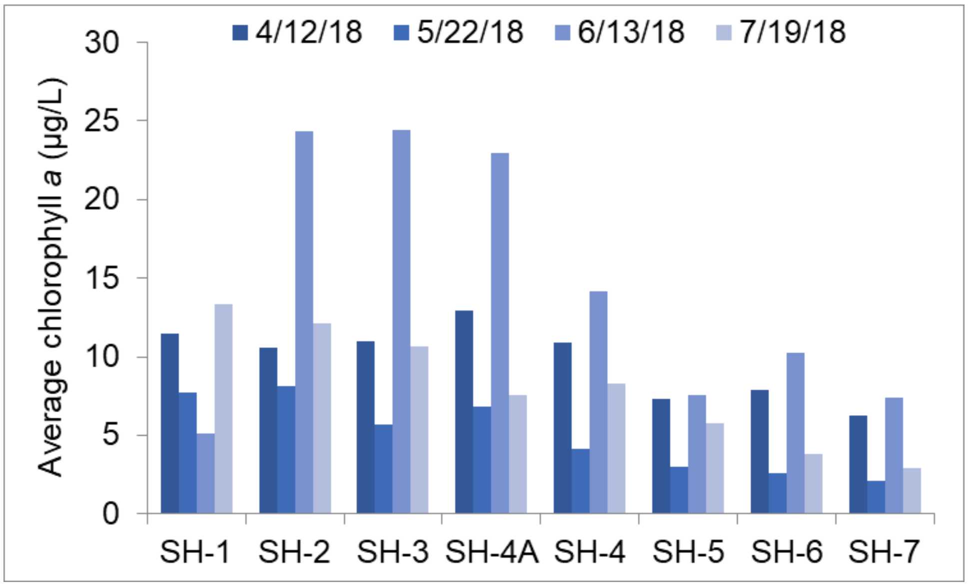


Figure 2.A.5. Average chlorophyll *a* values in Stamford Harbor in 2018.

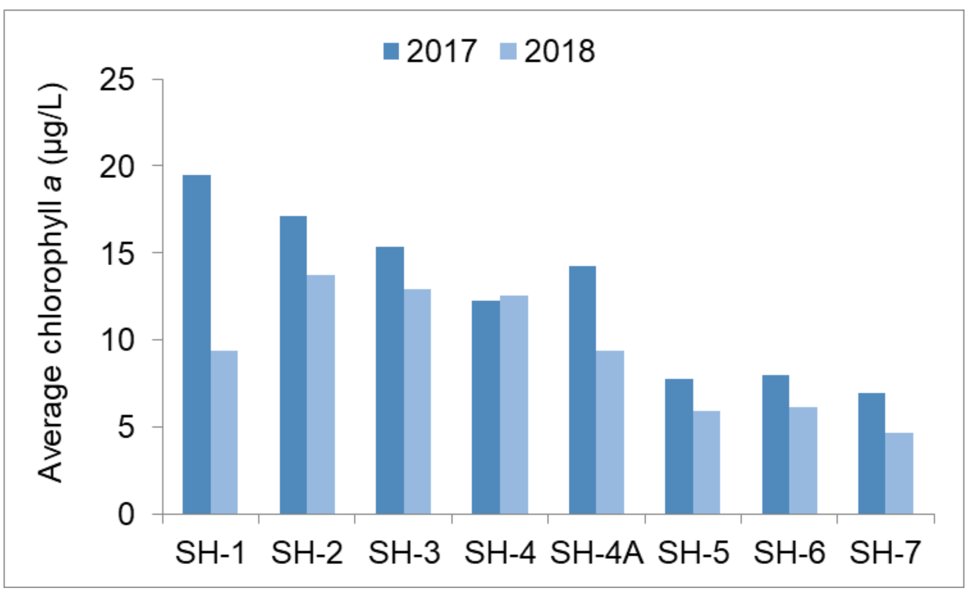
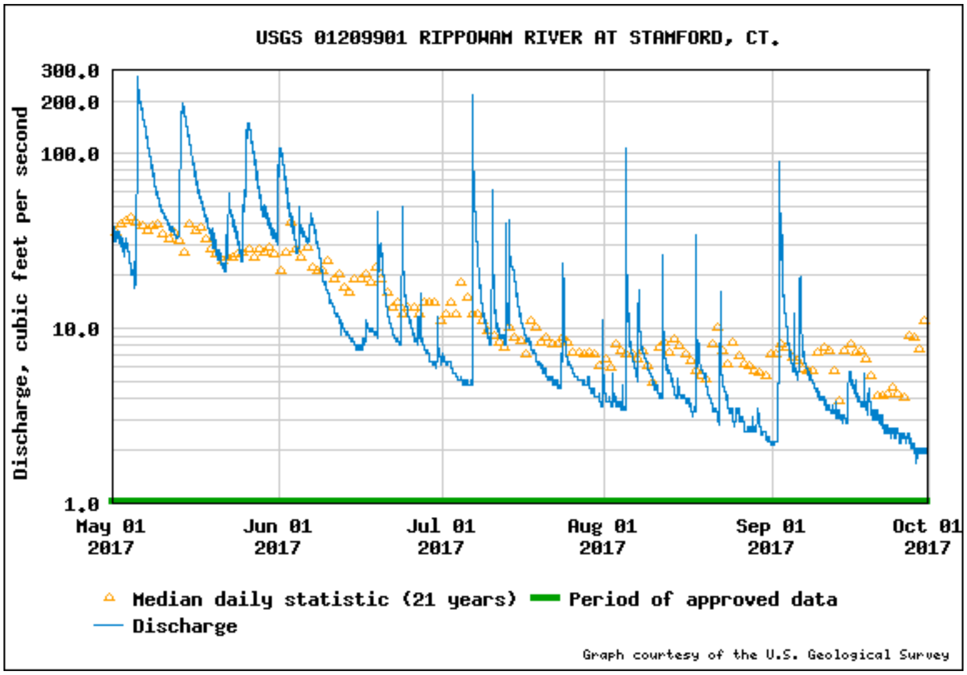


Figure 2.A.6. Comparison of average chlorophyll *a* values at each station in Stamford Harbor in 2017 and 2018.

Rippowam River Discharge

The figures below illustrate discharge in cubic feet per second recorded at the United States Geological Survey (USGS) 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 2018, discharge was observed to be episodically much higher than the prior year during storm events. 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.



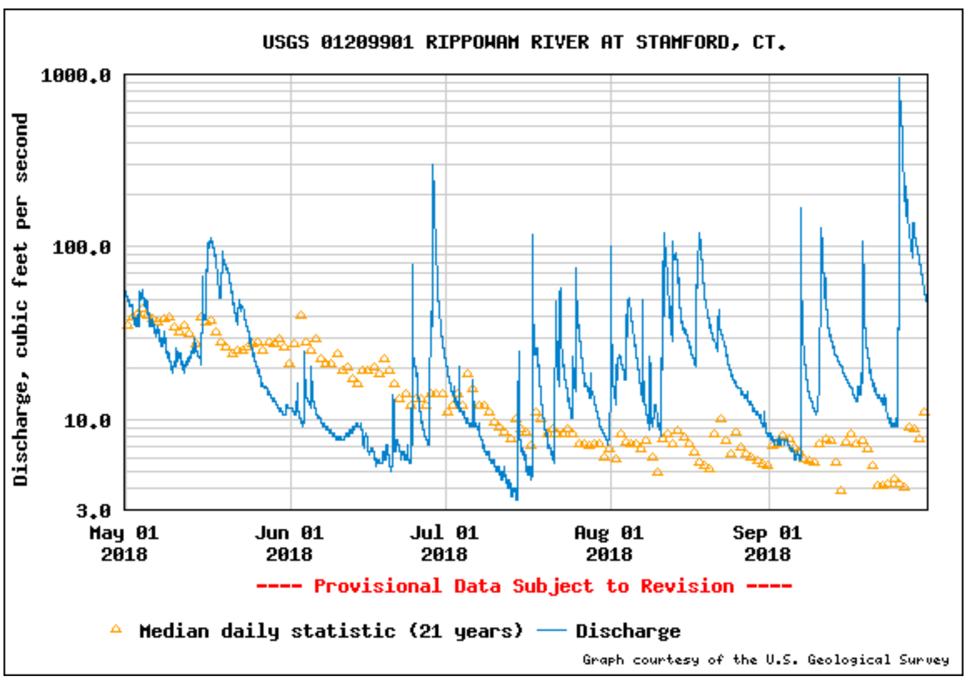


Figure 2.A.7. USGS flow data in $feet^3/s$ for the period of May 1 through October 1, 2017 (above) and May 1 through September 30, 2018 (below), respectively for the Rippowam River in Stamford, CT (Graphs courtesy of the U.S. Geological Survey). Please note the difference in scale on the x-axis.

Temperature and Salinity
Temperature of the water in Stamford Harbor differed less than the dissolved oxygen levels between the surface and the bottom (Figure 2.A.8). Lower surface salinity at the first station reflects stronger seasonal riverine input versus 2017 (Figure 2.A.7, Figure 2.A.9).

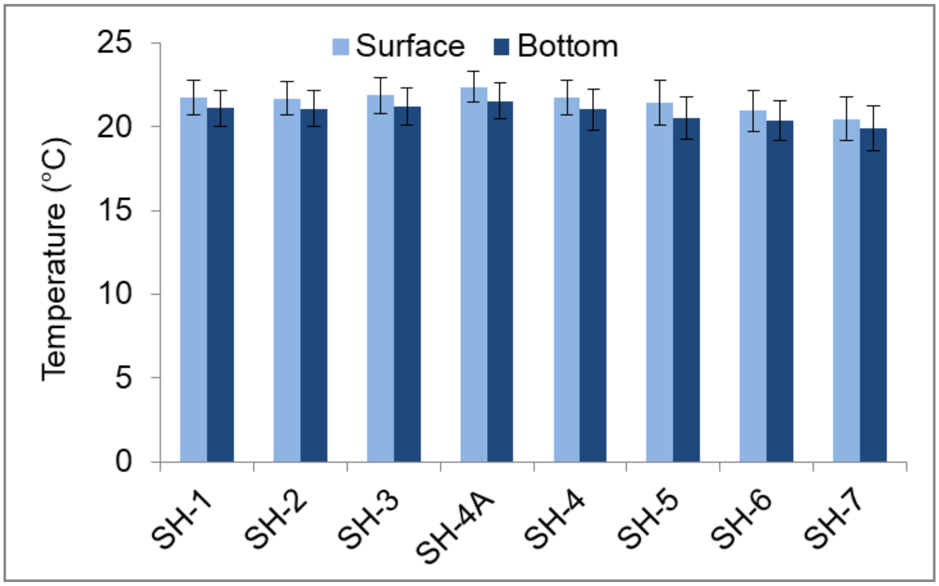


Figure 2.A.8. Mean water temperature at the surface and bottom at each sampling station in Stamford Harbor in 2018. Error bars represent standard error.

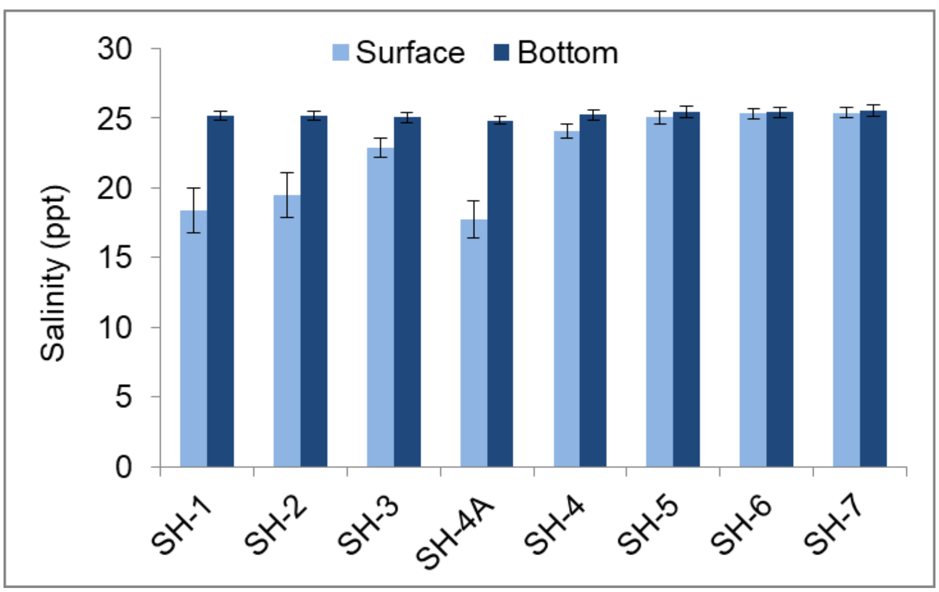


Figure 2.A.9. Mean salinity at the surface and bottom at each sampling station in Stamford Harbor in 2018. Error bars represent standard error.

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.

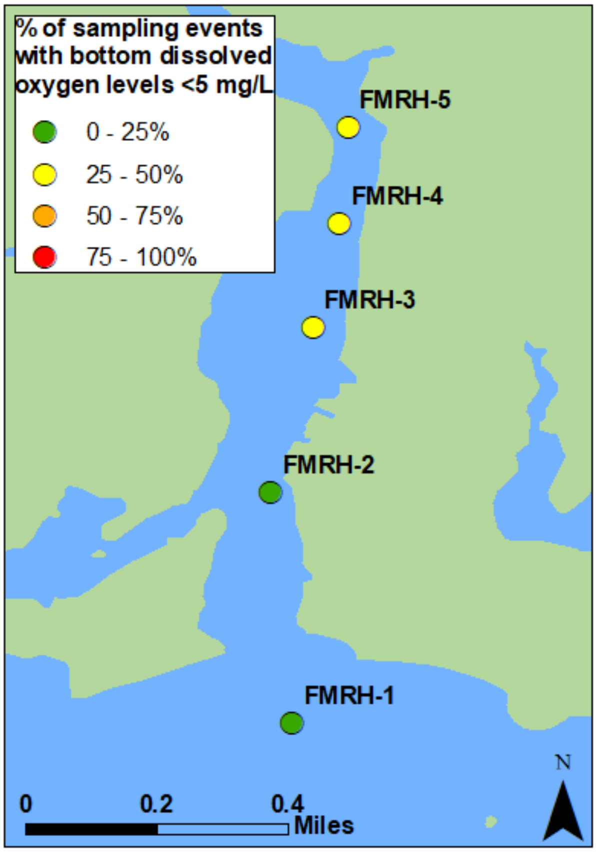


Figure 2.B.1. Map of Five Mile River Harbor sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 5 mg/L in 2018.

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) on 10 days during the monitoring season. Surface and bottom dissolved oxygen concentrations observed at all sites had mean values above 5 mg/L (Figure 2.B.2). However, individual dissolved oxygen concentration readings below 5 mg/L were observed at some stations on some dates (Figure 2.B.4). Station FMRH-5 had the lowest observed dissolved oxygen levels, likely due to the decrease in mixing as the harbor becomes narrower further inland. The low dissolved oxygen levels at this station likely also resulted from the water in the incoming tidal wedge from Long Island Sound being in contact with oxygen-reducing bottom sediments along the length of the harbor. Dissolved oxygen concentrations generally decreased from May to July, after which there was evidence of a recovery continuing into the fall (Figure 2.B.4). The highest concentration of dissolved oxygen observed was 11.57 mg/L and the lowest observed was 2.70 mg/L. Twenty-six percent of the dissolved oxygen observations were less than 5 mg/L, and 2% were less than 3 mg/L.

During the 2018 season, bottom mean values of 5.3 mg/L for dissolved oxygen at station FMRH-5 increased downstream to 7.05 mg/L at station FMRH-1 (Figure 2.B.2). Surface dissolved oxygen at stations FMRH-5 and FMRH-1 were 8 mg/L and 7.98 mg/L respectively (Figure 2.B.2). The increase in surface dissolved oxygen values during the 2018 season is possibly due to the increase in the Five Mile River flow bringing in larger volumes of well oxygenated fresh water during 2018 (Figure 2.B.6). In comparison, mean dissolved oxygen values in Five Mile River Harbor during the 2017 season showed mean bottom values that gradually increased from 6.02 mg/L at the northern-most station, FMRH-5, to 7.18 mg/L at the southern-most station, FMRH-1 (Figure 2.B.1, Figure 2.B.3). Surface dissolved oxygen values gradually increased from 6.57 mg/L at station FMRH-5 downstream to 7.29 mg/L at station FMRH-1 (Crosby et al. 2018b).

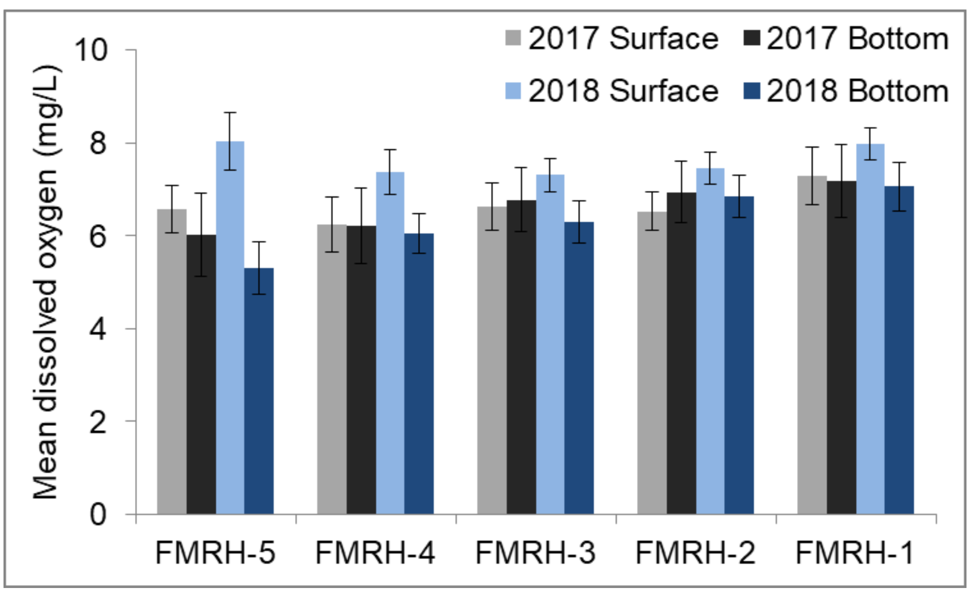


Figure 2.B.2. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Five Mile River Harbor in 2017 and 2018. Error bars represent standard error.

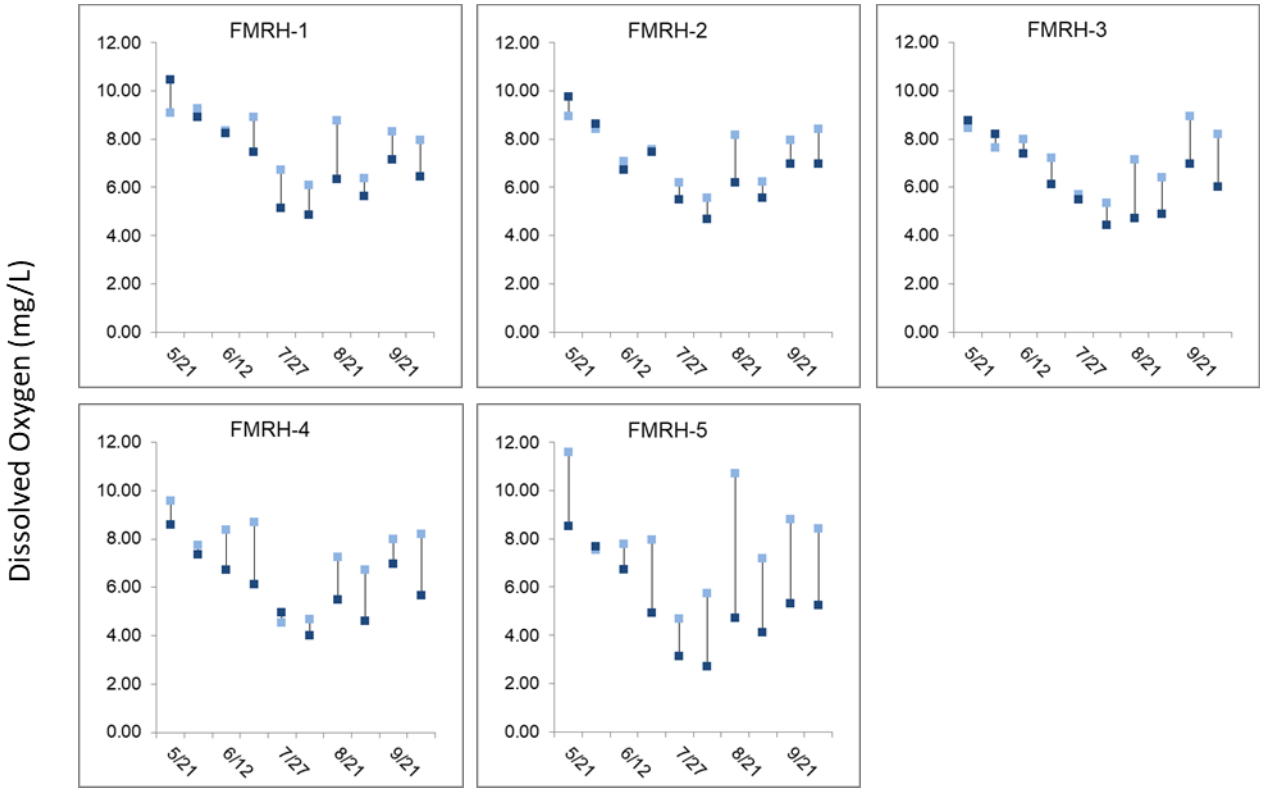


Figure 2.B.4. Surface and bottom dissolved oxygen values at each Five Mile River Harbor sampling station on each monitoring date during the 2018 season. Light blue squares represent surface dissolved oxygen values and dark blue squares represent bottom dissolved oxygen values.

Chlorophyll a

Chlorophyll *a* samples were taken on 5/21, 5/25, 7/23, 8/6, and 8/21/2018. Five 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.5, Table 2.1). Results from the 2018 study were similar to those observed during the 2016 and 2017 seasons with the exception that higher concentrations (possibly phytoplankton blooms) appear to be centered on lower harbor stations (Figure 2.B.5, Crosby et al., 2017, and 2018b) The higher concentrations observed on 7/23 and 8/21 may have been influenced by rainfall prior to monitoring, (i.e., 0.86 inches fell on the estuary one day prior to testing on 7/23 and a total of 0.55 inches fell two days prior to testing on 8/21; Figure 2.B.5, Norwalk Health Department Raingauge). The rain may have increased the supply of available nitrogen to the harbor and could have contributed to the growth of phytoplankton (Figure 2.B.5).

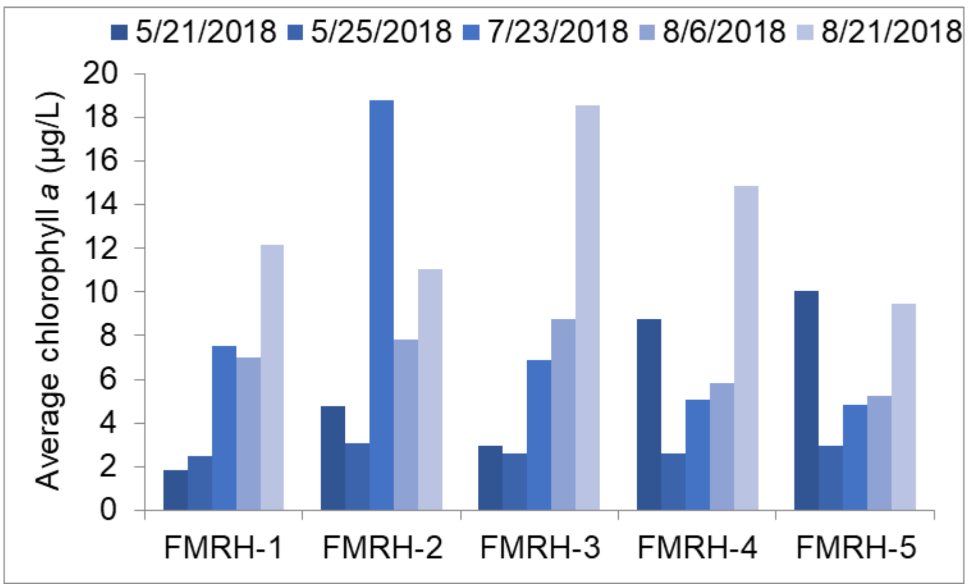
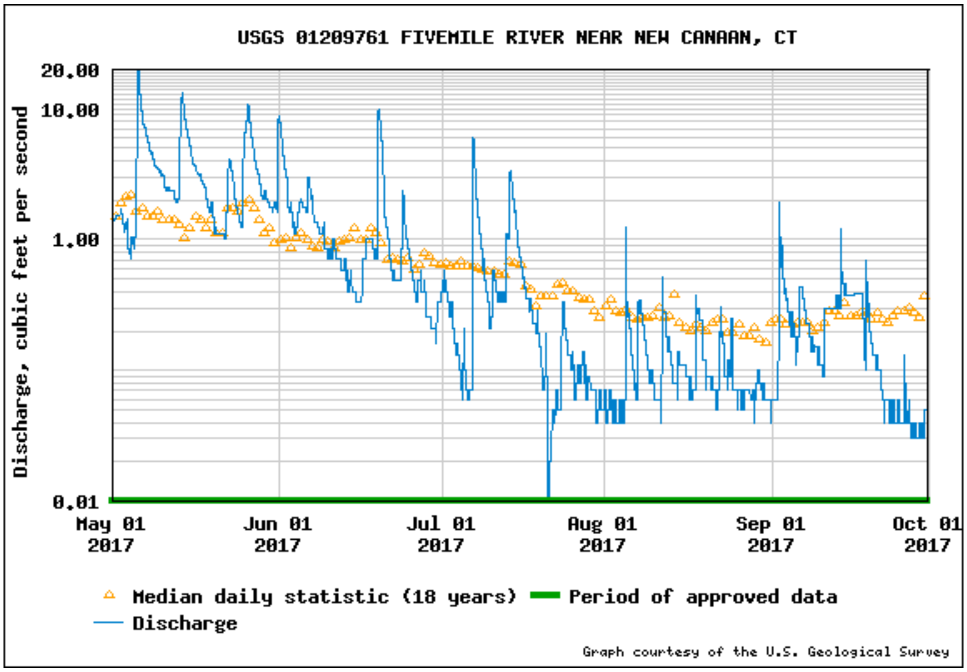


Figure 2.B.5. Average chlorophyll *a* values in Five Mile River Harbor in 2018.

Five Mile River Discharge

The figures below illustrate discharge rates recorded at the United States Geological Survey monitoring station on the Five Mile River in New Canaan, CT. Yellow triangles represent the daily median value over the last 18 years, and the blue line represents the recorded discharge for a particular date. In 2017, larger storm events were observed early in the monitoring season, while in 2018, several major storm events with heavy discharge rates were observed that greatly exceeded the 18 year average flow during August and September (Figure 2.B.6).



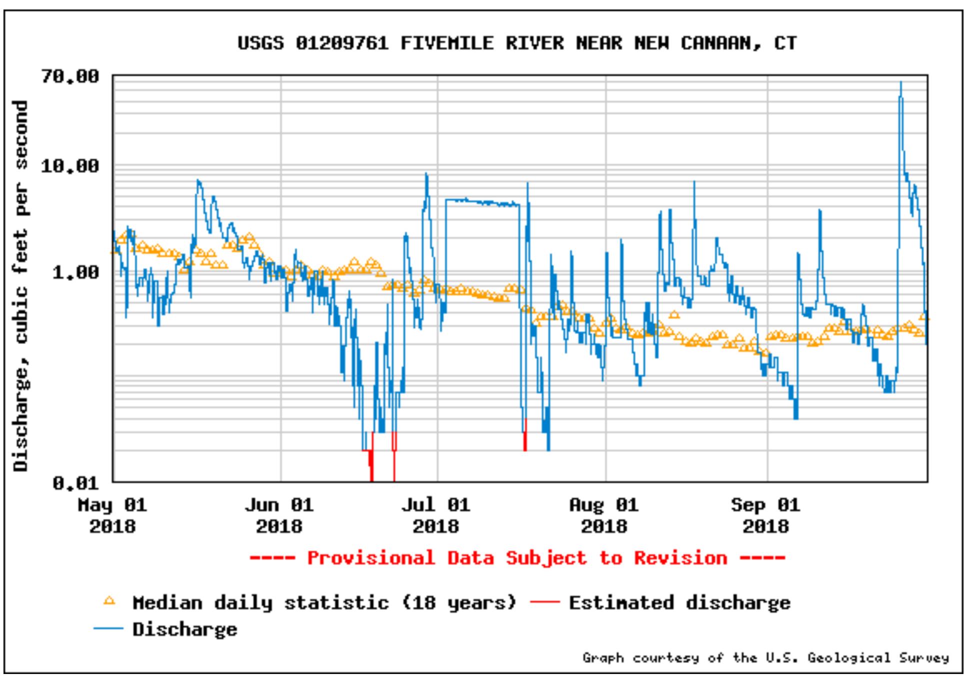


Figure 2.B.6. USGS discharge rates for the period of May 1st through October 1st for the 2017 and 2018 monitoring seasons respectively for the Five Mile River in New Canaan, CT (Graphs courtesy of the U.S. Geological Survey). Please note the difference in the scale of the x-axis.

Temperature and Salinity

Temperature of the water in Five Mile River Harbor differed less than the dissolved oxygen levels between the surface and the bottom, though on average the marine water at the harbor bottom was cooler at all sites (Figure 2.B.7). Lower salinity observed at the surface in the soundward end of the estuary reflects the impact of riverine input from the north, where the harbor is less well mixed (Figure 2.B.8).

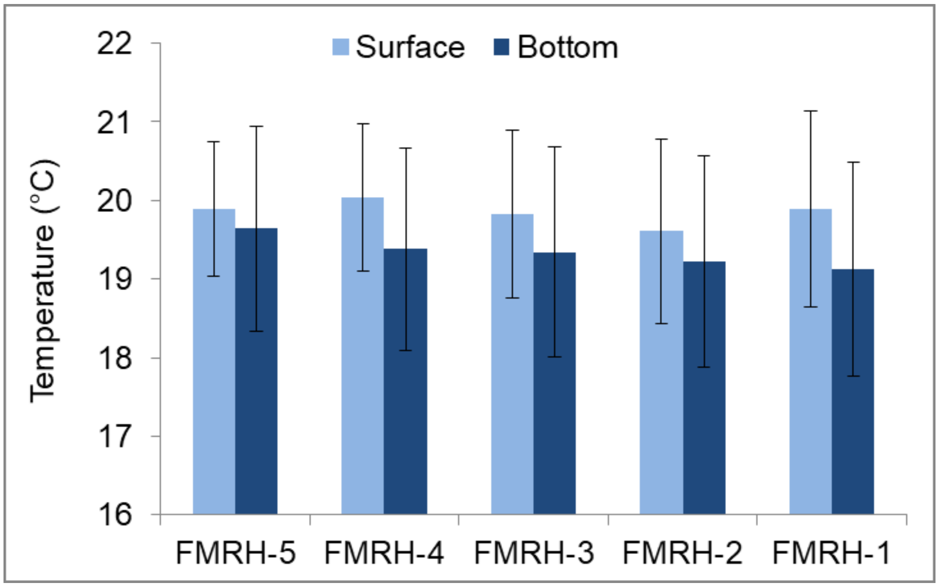


Figure 2.B.7. Mean water temperature at the surface and bottom at each sampling station in Five Mile River Harbor in 2018. Error bars represent standard error.

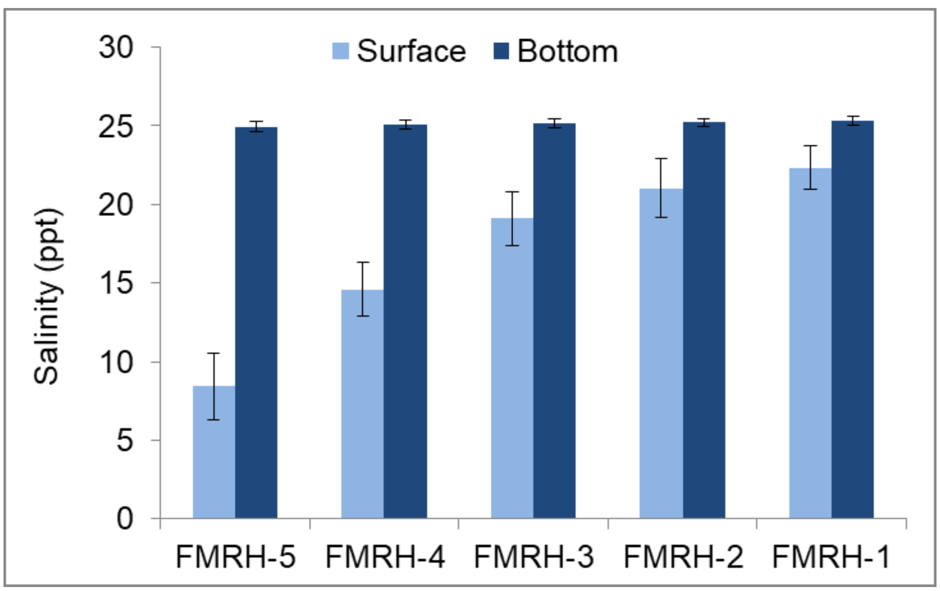


Figure 2.B.8. Mean salinity at the surface and bottom at each sampling station in Five Mile River Harbor in 2018. Error bars represent standard error.

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 includes 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 included the length of the estuary (Figure 2.C.2) from Wall Street to the Norwalk Islands, had 8 monitoring stations. The outer harbor 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. The latter was monitored by volunteers from USCG Flotilla 72.

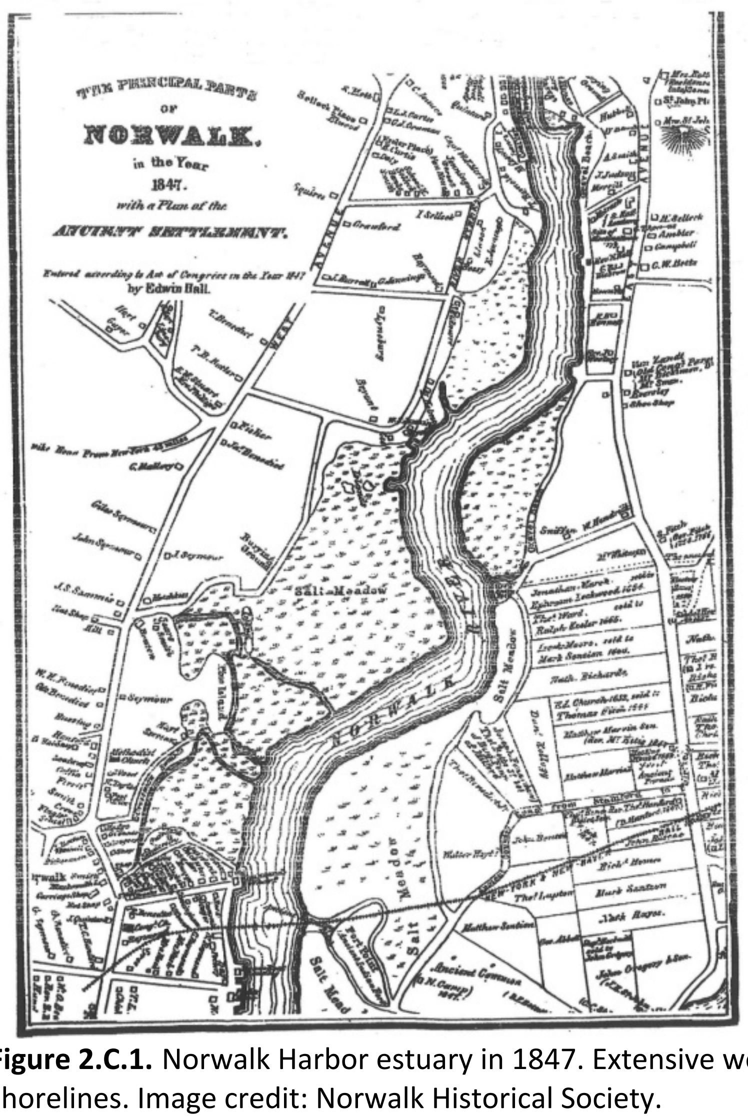


Figure 2.C.1. Norwalk Harbor estuary in 1847. Extensive wetlands once dominated both shorelines. Image credit: Norwalk Historical Society.

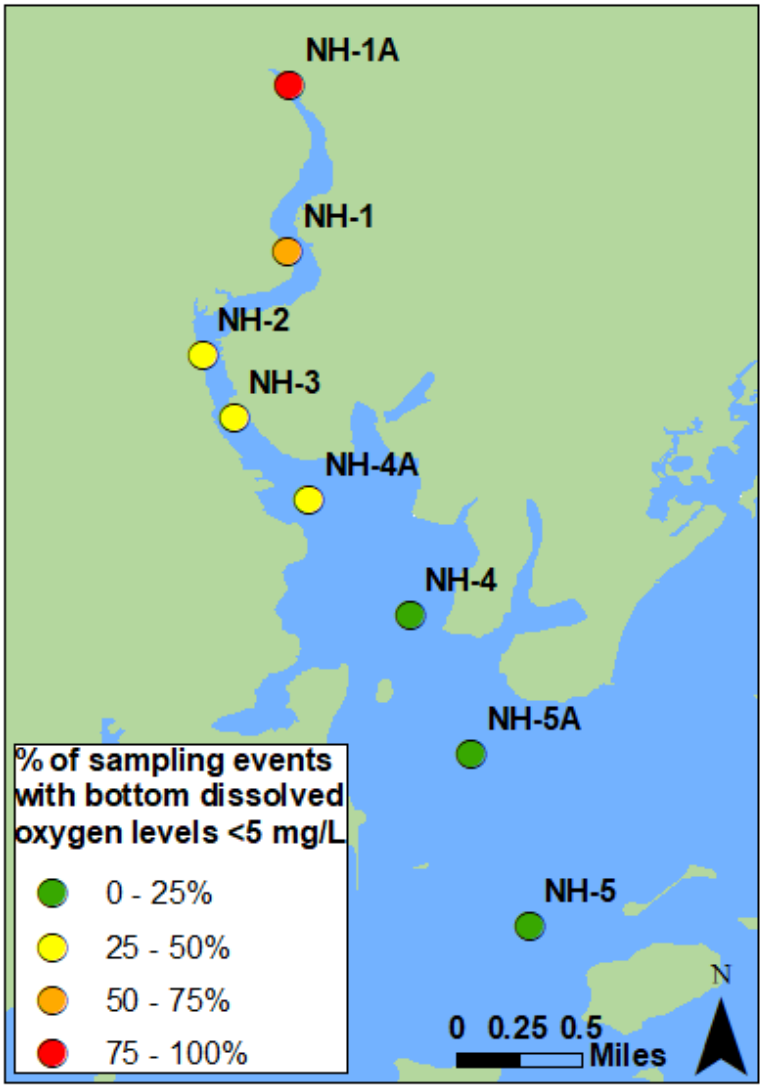


Figure 2.C.2. Map of Norwalk Harbor sampling stations in the inner harbor for 2018. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 5 mg/L.

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 19 times between May and October 2018. Mean dissolved oxygen concentrations ranged from 2.64 mg/L at the bottom to 8.29 mg/L at the surface at station NH-1A (Figure 2.C.3). Thirty-seven percent of the dissolved oxygen observations were less than 5 mg/L, while 13% were less than 3 mg/L.

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 steadily increasing flow of fresh water from heavy rainfall entering the harbor from the Norwalk River (Figure 2.C.3, Figure 2.C.9, Figure 2.C.11). This stratification led to station NH-1A consistently being the site with the most impaired water in the harbor for dissolved oxygen.

Figure 2.C.4 shows what appears to be almost a single dot representing dissolved oxygen concentrations observed on 6/29 at station NH-1A. Salinity values were observed at 0.02 ppt from surface to bottom, indicating that the entire site was comprised of freshwater from the Norwalk River. On 6/28, rainfall of 3.97 inches was recorded at the Norwalk Health Department Raingauge which resulted in this surge in fresh water at station NH-1A. Storms of this magnitude are increasingly common due to climate change. Rainfall of 73.55 inches recorded at

the Norwalk Health Department Raingauge for the year 2018 was a new record since record keeping began in 1987 and was 27.14 inches more than what was observed during 2017. The toe of the tidal wedge at the bottom of station NH-1A represents marine water that spends the longest time in the estuary and is oxygen depleted due to strongly-reducing bottom sediments. As the fresh water flowing along the surface from the Norwalk River moves seaward the mixing increases, 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, Norwalk WPCA Website).

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. The stations south of NH-4A exhibit less stratification as the fresh water becomes increasingly diluted. Typically, dissolved oxygen concentrations tend to decrease when air temperatures rise as the summer progresses, as observed in 2018 (Figure 2.C.4). There was a slight recovery in dissolved oxygen concentrations toward the end of September, but less so than was observed in some of the other harbors studied.

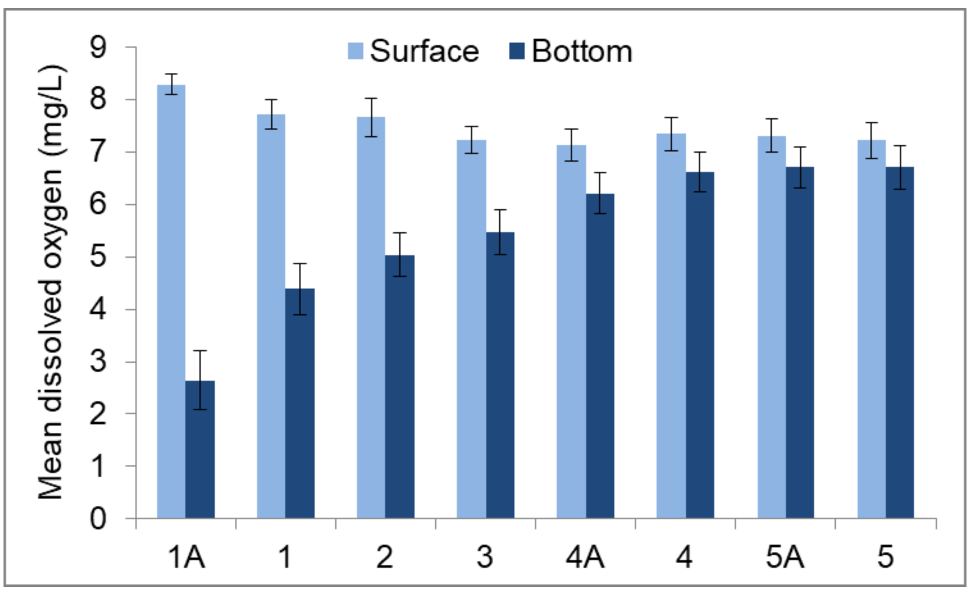


Figure 2.C.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Norwalk Harbor during 2018. Error bars represent standard error.

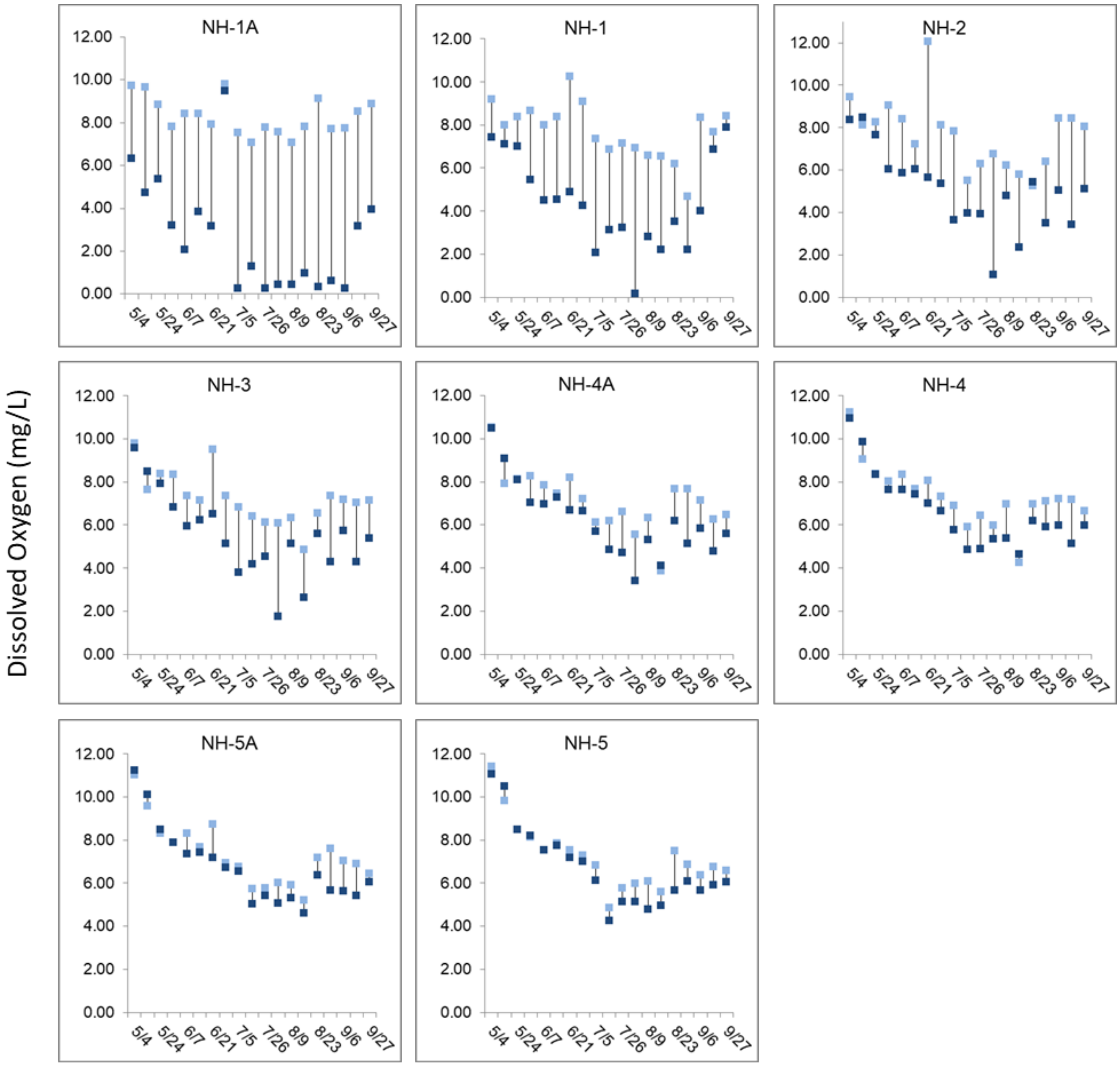
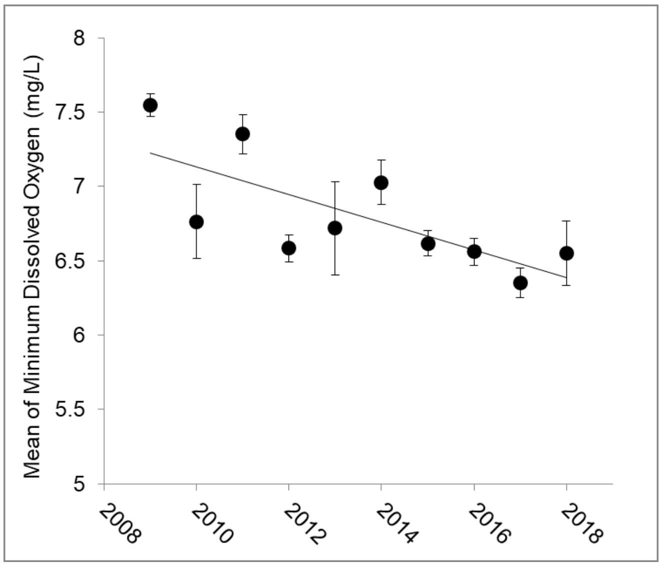


Figure 2.C.4. Surface and bottom dissolved oxygen values at each Norwalk Harbor sampling station on each monitoring date during the 2018 season. Light blue squares represent surface dissolved oxygen values and dark blue squares represent bottom dissolved oxygen values.

Outer Harbor Dissolved Oxygen

Profiles in the outer harbor were conducted at sampling locations by Coast Guard Flotilla 72 members. Dissolved oxygen levels observed in this area can be indicative of whether dissolved oxygen-impaired water may be entering 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, so the two Norwalk Harbor datasets are not directly comparable.

The observed dissolved oxygen data collected as a result of this partnership with Flotilla 72 is presented in context of the last 12 years. Unfortunately, the dissolved oxygen conditions in the outer harbor stations have declined. The mean across the stations of the minimum dissolved oxygen level (i.e., the lowest reading observed on a given monitoring day) has declined (Figure 2.C.5). Also, the percentage of all readings with concentrations below 5 mg/L has steadily risen since 2009 (Figure 2.C.6). Finally, the mean of the dissolved oxygen levels within a given year has also slowly declined (Figure 2.C.7). These trends are consistent with those observed in the inner harbor over the past 30 years (Crosby et al. 2018b) and are likely indicative of the combined effects of warming temperatures and eutrophication.



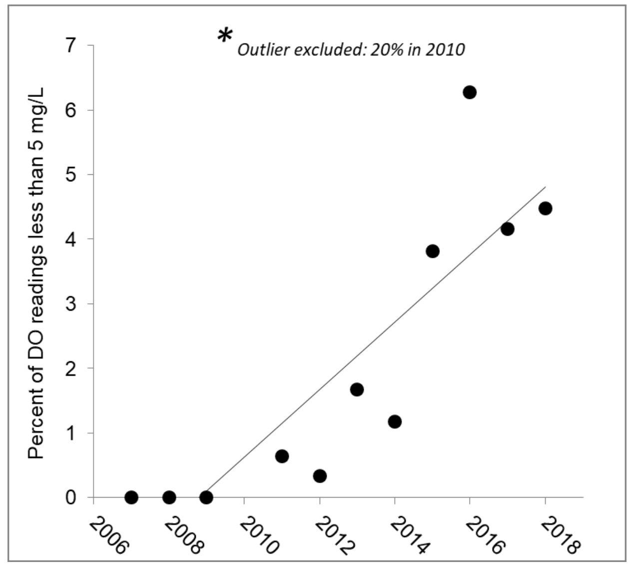


Figure 2.C.5 (Left). Mean of the minimum dissolved oxygen level observed at each of 8 outer harbor sites. **Figure 2.C.6 (Right).** Percentage of all readings across all outer harbor sites in a given year that fell below a dissolved oxygen concentration of 5 mg/L.

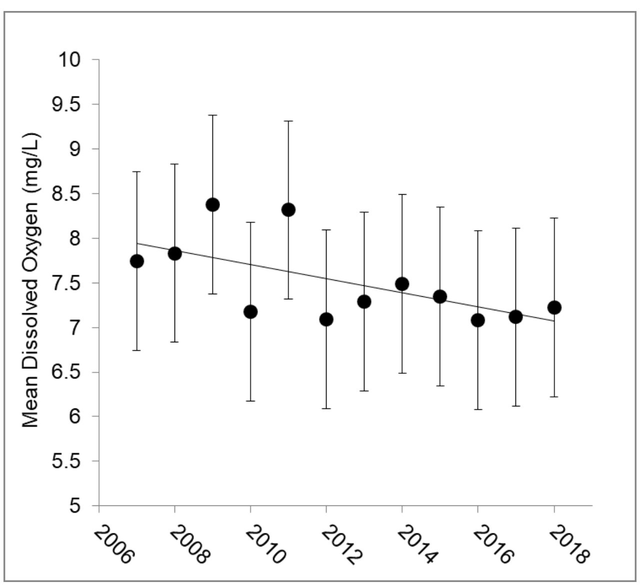


Figure 2.C.7. Mean of the mean dissolved oxygen level observed at each of 8 outer harbor sites.

Chlorophyll a

Water samples for chlorophyll *a* monitoring were collected during 5 monitoring events on 5/4, 5/24, 6/29, 8/9, and 9/6 at each of the inner harbor stations. The harbor was classified as medium eutrophic (> 5 µg/L, ≤ 20 µg/L) according to the Bricker scale with one station falling in the high eutrophic category (> 20 µg/L, ≤ 60 µg/L) at station NH-3 (Table 2.1, Figure 2.C.8). The large chlorophyll *a* values recorded on 5/4 at NH-3 and NH-4A could have been a phytoplankton bloom due possibly to a coincidence with a number of favorable conditions, including sunlight, nutrients, and temperature. With little rain recorded, these spikes may have been related to a nitrogen input from another source, such as a storm drain. Heavy rainfall of 3.97 inches on 6/28 appeared to have little effect on chlorophyll *a* levels observed on 6/29. The distribution of chlorophyll *a* with the exception of the value observed in 5/4 was uniform throughout the harbor in contrast with the chlorophyll *a* concentrations observed during 2017 (Crosby et at. 2018a). The effect of heavy flow from the Norwalk River helped produce a better mixed and more uniform water column (Figure 2.C.9).

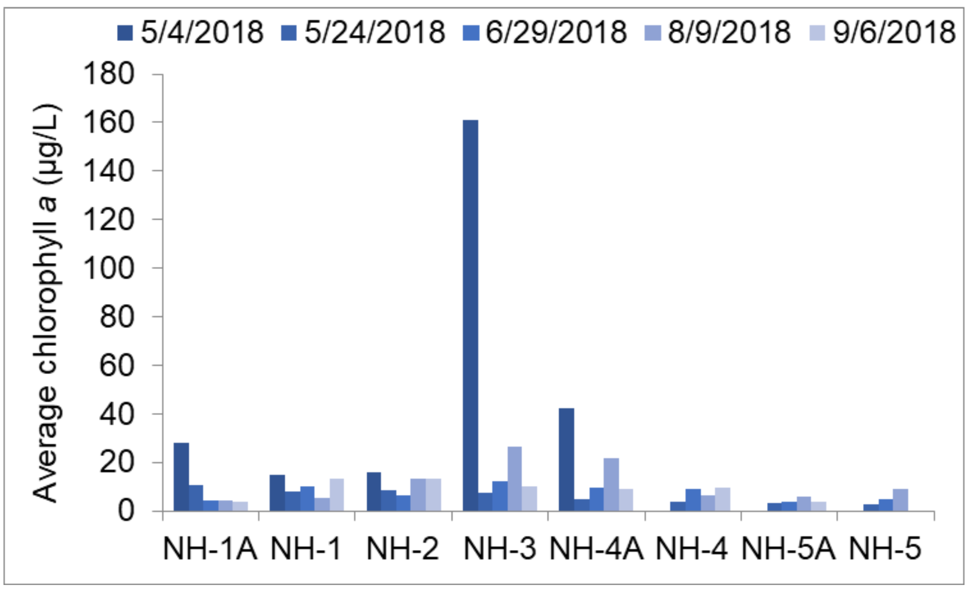


Figure 2.C.8. Average chlorophyll *a* values in Norwalk Harbor in 2018.

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 55 years, and the blue line represents the recorded discharge for a particular date. There were many high flow rainfall events in 2018, an apparent increase over 2017, with one especially high discharge event at the end of September (Figure 2.C.9).

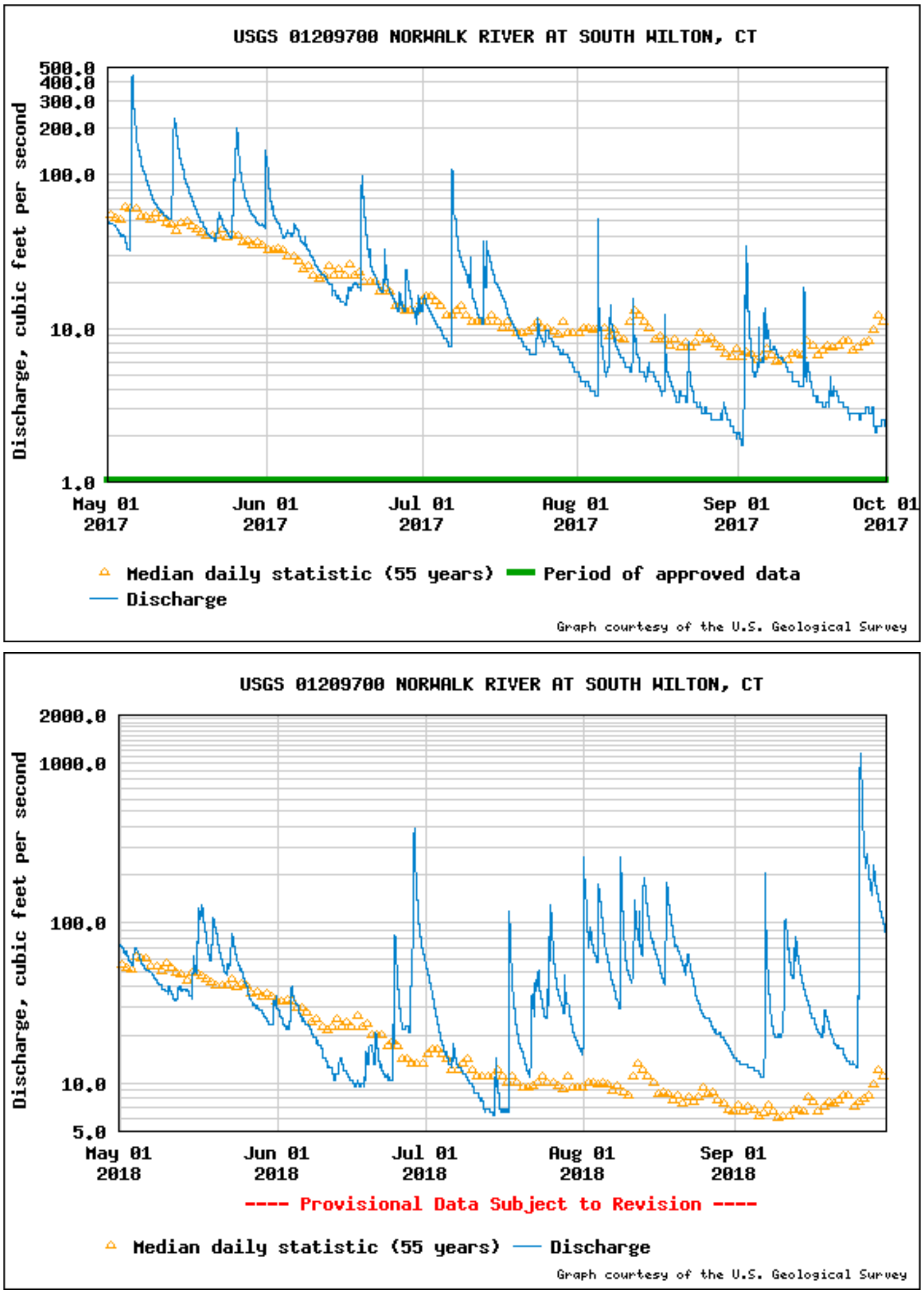


Figure 2.C.9. USGS flow data in feet^3/s for the period of May 1 through October 1 for 2017 and 2018 respectively for the Norwalk River in South Wilton, CT (Graphs courtesy of the U.S. Geological Survey). Please note the difference in scale of the X-axis.

Temperature and Salinity
Temperature of the water in the inner Norwalk Harbor differed less than the dissolved oxygen levels between the surface and the bottom, though on average the water at the harbor bottom was cooler at all sites (Figure 2.C.10). Salinity was lower at the surface than the bottom in the inner harbor stations, reflecting the impact of the above average riverine inputs from the north where the harbor is less well mixed (Figure 2.C.9, Figure 2.C.11). For example, on 6/28 recorded rainfall of 3.97 inches changed station NH-1A to fresh water. This salinity stratification was more pronounced in Norwalk Harbor than the other harbors studied.

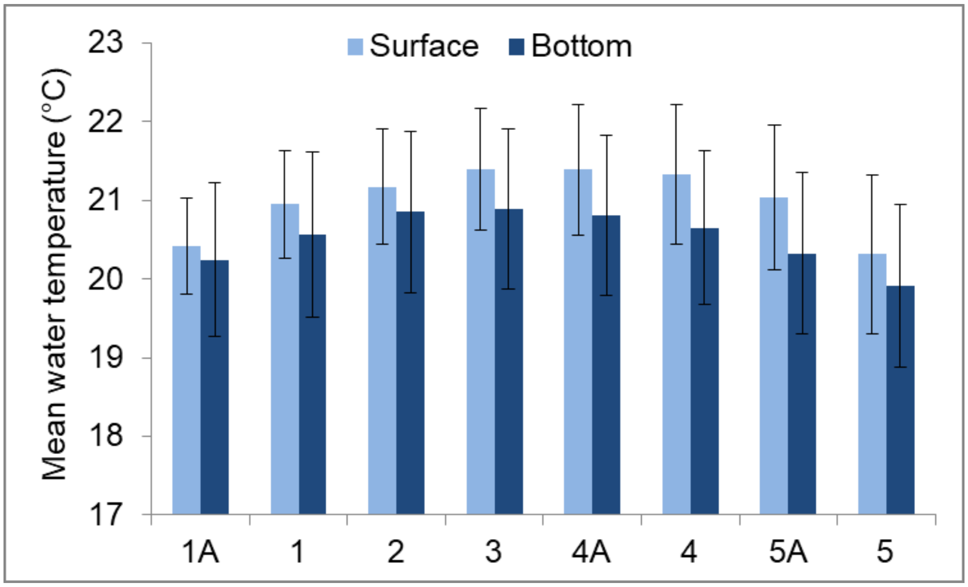


Figure 2.C.10. Mean water temperature at the surface and bottom at each sampling station in Norwalk Harbor in 2018. Error bars represent standard error.

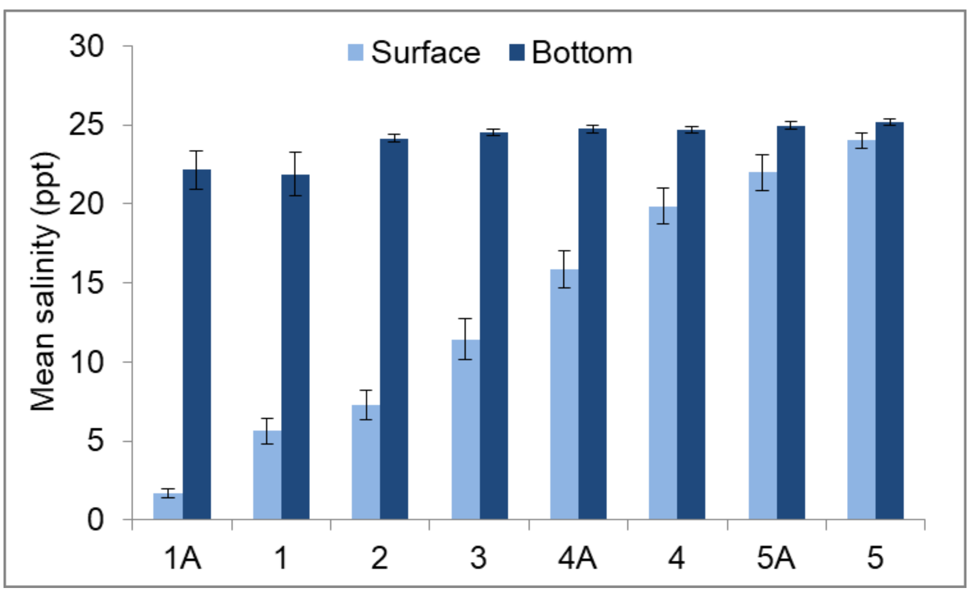


Figure 2.C.11. Mean salinity at the surface and bottom at each sampling station in Norwalk Harbor in 2018. Error bars represent standard error.

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 wide but shallow harbor ¼ mile downstream from the Metro North railroad bridge (Figure 2.D.2). 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 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 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.

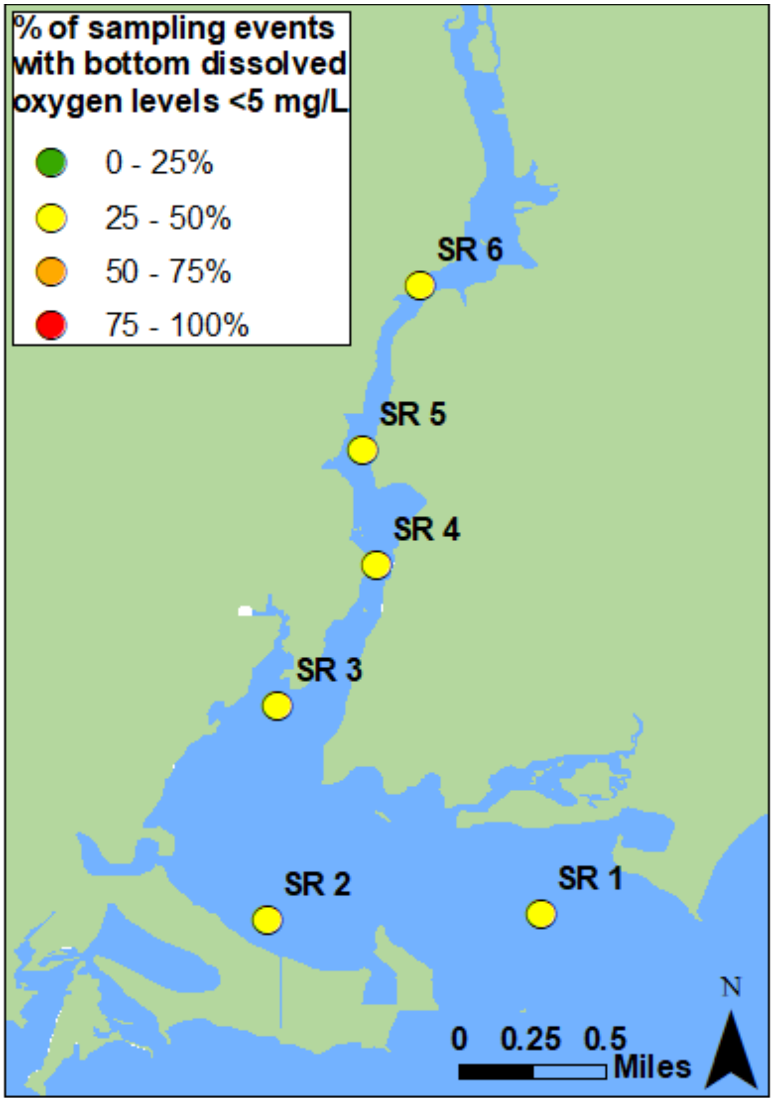


Figure 2.D.2. Map of Saugatuck Harbor sampling stations in 2018. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 5 mg/L.

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

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

Dissolved Oxygen
Profiles were taken at 6 stations on 12 sampling days from May to October 2018. Mean dissolved oxygen levels ranged between 6.05 mg/L at the bottom of station SH-5 to 7.76 mg/L at the surface of station SH-1 (Figure 2.D.3). These results were very similar to 2017. Nearly all individual readings at each station were above 3 mg/L (Figure 2.D.4). Only 1% of dissolved oxygen observations fell below 3 mg/L, while 41% of observations fell below 5 mg/L. The maximum dissolved oxygen value observed was 11.37 mg/L, while the minimum observed was 2.77 mg/L. While dissolved oxygen values at all stations fell starting in May, a recovery began during early August. All bottom dissolved oxygen levels exceeded 5 mg/L by 10/3 (Figure 2.D.4).

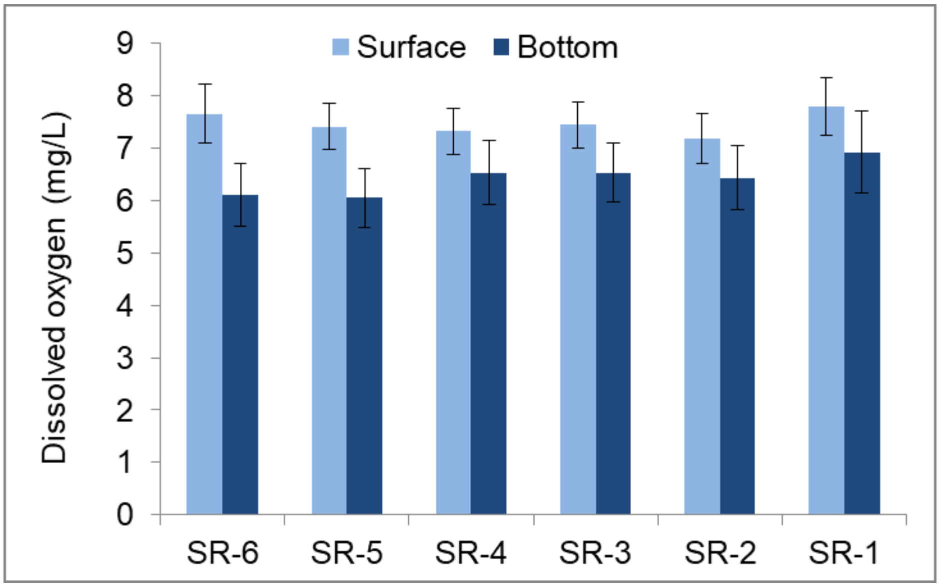


Figure 2.D.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Saugatuck Harbor in 2018. Error bars represent standard error.

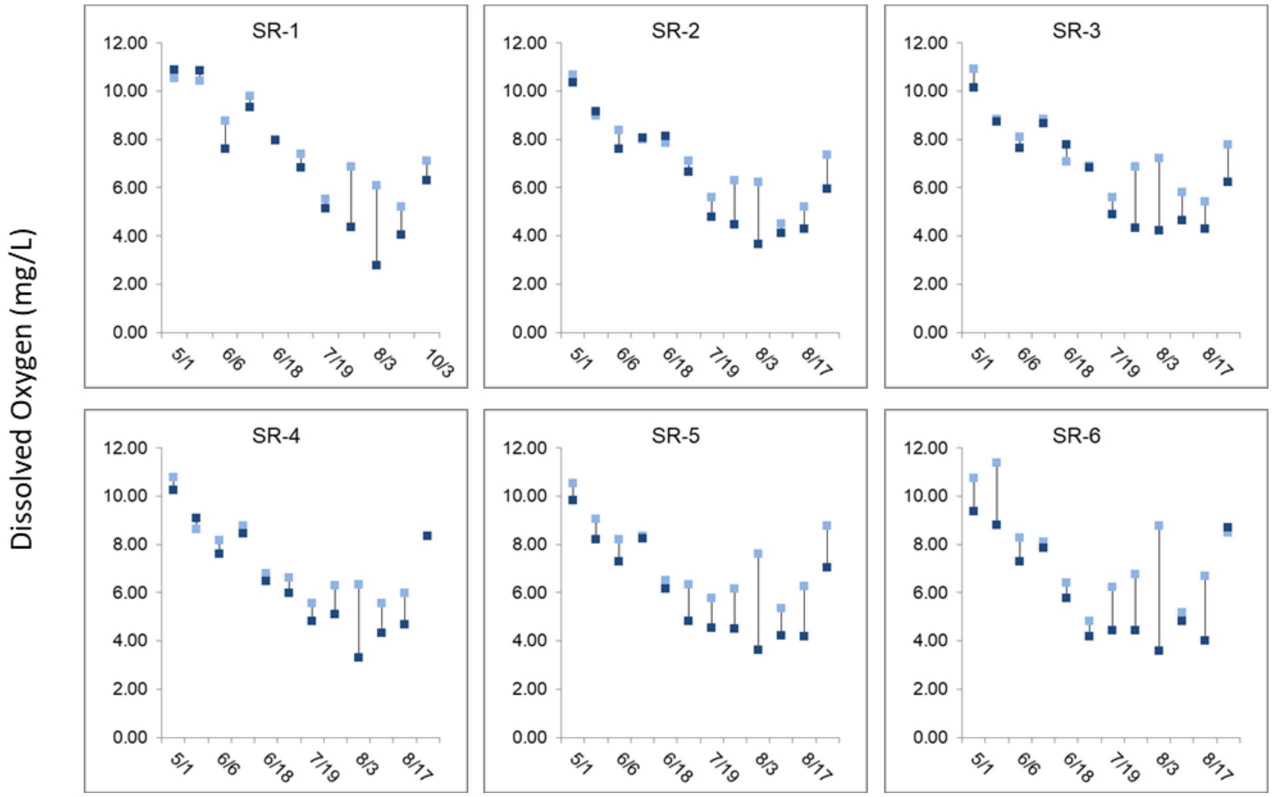


Figure 2.D.4. Surface and bottom dissolved oxygen values at each Saugatuck Harbor sampling station on each monitoring date during the 2018 season. Light blue squares represent surface dissolved oxygen values and dark blue squares represent bottom dissolved oxygen values.

Chlorophyll a

Chlorophyll *a* sampling was conducted during 5 monitoring events on 5/18, 5/22, 6/12, 7/13, 7/19. This harbor can thus be classified as medium eutrophic (> 5 µg/L, ≤ 20 µg/L) based on the Bricker classification system (Table 2.1, Figure 2.D.5). During 2017, observed chlorophyll *a* values were elevated at the upper stations SR-4, SR-5, and SR-6 reaching as high as 40 µg/L (station SR-6, 7/12/18) and 52 µg/L (station SR-4, 8/11/17), classifying the harbor as highly eutrophic for 2017. Distribution of chlorophyll along the length of the harbor was more uniform during 2018, without the large spikes observed at the upper end. This may be due to higher freshwater input from the Saugatuck River which may have led to a better distribution of chlorophyll *a* throughout the harbor (Figure 2.D.6).

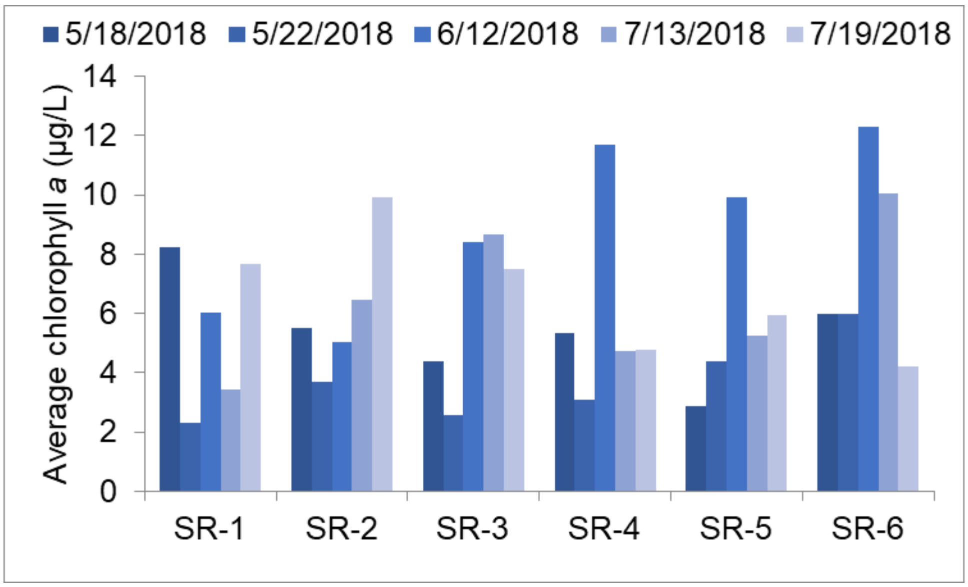


Figure 2.D.5. Average chlorophyll *a* values in Saugatuck Harbor in 2018.

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 43 years, and the blue line represents the recorded discharge for a particular date. There were many large discharge precipitation events in 2018, especially toward the end of the monitoring season.

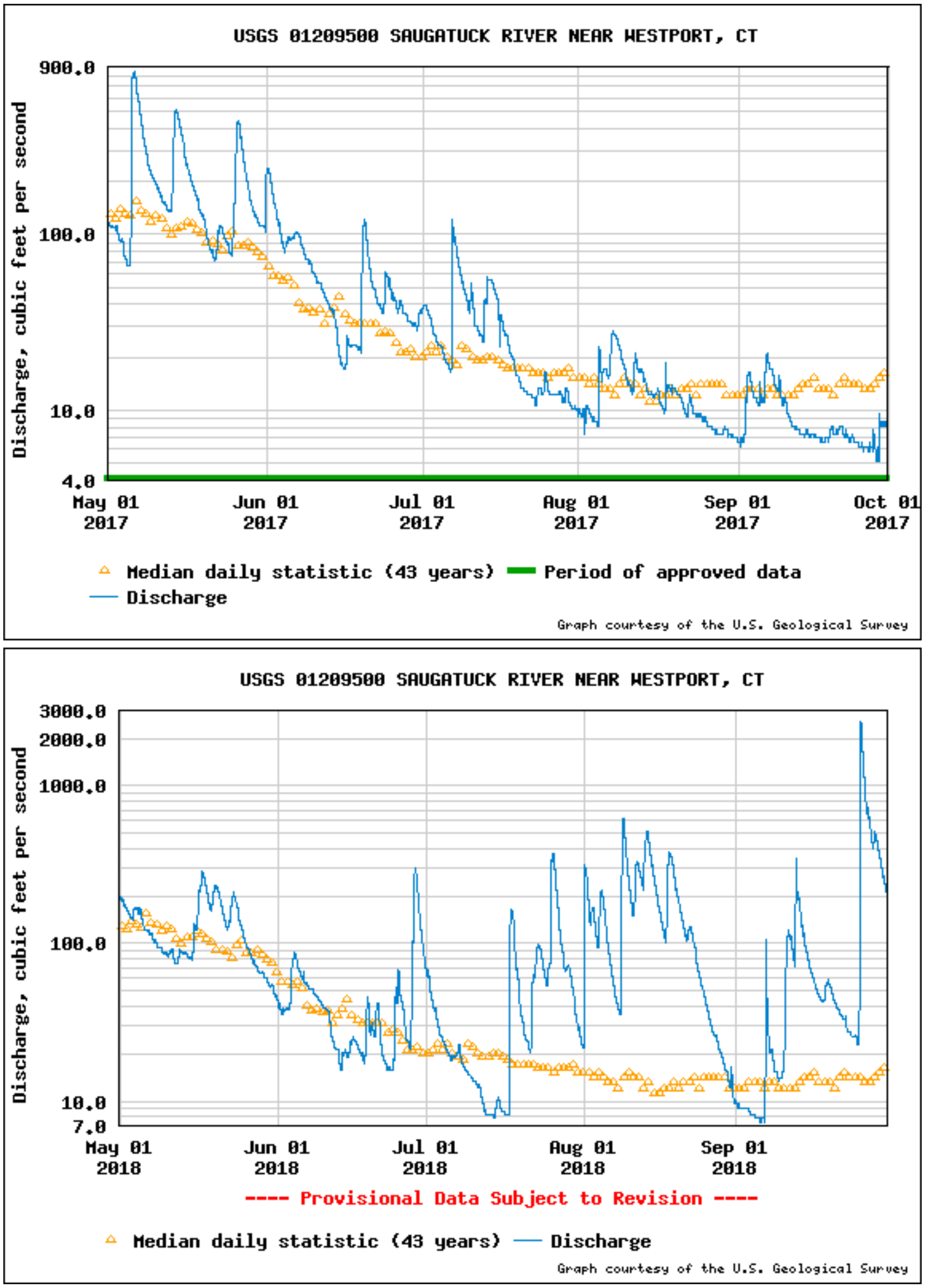


Figure 2.D.6. USGS flow data in feet^3/s for the period of May 1 through October 1 for the 2017 and 2018 respectively for the Saugatuck River near Westport, CT (Graphs courtesy of the U.S. Geological Survey). Please note the difference in scale on the x-axis.

Temperature and Salinity

Temperature of the water in Saugatuck Harbor differed less than the dissolved oxygen levels between the surface and the bottom, though on average the water at the harbor bottom was cooler at all sites except for the two inner-most stations (Figure 2.D.7). Salinity was lower at the surface than the bottom at all stations and that difference was most pronounced in the inner harbor stations, reflecting the impact of the increased riverine inputs from the north where the harbor is less well mixed (Figure 2.D.6, Figure 2.D.8).

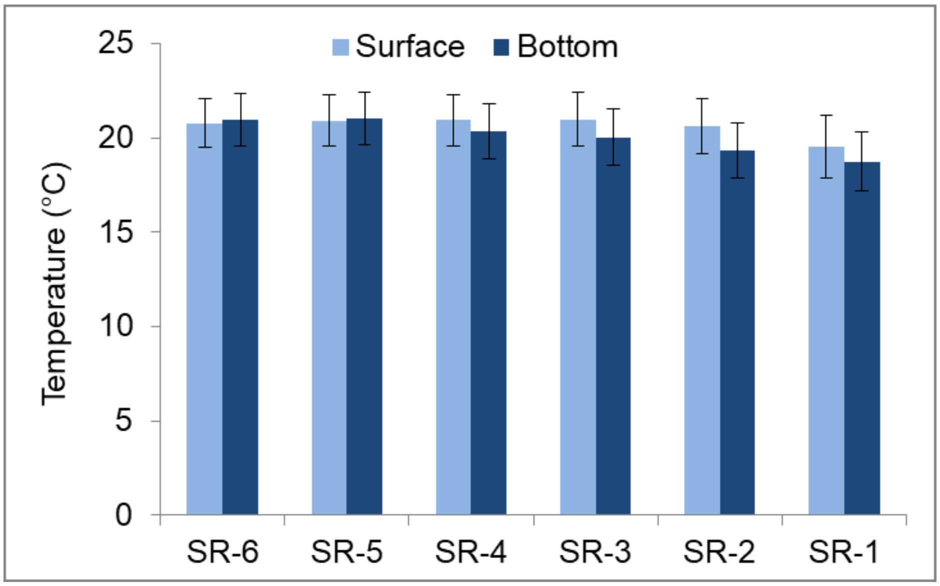


Figure 2.D.7. Mean water temperature at the surface and bottom at each sampling station in Saugatuck Harbor in 2018. Error bars represent standard error.

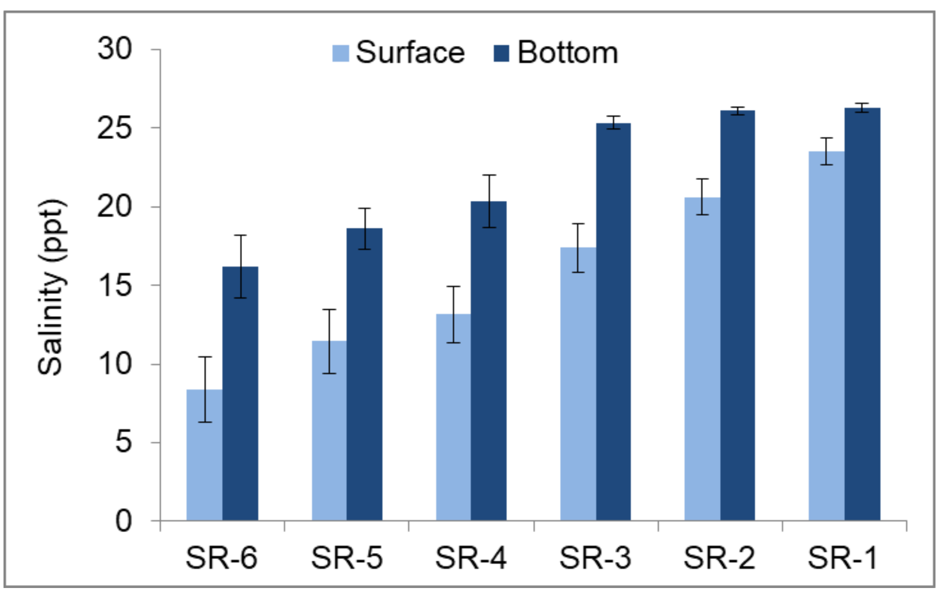


Figure 2.D.8. Mean salinity at the surface and bottom at each sampling station in Saugatuck Harbor in 2018. Error bars represent standard error.

E. Bridgeport Harbor (Johnson's Creek and Lewis Gut sections)

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 Lewis Gut during tidal cycles (Figure 2.E.1). The 2 water bodies present a significant contrast in terms of water quality. 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.

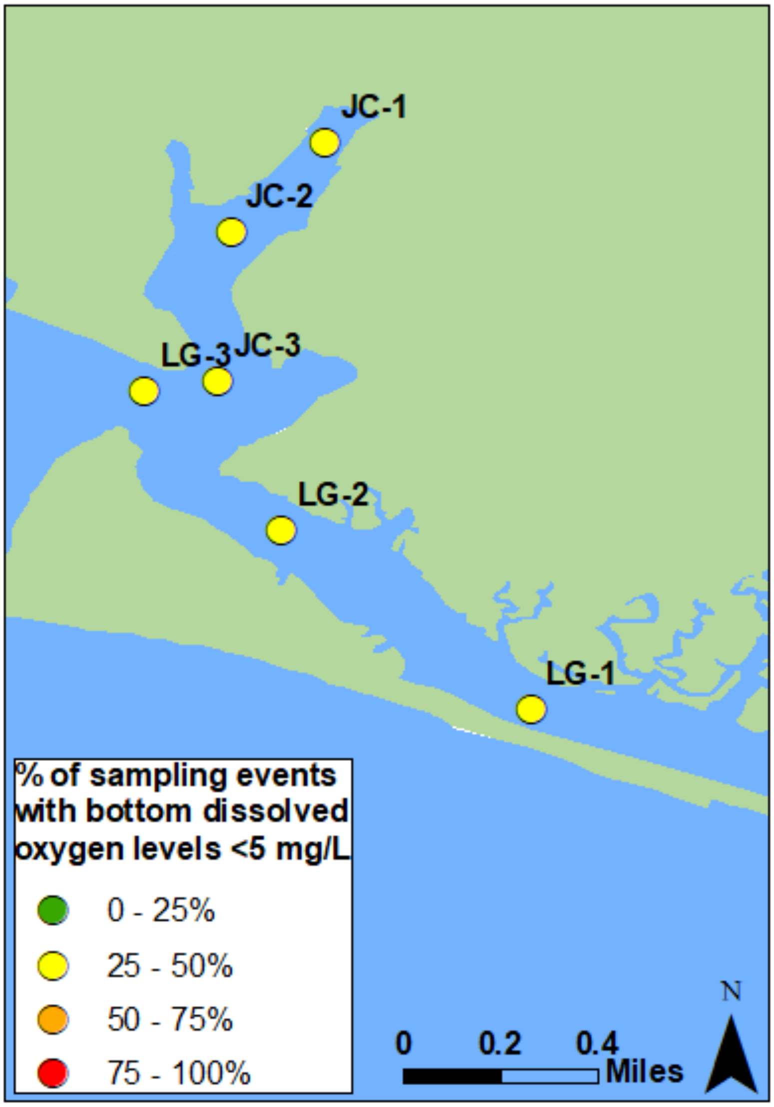


Figure 2.E.2. Map of Johnson's Creek and Lewis Gut sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 5 mg/L.

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 tended to be slightly higher in Johnson's Creek than in Lewis Gut at the surface, an opposite pattern to that observed in 2017 (Figure 2.E.4, Crosby et al. 2018b). All sites had mean dissolved oxygen levels above 3 mg/L (Figure 2.E.4). The similarity of dissolved oxygen concentrations at the surface and the bottom is due in part to the waters being well mixed in this section of the harbor (Figure 2.E.5). Johnson's Creek is heavily impacted by sewage pollution (and the resultant nutrient inputs) from Bruce Brook with some residual pollution impacting Lewis Gut from tidal flow (Crosby et al., 2018c), without which the dissolved oxygen conditions might have been higher than what was observed. The maximum dissolved oxygen observed was 10.49 mg/L and the minimum value observed was 2.68 mg/L. The mean dissolved oxygen maximum was 7.58 mg/L and the mean dissolved oxygen minimum was 6.11 mg/L. Thirty-three percent of the dissolved oxygen observations were below 5 mg/L, while 2% were below 3 mg/L. Dissolved oxygen values dropped sharply in May, bottomed out in early July and began to recover during the last two weeks in August (Figure 2.E.5).

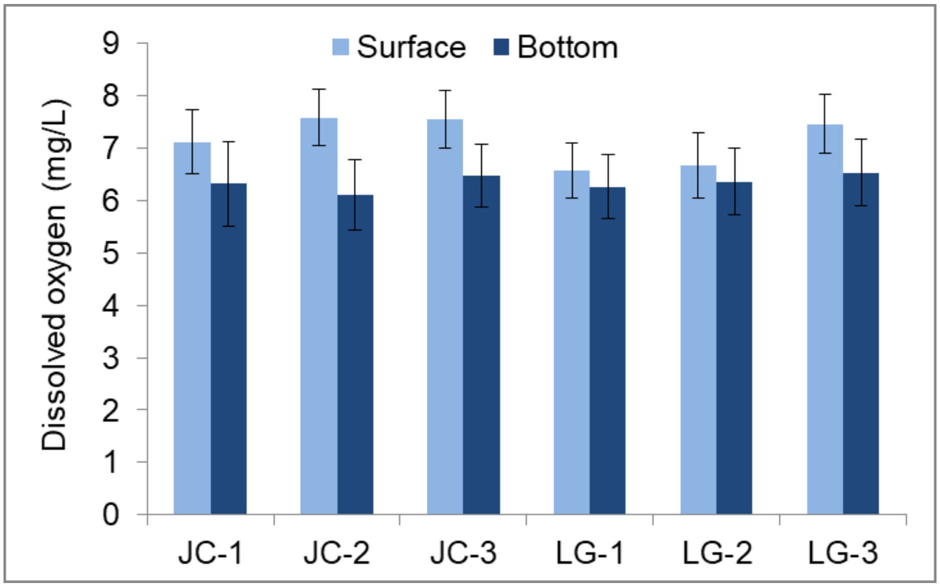


Figure 2.E.4. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in Johnson's Creek and Lewis Gut. Error bars represent standard error.

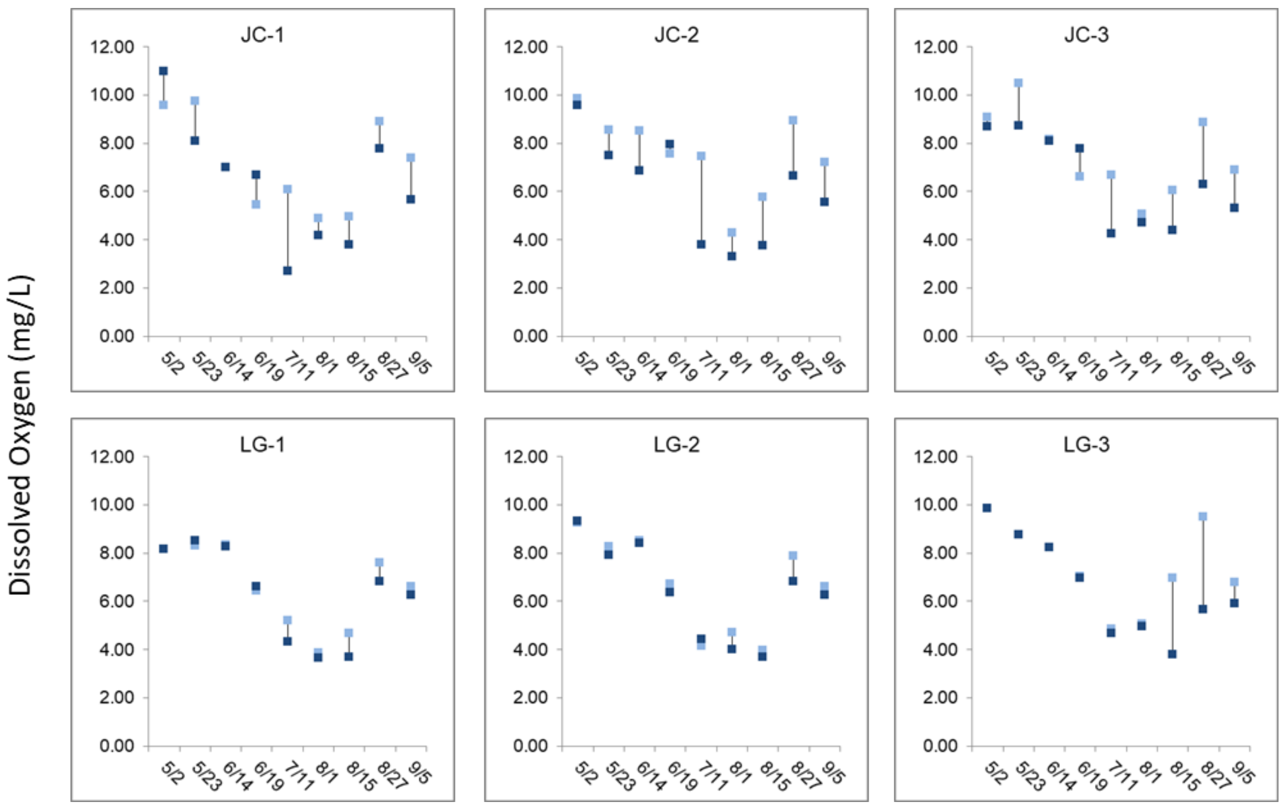


Figure 2.E.5. Surface and bottom dissolved oxygen values at each Johnson's Creek and Lewis Gut sampling station on each monitoring date during the 2018 season. Light blue squares represent surface dissolved oxygen values and dark blue squares represent bottom dissolved oxygen values.

Chlorophyll a

Chlorophyll *a* samples were taken 6 times during the 2018 monitoring season in Johnson's Creek and Lewis Gut (Figure 2.E.6). 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 an ebb tide. The net result is typically lower productivity in Lewis Gut (Figure 2.F.6). Johnson's Creek can be classified as having medium eutrophic characteristics (> 5 µg/L, ≤ 20 µg/L; Table 2.1), while Lewis Gut would be categorized as low to medium eutrophic. Results are similar to 2017, with a slight reduction in apparent bloom activity. Increased dissolved oxygen levels observed at the surface on 7/11 may partially be the result of a potential phytoplankton bloom, with higher concentrations of chlorophyll *a* observed on the same date (Figure 2.E.5, Figure 2.E.6). Other observed increases in dissolved oxygen on 8/15 and 8/27 could have also been related to phytoplankton blooms later in the season, although no chlorophyll *a* sampling was done on those dates.

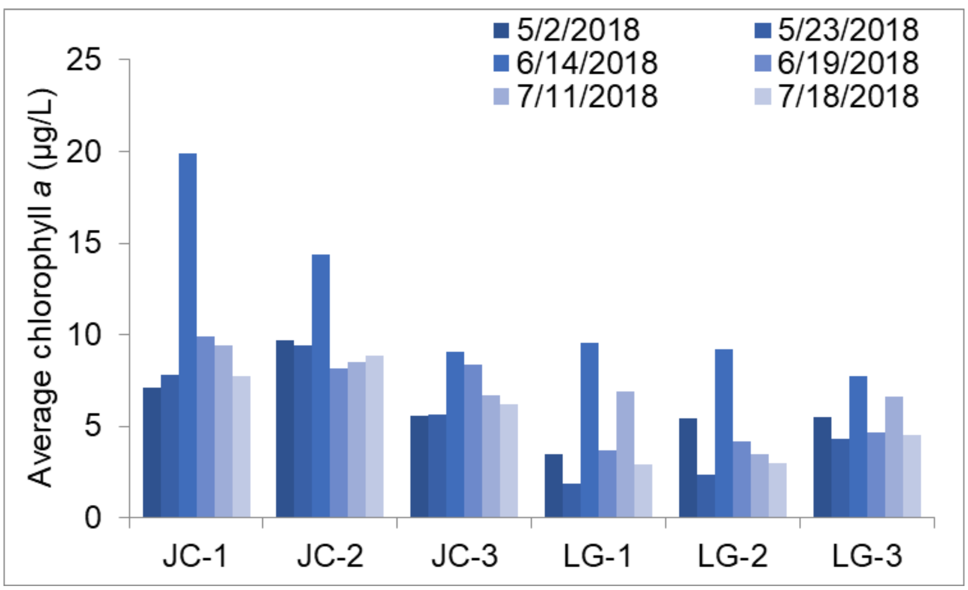


Figure 2.E.6. Average chlorophyll *a* values in Johnson's Creek and Lewis Gut in 2018.

Temperature and Salinity
Temperature of the water in Johnson Creek and Lewis Gut on average was cooler at the harbor bottom at all sites (Figure 2.E.7). Salinity was lower at the surface than the bottom in the Johnson's Creek stations, where the harbor is less well mixed (Figure 2.E.8). Salinity in Johnson's Creek showed a very weak gradient in the water column relative to the other harbors studied. 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 can drive periodic stratification. 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.

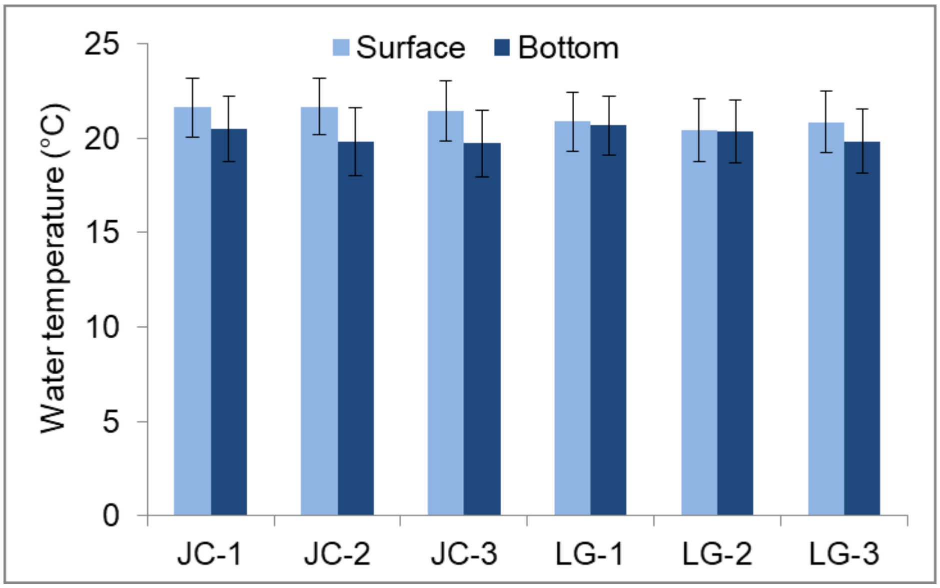


Figure 2.E.7. Mean water temperature at the surface and bottom at each sampling station in Johnson Creek and Lewis Gut in 2018. Error bars represent standard error.

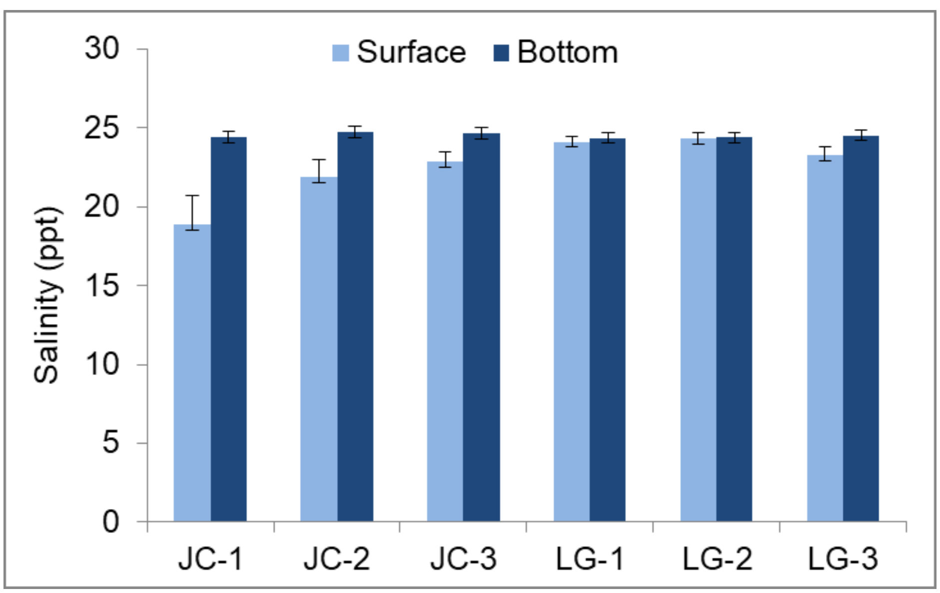


Figure 2.E.8. Mean salinity at the surface and bottom at each sampling station in Johnson Creek and Lewis Gut in 2018. Error bars represent standard error.

F. New Haven Harbor (Quinnipiac River section)

The Quinnipiac River 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 New Haven 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 New Haven Harbor with extensive wetlands on the eastern shore.

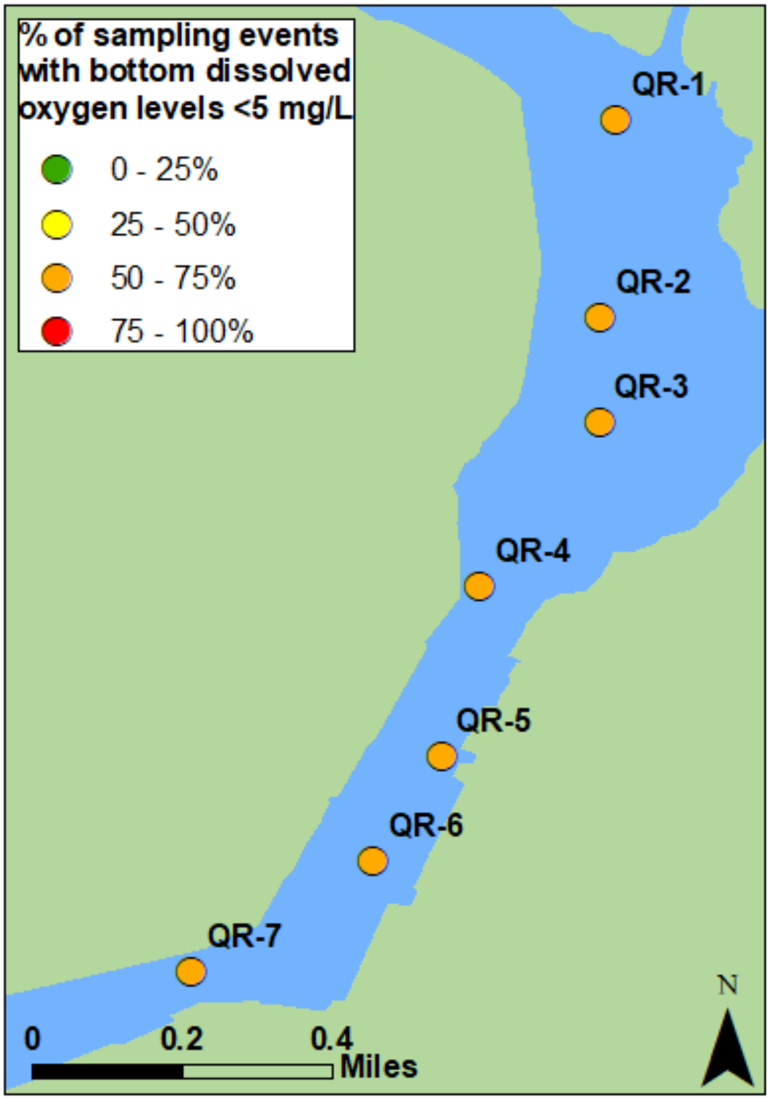


Figure 2.F.2. Map of Quinnipiac River sampling stations. Colored dots represent the % of sampling events with bottom dissolved oxygen levels less than 5 mg/L.

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

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

Dissolved Oxygen

Seven stations were monitored in the Quinnipiac River over 5 days from June through September. Water monitoring in this river section, as in past years, was difficult and some of the 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. Similar to the 2017 season, there were no observed instances of hypoxia (3 mg/L or below) in 2018 (Figure 2.F.3, Figure 2.F.4). The maximum dissolved oxygen value observed was 7.70 mg/L, while the minimum was 3.32 mg/L. The mean dissolved oxygen maximum was 5.83 mg/L and the mean dissolved oxygen minimum was 4.93 mg/L. While no sites had dissolved oxygen values less than 3 mg/L, 60% of the dissolved oxygen observations fell below 5 mg/L.

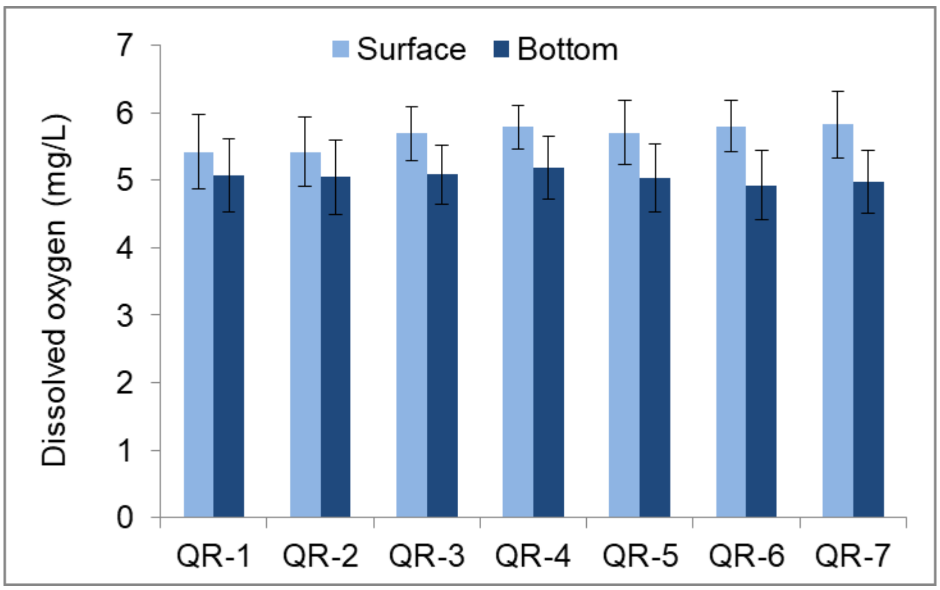


Figure 2.F.3. Mean dissolved oxygen concentrations at the surface and bottom at each sampling station in the Quinnipiac River. Error bars represent standard error.

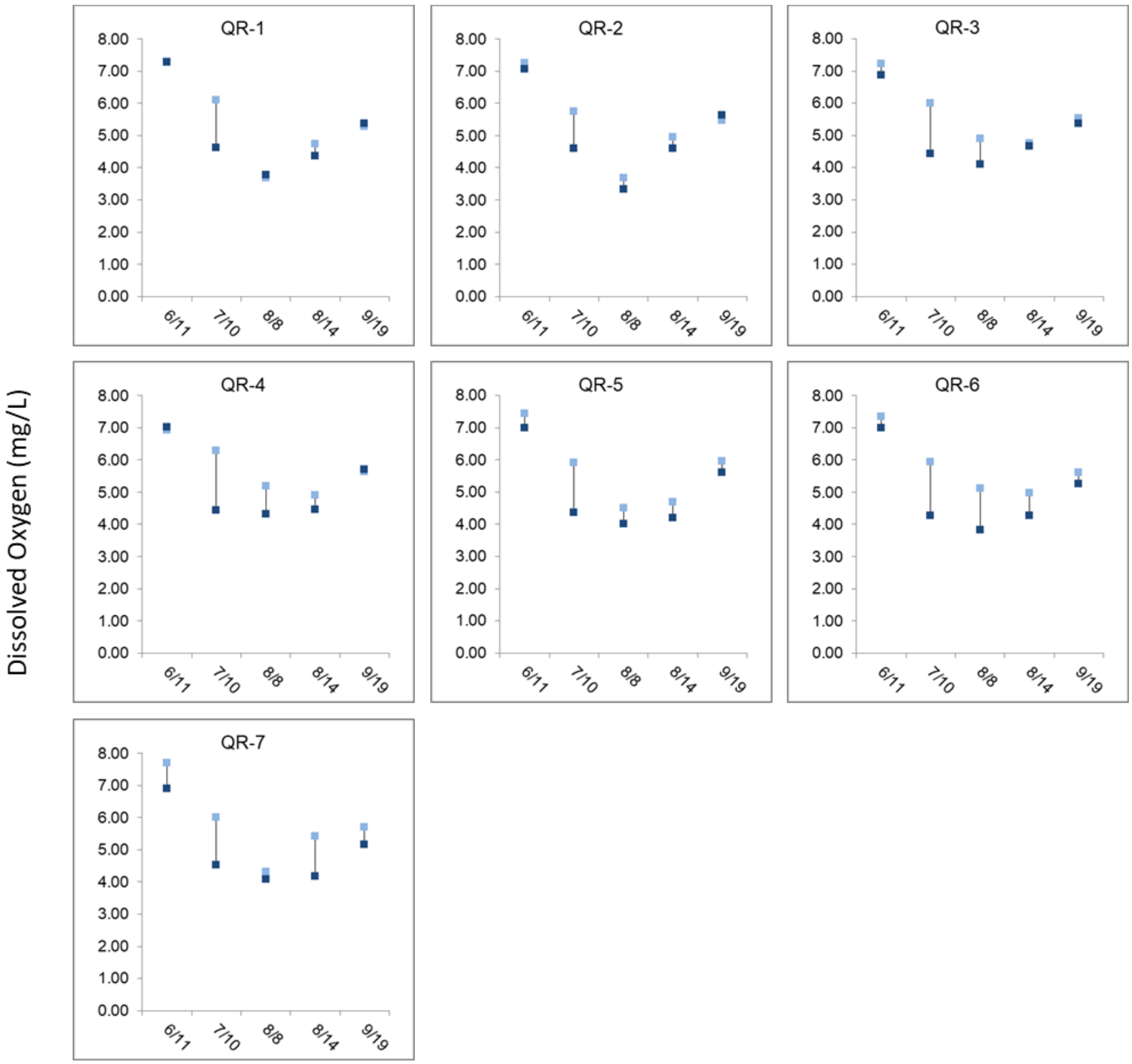


Figure 2.F.4. Surface and bottom dissolved oxygen values at each Quinnipiac River sampling station on each monitoring date during the 2018 season. Light blue squares represent surface dissolved oxygen values and dark blue squares represent bottom dissolved oxygen values.

Chlorophyll a

Samples were obtained during 4 monitoring events on 6/26, 7/10, 8/8 and 8/14 (Figure 2.F.5). The Quinnipiac River can be characterized as medium eutrophic (> 5 µg/L, ≤ 20 µg/L; Table 2.1).

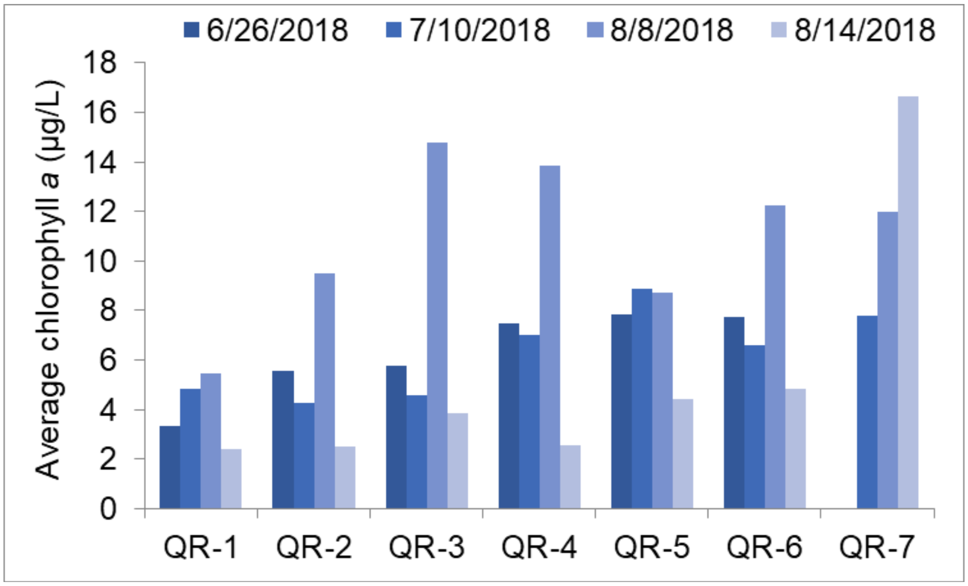
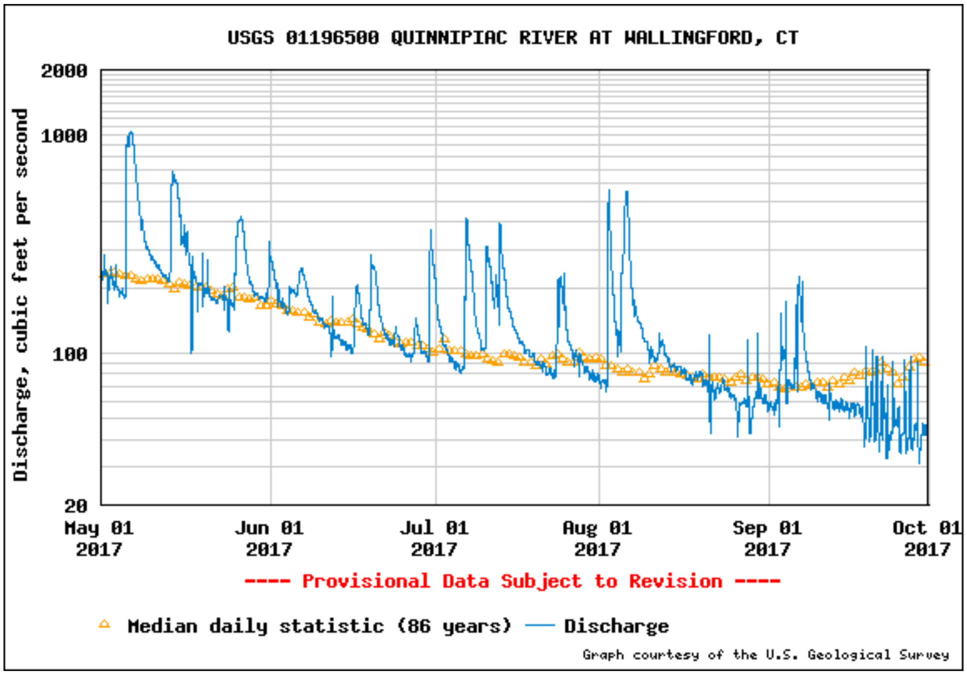


Figure 2.F.5. Average chlorophyll a values in the Quinnipiac River in 2018.

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. Unlike in 2017, rain events seemed to increase later in the monitoring season, with one especially large precipitation event in late September.



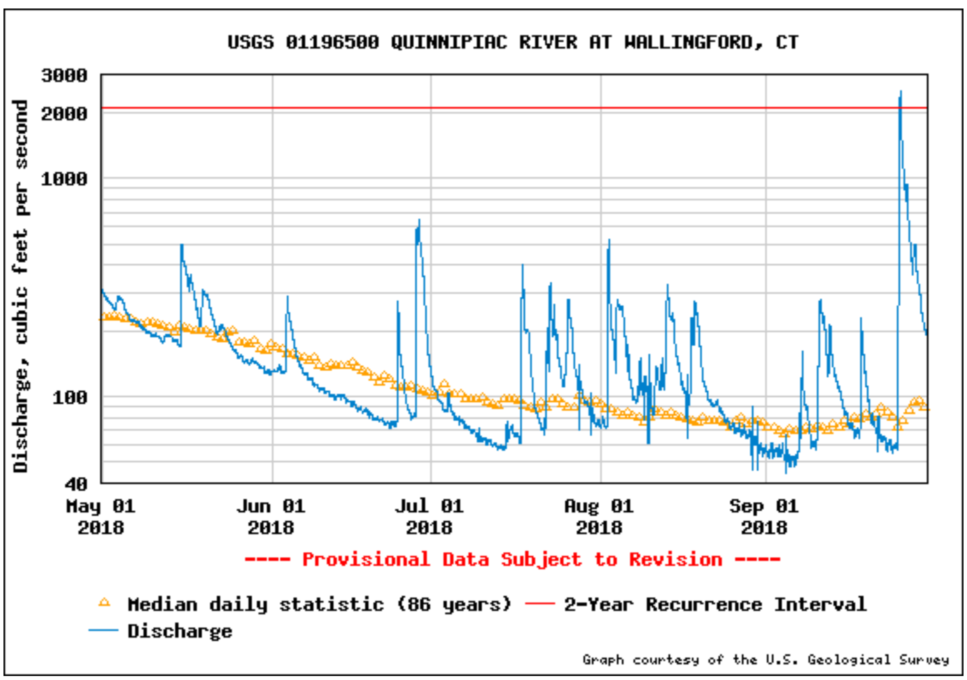


Figure 2.F.6. USGS flow data in feet^3/s for the period of May 1 through October 1 respectively for the Quinnipiac River in Wallingford, CT (Graphs courtesy of the U.S. Geological Survey). Please note the difference in scale on the x-axis.

Temperature and Salinity

Temperature of the water in the Quinnipiac River was cooler on average at the harbor bottom at all sites (Figure 2.F.7.). Salinity was lower at the surface than the bottom at all stations, and this difference was more pronounced at the outer river stations (Figure 2.F.8.). This trend in stratification was opposite the typical trend observed in the other harbors, where stratification was greater at the innermost sites.

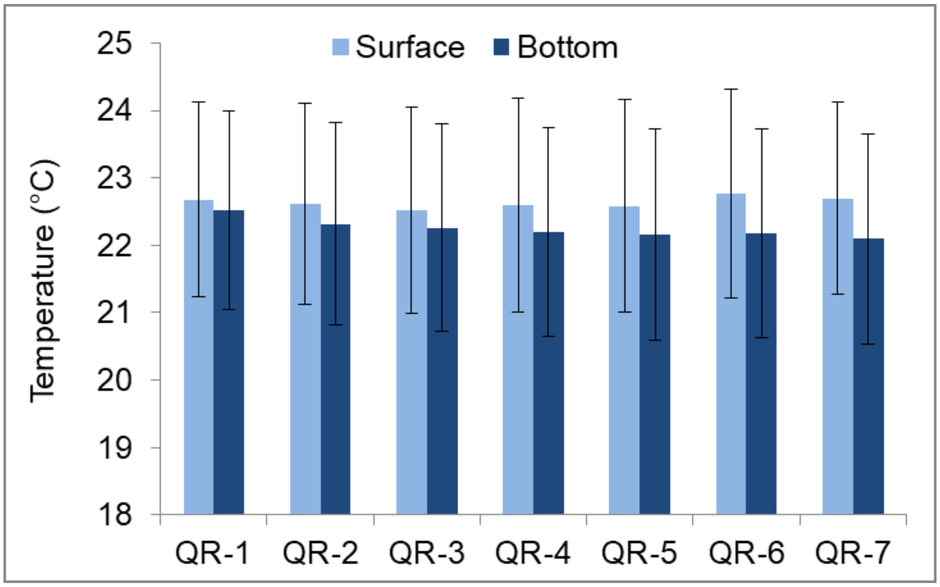


Figure 2.F.7. Mean water temperature at the surface and bottom at each sampling station in the Quinnipiac River in 2018. Error bars represent standard error.

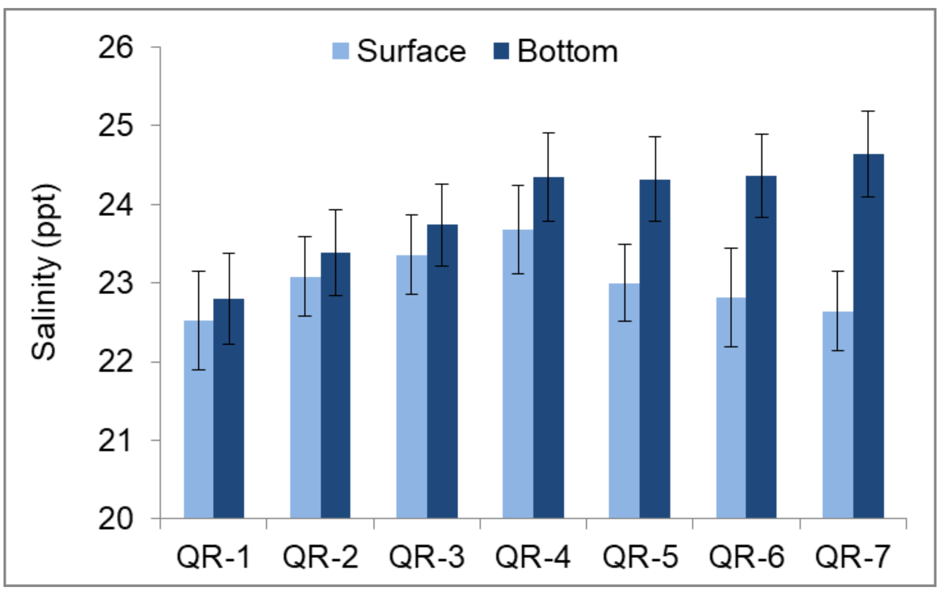


Figure 2.F.8. Mean salinity at the surface and bottom at each sampling station in the Quinnipiac River in 2018. Error bars represent standard error.

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