2016 Long Island Sound Hypoxia Season Review

Connecticut Department of Energy & Environmental Protection

79 Elm Street, Hartford, CT 06106

Robert J. Klee, Commissioner

Interstate Environmental Commission

2800 Victory Boulevard, Building 6S Room 106

College of Staten Island—CUNY Campus

Staten Island, NY 10314

Introduction

Designated as an estuary of national significance by Congress in 1987, Long Island Sound is home to a diverse network of flora and fauna and over 4 million people. It is an estuary of recreational, commercial, and socioeconomic value. The Sound is bordered by the states of Connecticut and New York and has a watershed area extending through Maine and Quebec that encompasses over 16,000 square miles and 9 million people. Over time, the Sound has been subject to the effects of increased nutrient loading as a result of urbanization and changes in land use (Latimer *et al.*, 2014) . Seasonal weather patterns, particularly during the summer months, exacerbate the effects of nutrient loading, causing hypoxic conditions in the Sound, most prominently in the Western Basin. This, in turn, negatively impacts the water quality of this estuary, the ecosystem services and resources it provides, and the habitat that is home to its many species. In response to the critical need to document summer hypoxic conditions in Long Island Sound and its embayments as defined in the Long Island Sound Study's Comprehensive Conservation and Management Plan, the Connecticut Department of Energy and Environmental Protection (CT DEEP) and the Interstate Environmental Commission (IEC), have monitored dissolved oxygen, as well as key water quality parameters relevant to hypoxia, in Long Island Sound since 1991.

This report presents a summary of *in situ* data collected by CT DEEP and IEC during the 2016 hypoxia season. The hypoxia season is defined as June-September. Data from the Long Island Sound Integrated Coastal Observing System (LISICOS) are presented with permission for informational purposes. Sampling and analyses were conducted under EPA-approved Quality Assurance Project Plans.

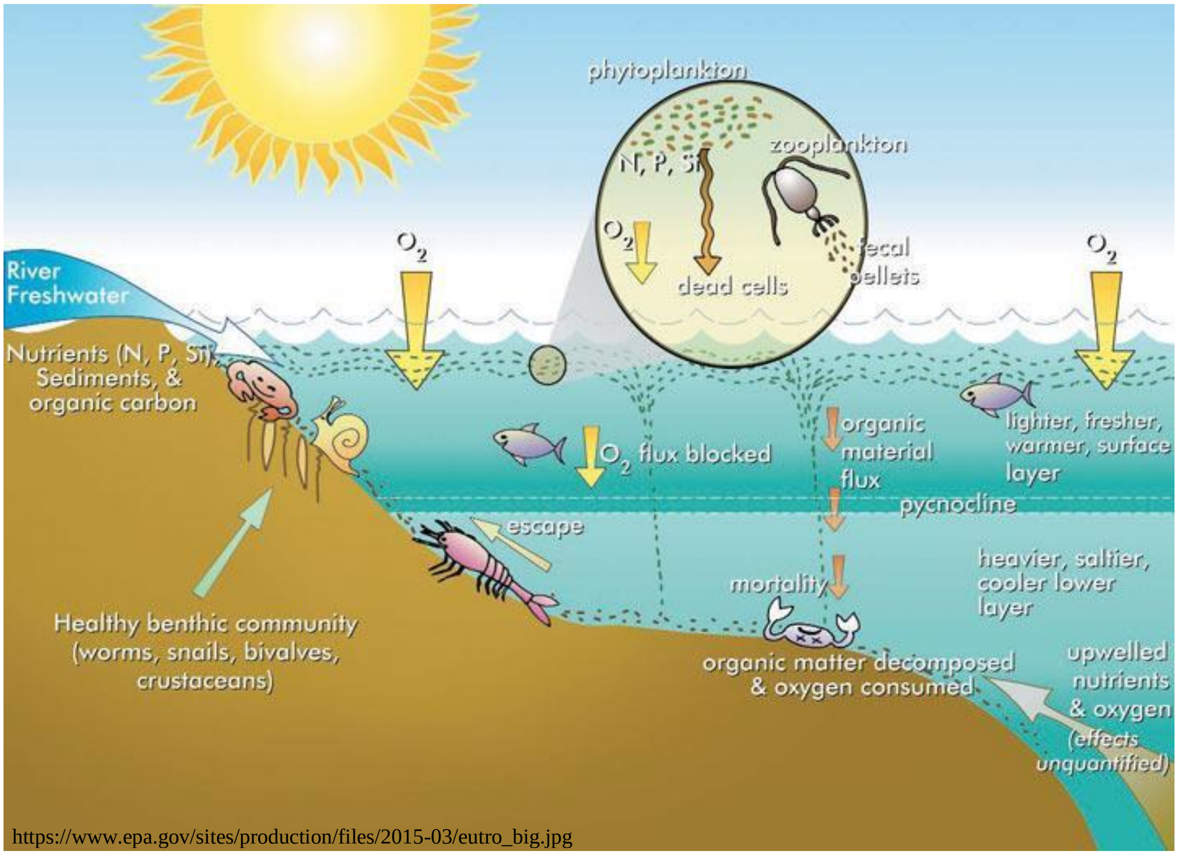
The CT DEEP and IEC Long Island Sound (LIS) Water Quality Monitoring Programs are synoptic in nature and are intended to characterize water quality conditions at one moment in time over a broad area (the entire Sound). Both programs support long term monitoring databases designed to detect changes in hypoxia due to changing conditions *(e.g.*, management actions, climate change, productivity). Both programs also provide data (*e.g.* nutrient, BOD, TSS, chlorophyll a) not currently available from fixed station buoy applications. In addition, CTDEEP provides limited biological data (plankton communities).

The LISICOS water quality sensors are attached to fixed locations and provide a holistic view of the conditions over a more detailed span of time (*i.e.*, data measured every 15 minutes from one station as opposed to every two weeks). The LISICOS continuously recording buoys have shown instances where vertical mixing within the water column raises the DO concentrations above the hypoxic threshold of 3.0 milligrams per liter (mg/L) for extended periods of time (*e.g.*, days). These episodic conditions are not captured by CT DEEP or IEC surveys.

As such, CT DEEP and IEC data provide a snapshot of hypoxic conditions at one time while the LISICOS data provide a continuous measurement of hypoxia at specific buoy locations. Together these monitoring programs are better able to characterize the extent and duration of hypoxia across LIS. Both types of data contribute to a better understanding of hypoxia in LIS.

What is Hypoxia?

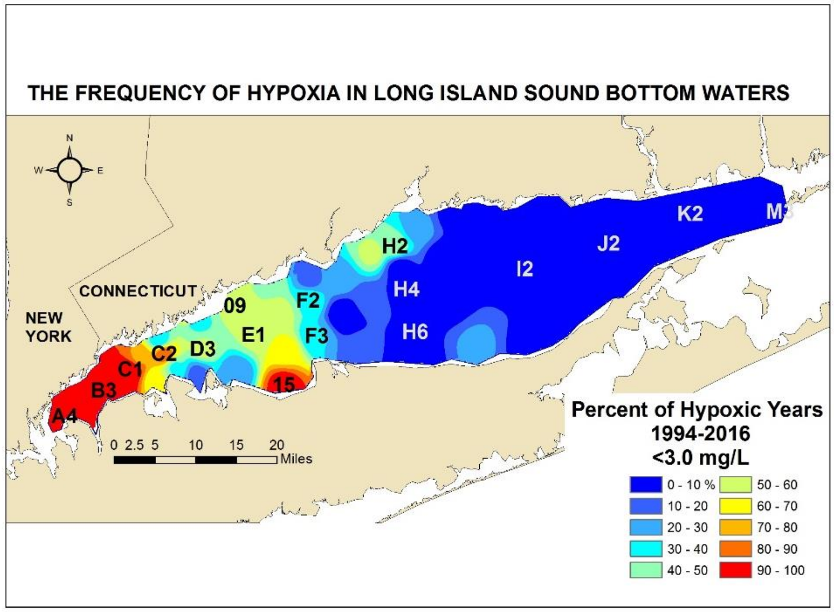
The term "hypoxia" means low dissolved oxygen ("DO") concentrations in the water. Marine organisms need oxygen to live, and low concentrations, depending on the duration and the size of the area affected, can have serious consequences for a marine ecosystem. As defined by the Long Island Sound Study, hypoxia exists when DO drops below a concentration of 3 mg/L, although research suggests that there may be adverse effects to organisms even above this level, depending upon the length of exposure (EPA, 2000 and Simpson *et al.*, 1995). The Connecticut Department of Energy & Environmental Protection, the New York State Department of Environmental Conservation and the Interstate Environmental Commission have water quality criteria for dissolved oxygen. These criteria, designed to protect the state's waters from degradation, define hypoxia as DO concentrations below 3.0 mg/L. Low oxygen levels can occur naturally in estuaries during the summer, when calm weather conditions prevent the mixing of the water column that replenishes bottom water oxygen during the rest of the year. However, excess nitrogen tends to exasperate hypoxia beyond that which may be caused by natural conditions.



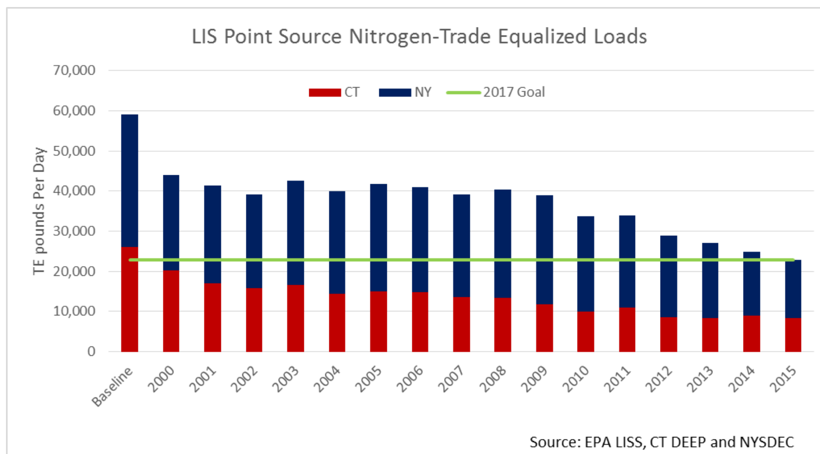
https://www.epa.gov/sites/production/files/2015-03/eutro_big.jpg

How Does Low Oxygen Impact the Sound?

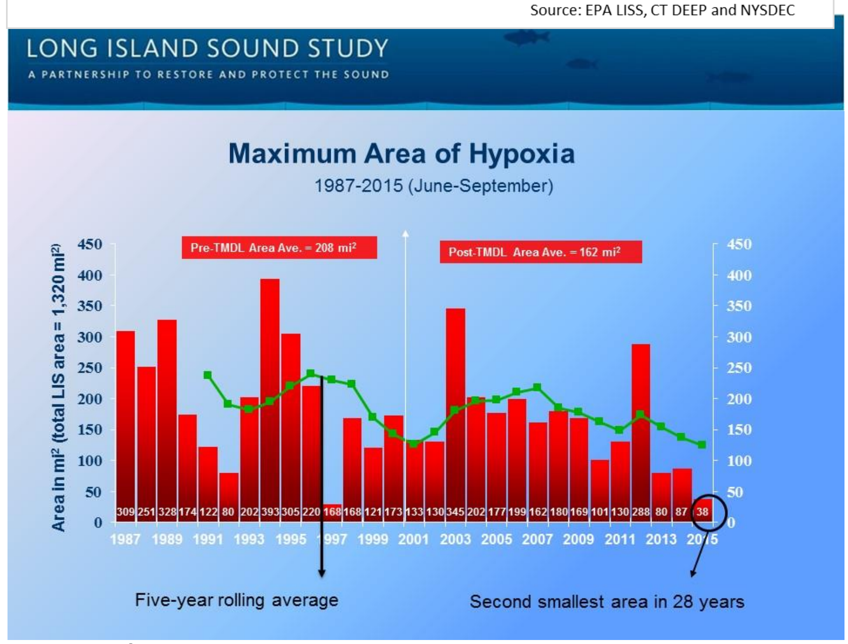
Each summer low oxygen levels render hundreds of square miles of bottom water unhealthy for aquatic life. Dissolved oxygen levels follow seasonal patterns with a decrease in bottom water DO over the course of the summer. Hypoxic conditions during the summer are mainly confined to the Narrows and Western Basin of Long Island Sound (map right). Those areas comprise the section of the Sound west of a line from Stratford, CT to Port Jefferson, NY. The maximum extent of the hypoxic condition typically occurs in early August.



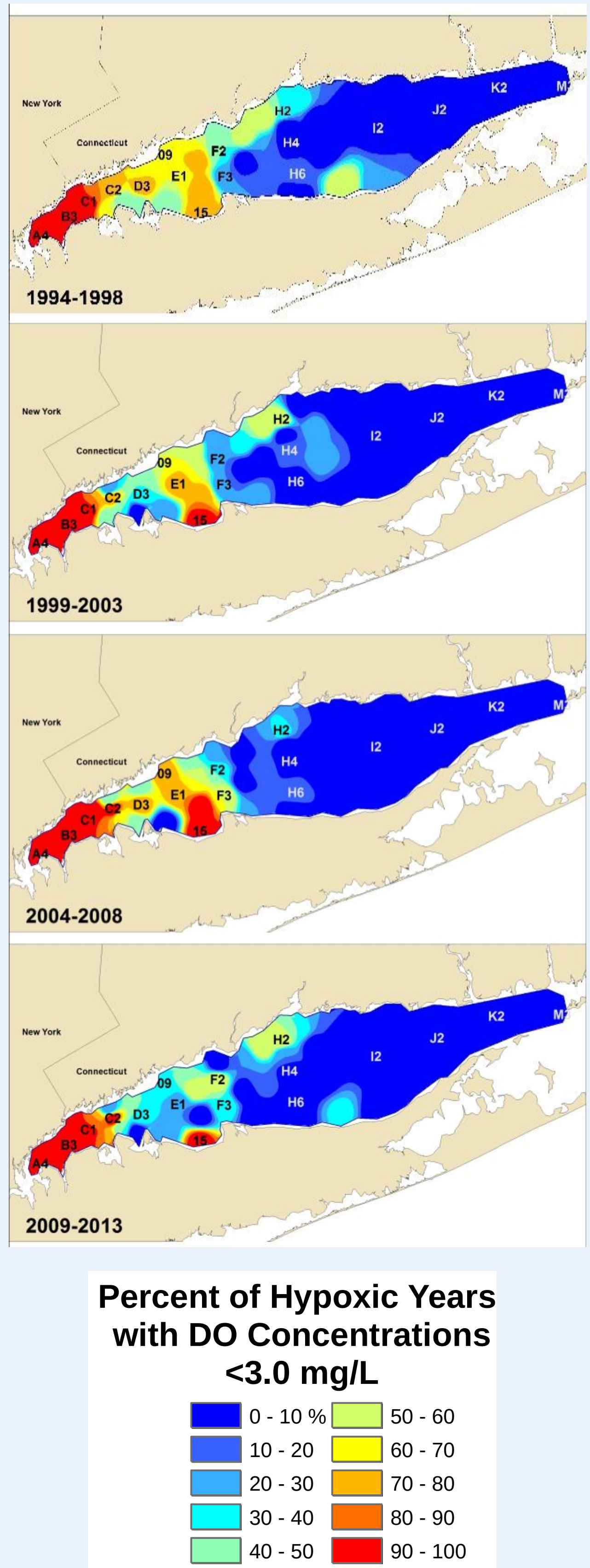
EPA, NY and CT implemented the *Total Maximum Daily Load to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound (2000 TMDL)* which has resulted in significant progress in reducing open water Sound hypoxic conditions. Across Connecticut and New York, 106 wastewater treatment plants have been upgraded and 40 million fewer pounds of nitrogen have entered the Sound (51.5% reduction).



EPA estimates a 40% reduction in the five year rolling average area of hypoxia across the Sound, compared to pre-TMDL levels (EPA 2015).



The maps in the sidebar display the percentage of years when dissolved oxygen concentrations at each station were below 3.0 mg/L in the bottom waters of Long Island Sound in five year intervals. The maps show the area of hypoxia reducing in the Western Sound (Stations 09, E1, D3), but continuing to persist in the Narrows (Stations A4, B3, C1). The maps are based on CT DEEP monitoring data only. Updates to hypoxia maps combining IEC and CT DEEP data have not been completed for years prior to 2016.



Habitat Impairment Associated With Hypoxia

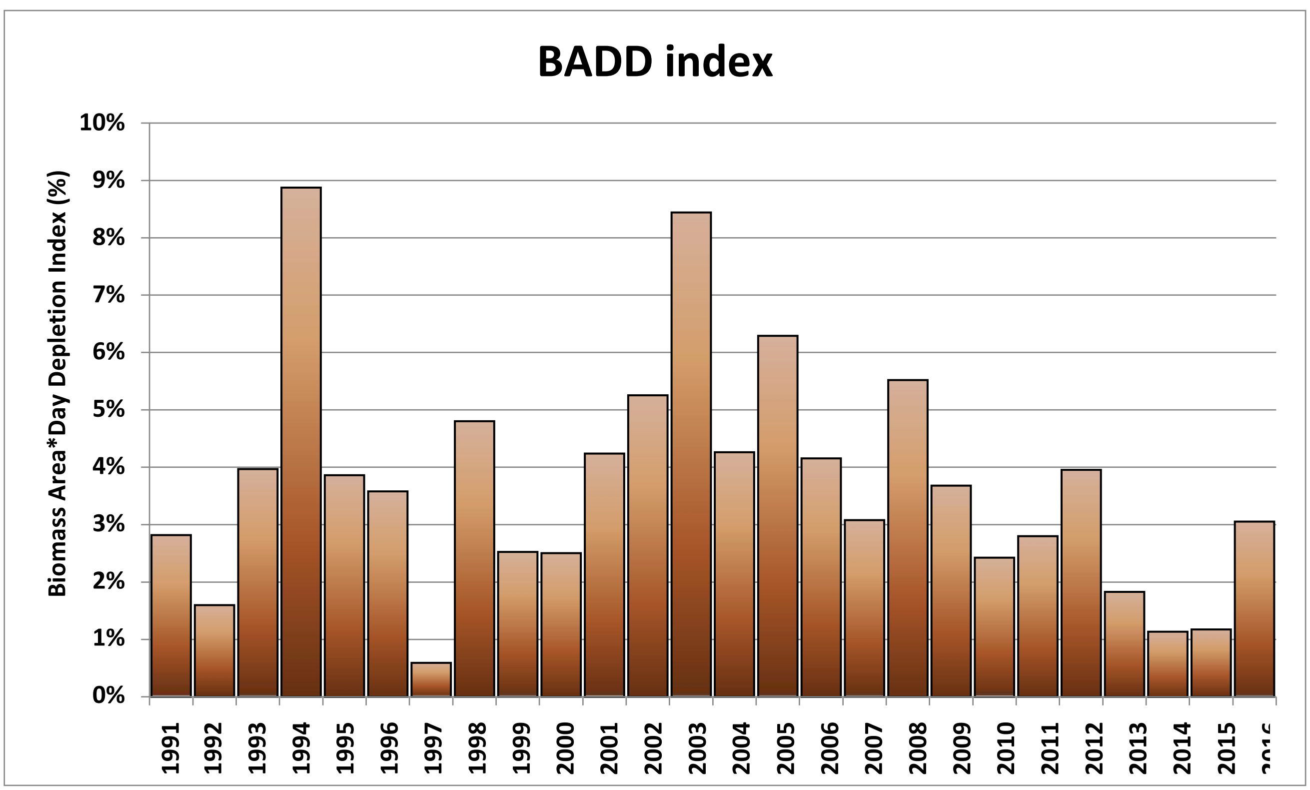
The following description of the "Biomass Area-Day Depletion (BADD) index of habitat impairment was excerpted from an article written by CT DEEP Marine Fisheries Biologist Penny Howell for the July/August 2014 edition of CT Wildlife Magazine.

For Long Island Sound, DO levels below 3 mg/L are considered hypoxic, causing mobile animals to leave and sessile animals to die or be physically or behaviorally impaired. However, DO can become limiting below 4.8 mg/L for sensitive fish species, such as whiting and scup, while more tolerant species, such as butterfish, bluefish, lobster and Atlantic herring, are not affected until DO falls below 2 mg/L (Simpson *et al*, 1995, 1996).

An index of habitat impairment, "Biomass Area-Day Depletion" (BADD) was developed by CT DEEP Marine Fisheries Division based on extensive sampling in the Sound from 1986-1993 (Simpson *et al*, 1995,1996). *Instead of individual species' responses to low oxygen, an aggregate response of 18 demersal (bottom-dwelling) finfish species was calculated as a general index of the impact on living resources to low oxygen conditions at or near the bottom of the Sound. The total weight, or biomass, of these demersal finfish species captured in samples taken at various levels of low DO was quantified and the percent reduction in biomass from that captured in fully oxygenated water was computed. These studies showed that the finfish biomass is reduced by 100% (total avoidance) in waters with DO less than 1.0 mg/L. In waters with 1.0-1.9 mg/L DO, biomass is reduced by 82%, while a 41% reduction occurs at 2.0-2.9 mg/L DO, and a 4% reduction occurs at 3.0-3.9 mg/L DO* (Simpson *et al*, 1995, 1996).

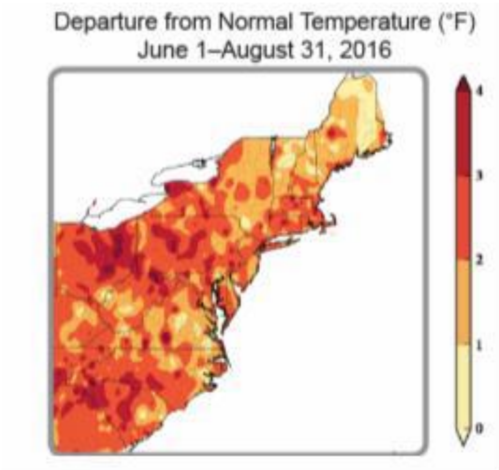
For each survey the total area of the Sound encompassing each 1-mg interval of DO is calculated and the depletion percentage applied. These area depletions are summed over the number of days they persist during the designated hypoxia season. The summed area-day depletion is then expressed as a percentage of the total available area (total sample area of 2,723 km^2) multiplied times the total season (94 days). A maximum BADD index of 100% would result from severe hypoxia occurring over the entire study area for the entire hypoxia season.

In an average year, hypoxic waters cover ~440 km^2 (169 miles^2) for 55 days and result in a BADD impairment index of 2.5%. In the worst year (1994), hypoxia spread over 1,000 km^2 (395 miles^2) for the entire season, resulting in a BADD index of almost 9%. In 2016, the BADD index was 3.05% up from 0.77% in 2015.

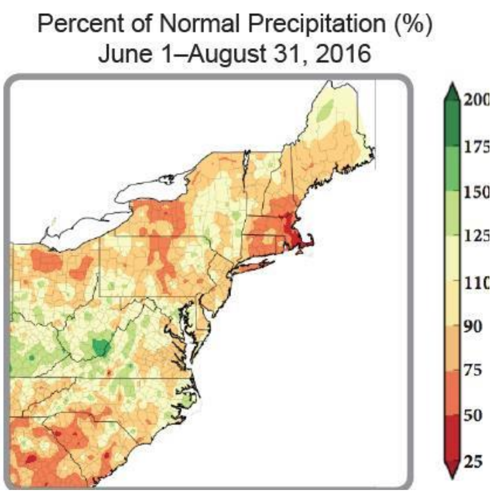


2016 Summer Weather Conditions

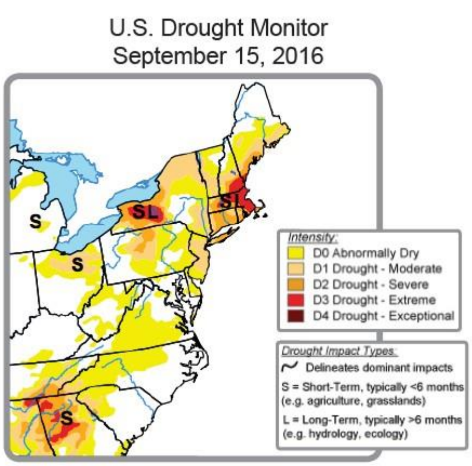
The Northeast Regional Climate Center (NRCC) at Cornell University is tasked with disseminating climate data and information for 12 states. The NRCC included the graphics at the left in their Eastern Region Quarterly Climate Impacts and Outlook Summary September 2016 (NRRC 2016a).



The summer of 2016 was warm and dry, with this summer being recorded as the second warmest on record for the Eastern region. Across the region, June was 0.8ºF above normal, July was 2.2 ºF above normal, August was 3.6ºF above normal, and September was 4.2ºF above normal. The warmth continued into November where the region as a whole was 2.0ºF above normal. The average August 2016 air temperatures at climate sites around Long Island Sound ranged from 78.4ºF in Bridgeport, CT (5.1ºF above normal) to 81.6 ºF at LaGuardia Airport in Queens, NY (5.3ºF above normal) to 77.3ºF at Islip, NY on Long Island (4.5ºF above normal).



Precipitation was below normal across the Eastern Region for the summer of 2016. At the beginning of June, NRRC noted that only about 1% of the Northeast was in a drought with the region receiving 89% of its normal precipitation. By September 37% of the Northeast was in a moderate, severe, or extreme drought. The lack of precipitation continued into November. Across Long Island Sound, precipitation totals varied widely from site to site and month to month. At Bridgeport, CT, June was very dry with only 35% of normal precipitation but July was wet with 139% of normal rainfall; during August and September rainfall was also below normal with 8-% and 78% or normal precipitation recorded. At LaGuardia Airport in Queens, NY, June was also dry with 57% of the normal precipitation falling, July was wet (111% of normal), but August was drier than in Bridgeport with only 27% of normal rainfall amounts recorded. September saw a slight improvement with 68% of normal precipitation reaching the ground at the Airport. On Long Island at Islip, NY June precipitation amounts were 26% of normal, July was 94% of normal, August was 23% of normal, and September was 85% of normal.



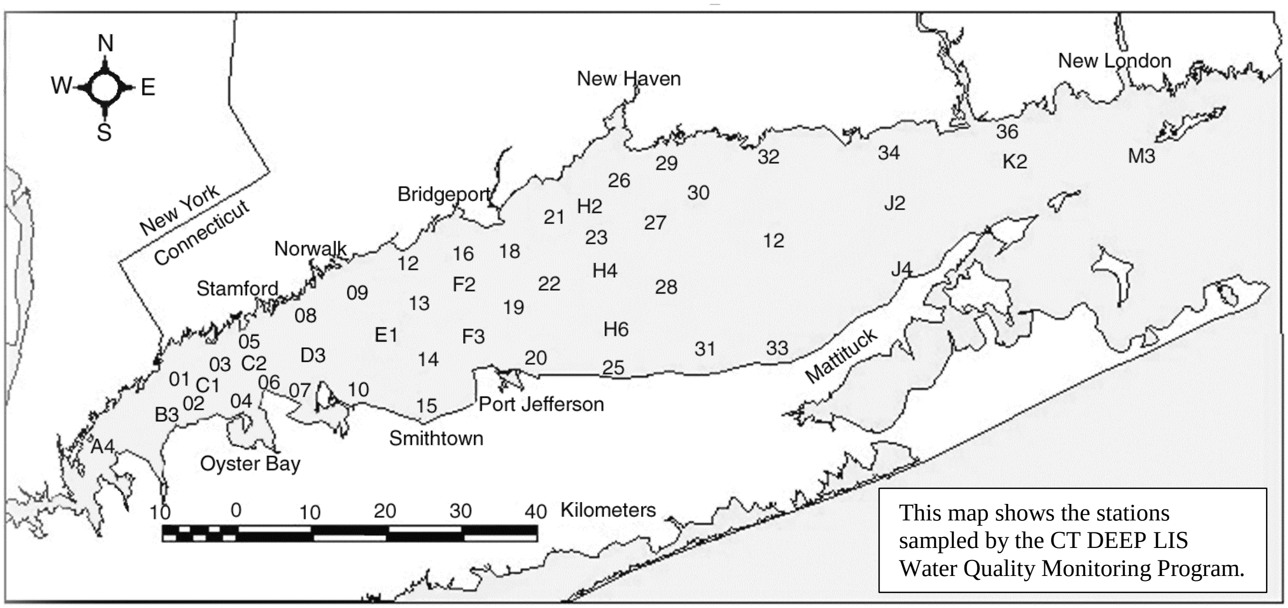
A Northeast Drought and Climate Outlook Forum was held in Boston in October to discuss the drought situation across the region (NRRC 2016b).

This climate information is useful as physical processes influence the timing and duration of hypoxia.

CT DEEP Program Overview

Since 1991, the Connecticut Department of Energy & Environmental Protection (CT DEEP, formerly the Department of Environmental Protection, (CTDEP) has conducted an intensive year-round water quality monitoring program on Long Island Sound (LIS). Water quality is monitored at up to forty-eight (48) sites by staff aboard the Department's Research Vessel *John Dempsey*. Data from the surveys are used to quantify and identify annual trends and differences in water quality parameters relevant to hypoxia (low dissolved oxygen), especially nutrients, temperature, and chlorophyll. These data are also used to evaluate the effectiveness of the management program to reduce nitrogen concentrations. During the summer (June - September) CT DEEP conducts additional summer hypoxia surveys at bi-weekly intervals to better define the areal extent and duration of hypoxia.

DEP stations in Long Island Sound



This map shows the stations sampled by the CT DEEP LIS Water Quality Monitoring Program.

CT DEEP Methods

From October to May, *in situ* data and nutrient samples are collected once a month from 17 sites. Bi-weekly hypoxia surveys start in mid-June and end in September with up to 48 stations being sampled during each survey for *in situ* parameters.

Dissolved oxygen, temperature, pH, and salinity data are collected *in situ* (on site in the water column) using an electronic instrument called a Conductivity Temperature Depth recorder (CTD) that takes measurements from the surface to the bottom of the water column. The CTD, a Sea-Bird model SBE-19 SeaCat Profiler equipped with auxiliary dissolved oxygen, photosynthetically-active radiation (PAR) and pH sensors, is attached to a Rosette Sampler and lowered through the water column at a rate of approximately 0.2 meters per second and measurements are recorded every 0.5 seconds. *In situ* data are reviewed in real-time.

Water samples are collected using Niskin water sampling bottles that are attached to the Rosette Sampler. The Rosette is lowered off the stern of the *Dempsey* and the bottles are triggered remotely to take a water sample at any specified depth (surface= 2 meters below the surface; and bottom = 5 meters above the bottom). Samples are filtered aboard the mini laboratory and preserved for later analyses at the University of Connecticut's Center for Environmental Science and Engineering in Storrs, Connecticut.

Parameters for which surface and bottom waters are tested include dissolved silica, particulate silica, particulate carbon, dissolved organic carbon, dissolved nitrogen, particulate nitrogen, ammonia, nitrate + nitrite, particulate phosphorus, total dissolved phosphorus, orthophosphate, chlorophyll a, and total suspended solids.

Since 2002, CT DEEP has collected zooplankton samples from six stations and phytoplankton from ten stations across Long Island Sound. The samples are sent to researchers at the University of Connecticut who identify species composition, abundance, community structure, and spatial and temporal distribution throughout the Sound.

All samples are collected and analyzed under EPA-approved Quality Assurance Project Plans.

IEC Program Overview

The Interstate Environmental Commission (IEC) is a tri-state water and air pollution control agency located in Staten Island, NY on the College of Staten Island campus. Established in 1936, the IEC serves the states of New York, New Jersey, and Connecticut. The IEC's area of jurisdiction runs west from New Haven, CT, and Port Jefferson, NY, on Long Island Sound. As of 2012, IEC has been in a temporary host relationship with the New England Interstate Water Pollution Control Commission (NEIWPCC).

Interstate Environmental Commission
A Tri-State Water and Air Pollution Control Agency
NY · NJ · CT

IEC has conducted monitoring in the far Western Long Island Sound and the Upper East River since 1991. IEC's monitoring program was designed to align with CT DEEP's program. The overall goal of IEC's seasonal monitoring program is to effectively measure key water quality indicators identified by the Long Island Sound Study (LISS), such as hypoxia and nutrient pollution, which are important for managing priority areas of concern.

NEIWPCC
New England Interstate Water Pollution Control Commission

IEC's monitoring program is conducted between June and September as dissolved oxygen concentrations in Long Island Sound typically reach their lowest levels during the summer. This allows for better characterization of hypoxia and identification of critical areas in the Sound. Between June and September, IEC collects *in situ* data from 22 stations in the Western portion of the Sound on a weekly basis. *In situ* parameters include water temperature, dissolved oxygen, salinity, pH, and water clarity (secchi disk depth). In addition, IEC collects biweekly samples for chlorophyll a, Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), and a suite of nutrient parameters. More information about IEC and its monitoring program can be found below or on the IEC website: (http://www.iec-nynjct.org).

IEC monitoring data incorporated in this report for hypoxia maps uses data from 13 of 22 stations. The nine stations not included are representative of embayments. IEC data represented in this report that is not dissolved oxygen data was derived from IEC's six axial stations, which was combined with CT DEEP's seven axial stations. IEC's six axial stations include the following: A1, A2M, A3, A4, A5, B3. CT DEEP's seven axial stations include the following: A4, B3, D3, F3, H4, I2, and M3. Additional IEC data can be derived from IEC's weekly season summaries.

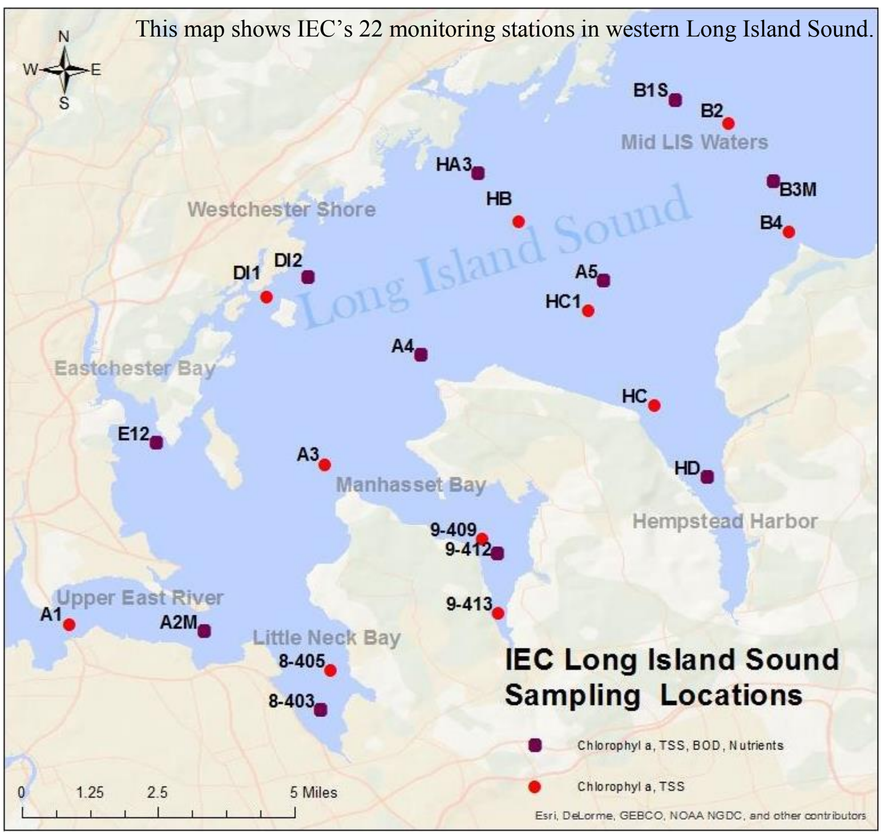
IEC staff preparing water quality sonde for deployment.

IEC staff recording *in situ* data.

IEC Methods

Dissolved oxygen, temperature, salinity, and pH data are collected using a YSI EXO 1 Multiparameter Sonde at bottom, mid, and surface depths at all 22 stations on a weekly basis from June through September. For stations with a depth of less than 10 meters, only surface and bottom measurements are collected. In addition, data collection includes percent cloud cover, sea state, water clarity as measured by Secchi disk depth as well as weather and precipitation data.

Surface grab samples (within one meter of the surface) are collected on a biweekly basis June through September for chlorophyll a and Total Suspended Solids (TSS) at all 22 stations and a suite of nutrient parameters and Biochemical Oxygen Demand (BOD) at 11 of the 22 stations. The map below highlights where sample collection takes place and for which parameters. Samples collected for chlorophyll a and TSS are collected directly into a clean, dry, 1000-mL polypropylene sample bottle and are stored in the dark. BOD and nutrient samples are collected using a clean, dry, 2000-mL polypropylene sample bottle. All samples are kept at ≤4°C during collection and transport to the IEC laboratory. The IEC laboratory is a nationally certified environmental testing laboratory with National Environmental Laboratory Accreditation Program (NELAP) accreditation.



The 11 stations for BOD and nutrient sampling, which was added to the program in 2014, were chosen based on feedback and input from the Long Island Sound Study Water Quality Monitoring Workgroup. The specific nutrient parameters that are analyzed include Ammonia, Nitrate+Nitrite, Particulate Nitrogen, Orthophosphate/DIP, Total Dissolved Phosphorus, Particulate Phosphorus, Dissolved Organic Carbon, Particulate Carbon, Dissolved Silica, and Biogenic Silica.

Chlorophyll a, TSS, BOD and all nutrient parameters (with the exception of Dissolved Organic Carbon and Particulate Carbon) are analyzed in-house at the IEC laboratory. Samples for Dissolved Organic Carbon and Particulate Carbon analysis are subcontracted to the University of Maryland's Center for Environmental Science, Chesapeake Biological Laboratory, Nutrient Analytical Services Laboratory in Solomons, MD. Further information on sampling and analytical methods can be found in the EPA-approved QAPP *Ambient Water Quality Monitoring in Far Western Long Island Sound, version 3.0.*

LISICOS

The Long Island Sound Integrated Coastal Observing System (LISICOS) was established in 2003 as a component of a regional/national ocean observing system. The system was conceptualized as part of a water quality monitoring program that combined the traditional ship-based point sampling surveys with continuous, real-time sampling stations. Funding for the program was first provided through the Environmental Protection Agency Environmental Monitoring for Public Access and Community Tracking (EMPACT) grant program and is now provided, in part, by the National Oceanic and Atmospheric Administration.

The initial goal was to develop “a capability to observe and understand the LIS ecosystem and predict its response to natural and anthropogenic changes.”

LISICOS monitors water quality parameters (*e.g.*, salinity, temperature, dissolved oxygen, surface waves, photosynthetically available radiation, chlorophyll) and meteorological parameters (*e.g.*, wind speed, direction, barometric pressure, wave height) at up to eight stations across the Sound. Sensors are attached to a moored buoy at various depths (surface, mid, bottom). Data are transmitted every 15 minutes in real-time via satellite where they are stored in a database and uploaded to the LISICOS website: http://lisicos.uconn.edu/index.php.

The system is maintained by the University of Connecticut.

2016 Important Facts

CT DEEP conducted eight cruises during the summer of 2016 between 10 June and 13 September. Over the course of the season, fifteen (15) different stations were documented as hypoxic and of the 275 site visits completed in 2016, hypoxic conditions were found during three surveys.

IEC conducted twelve cruises during the summer of 2016 between 28 June and 13 September. Hypoxic conditions were found during nine surveys (embayment stations included). 18 different stations were documented as hypoxic.

Cruise	Start Date	End Date	Number of stations	Number of hypoxic	Hypoxic Area (mi^2)
WQJUN16	6/8/16	6/14/16	1	0	0
HYJUN16	6/20/16	6/20/16	2	0	0
IEC Run	6/28/16	6/28/16	2	0	0
WQJUL16	7/5/16	7/7/16	4	0	0
IEC Run	7/5/16	7/5/16	2	0	0
IEC Run	7/12/16	7/12/16	2	2	NC
HYJUL16	7/18/16	7/19/16	4	1	19.0
IEC Run	7/19/16	7/19/16	2	11	NC
IEC Run	7/26/16	7/26/16	2	12	NC
WQAUG1	8/1/16	8/4/16	4	0	0
IEC Run	8/3/16	8/3/16	2	2	NC
IEC Run	8/9/16	8/9/16	2	2	NC
IEC Run	**8/16/16**	**8/16/16**	**2**	**15**	NC
HYAUG1	**8/16/16**	**8/18/16**	**4**	**15**	**197.5**
IEC Run	8/23/16	8/23/16	2	8	NC
WQSEP16	8/29/16	8/31/16	4	5	53.7
IEC Run	8/30/16	8/30/16	2	7	NC
IEC Run	9/9/16	9/9/16	2	0	NC
HYSEP16	9/12/16	9/13/16	3	0	NC
IEC Run	9/13/16	9/13/16	2	0	NC

NC= Not calculated
Bold= highest area of hypoxia

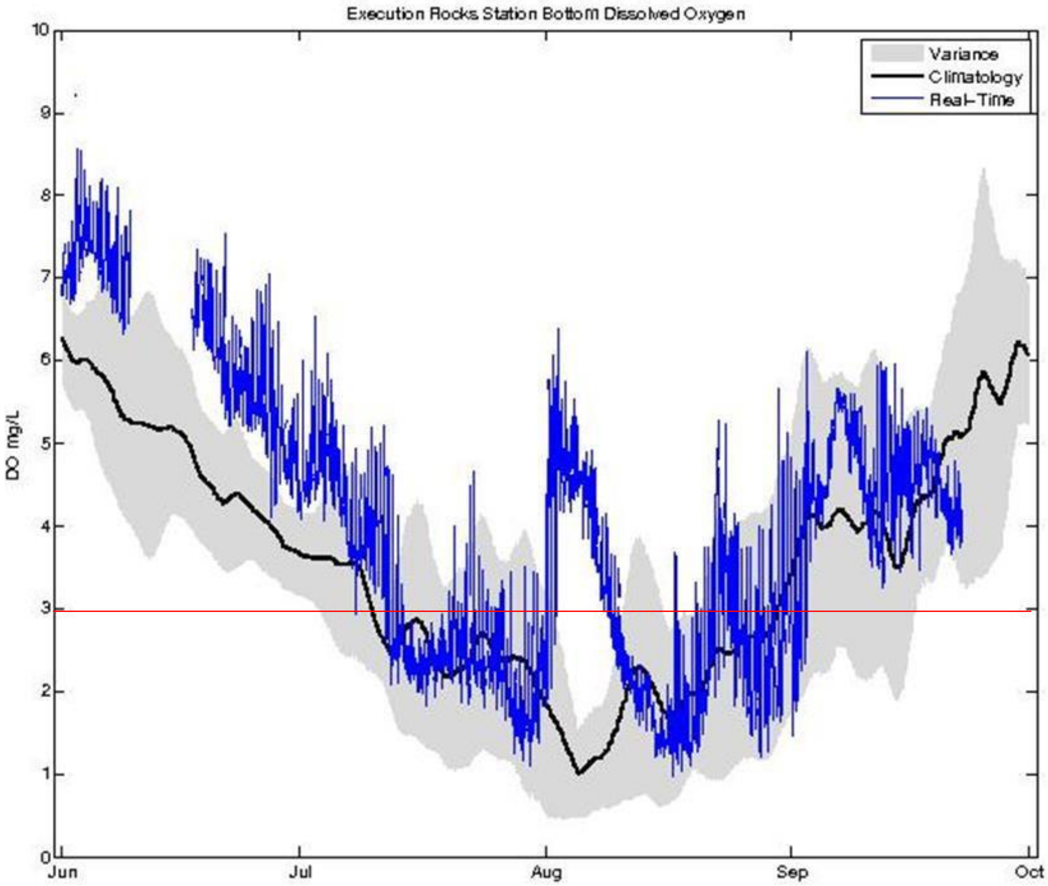
2016 Duration Estimates

Start dates and end dates for the hypoxic events are estimated by plotting CT DEEP and IEC data from stations A4 and B3 in an Excel spreadsheet and then using a line with markers chart to interpolate when the DO concentration drops below/rises above 3.0 mg/L. The 2016 hypoxic event was estimated to have begun on July 8th. There was a clear period in the beginning of August when DO concentrations rose above 3.0 mg/L and remained above this threshold for 8 days. This is also evident in data collected by the LISICOS Execution Rocks Buoy (next page). DO concentrations decreased below the hypoxia threshold again on 8 August and remained there for another 28 days, until the fourth of September when concentrations climbed above the 3.0 mg/L threshold. Compared to the previous 24-year average duration of 55 days, 2016 was near average, with the event lasting 51 days.

	Event #1	Event #2	Total
Estimated Start Date	**7/8/2016**	**8/8/2016**	
Estimated End Date	**7/30/2016**	**9/4/2016**	
Duration (days)	**23**	**28**	**51**
Maximum Area (mi^2)			**197.5**

Duration Based on Buoy Data Obtained from the LISICOS Network on 29 September 2016

The figure below is from the LISICOS website and depicts the 2016 real-time bottom dissolved oxygen data (blue line); the average of the 10-year dataset (black line); and the variability observed over the historical station record (gray shading) from the Execution Rocks Buoy. The Western Sound Buoy was offline the entire summer after sustaining damage over the winter of 2014-2015.



Based on LISICOS Buoy Data Collected Between 1 June to 28 September

Estimated Dates Event #1	7/8/16-7/31/16
Estimated Dates Event #2	8/8/16-9/5/16
Duration below 3.0 mg/L (cumulative days)	37.3
Duration below 2.0 mg/L (cumulative days)	12.9
Duration below 1.0 mg/L (cumulative days)	0.01
Minimum DO value (mg/L)	0.98 (17 August)
Days with no data	

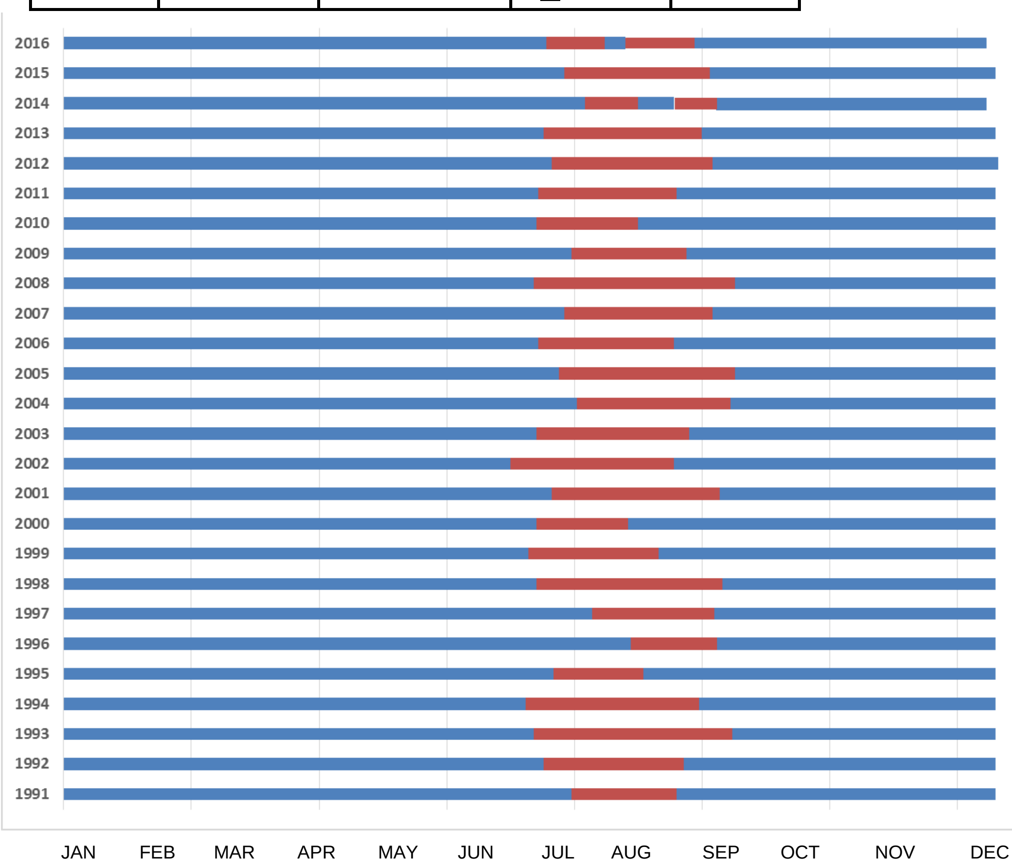
Data obtained from the LISICOS Execution Rocks Buoy Bottom Dissolved Oxygen Prediction Tool webpage (http://lisicos.uconn.edu/do_fcst.php?site=exrx). Duration is calculated by LISICOS by summing the time (in days) of the number of samples where DO was below the specified value (T. Fake, pers comm. 18 October 2012). ***Data are provisional and subject to change.***

Timing and Duration of Hypoxia, DEEP Data 1991 - 2016

Year	Estimated Start Date	Estimated End Date	Maximum Area (mi^2)	Duration (days)
1991	July 19	Aug 28	122	41
1992	July 7	Aug 30	80	55
1993	July 9	Sept 10	202	64
1994	July 1	Sept 6	393	68
1995	July 12	Aug 16	305	35
1996	Aug 10	Sept 12	220	34
1997	July 27	Sept 12	30	48
1998	July 5	Sept 16	168	73
1999	July 2	Aug 21	121	51
2000	July 2	Aug 6	173	35
2001	July 10	Sept 14	133	66
2002	June 25	Aug 28	130	65
2003	July 5	Sept 3	345	61
2004	July 20	Sept 12	202	55
2005	July 14	Sept 20	177	69
2006	July 6	Aug 27	199	53
2007	July 16	Sept 11	162	58
2008	July 3	Sept 19	180.1	79
2009	July 19	Sept 1	169.1	45
2010	July 5	August 13	101.1	40
2011	July 6	August 28	130.3	54
2012	July 10	Sept 10	288.5	63
2013	July 8	Sept 7	80.7	62
2014*	July 24	Sept 9	87.1	35
2015	July 16	Sept 10	38.3	57
2016*	July 8	Sept 3	197.5	51
Average	July 12	Sept 4	170.6	55
Deviation	±10 days	±12 days	± 87.8 mi^2	± 13 days

The table to the left and the graph below display the onset, duration, and end of the hypoxic events from 1991 through 2016. Based on the LISS standard of 3.0 mg/L, the average date of onset was July 12 (±10 days), the average end date was September 4 (±12 days), and the average duration was 55 days (±13 days). The earliest onset of hypoxia (red text) occurred on 25 June 2002 and the latest end date (green text) occurred on 20 September 2005.
The maximum area of hypoxia was 393 square miles (blue text) and occurred in 1994. The longest hypoxic event occurred in 2008 (magenta text) and lasted 79 days.

* In 2014 and 2016 there were clear periods where the DO concentration rose above the 3.0 mg/L threshold in the early/middle part of August before dipping again during late August and early September.



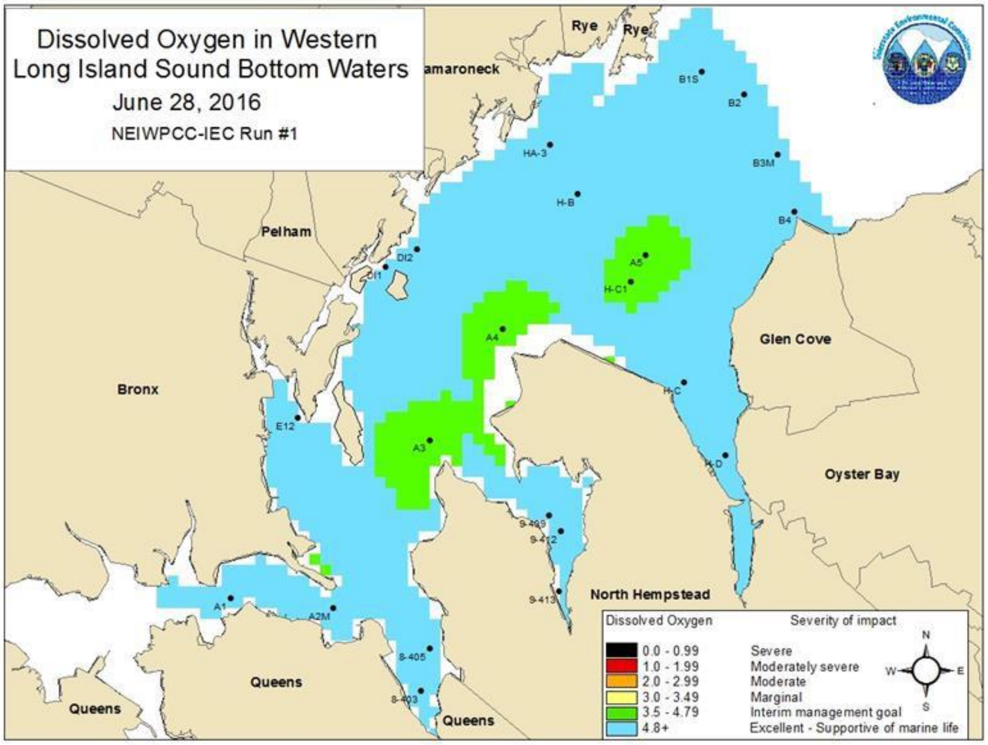
Hypoxia Maps

The following maps depict the development of hypoxia based on CT DEEP and IEC data through the 2016 season. Data for all surveys are available upon request.

Beginning with this year's *Season Summary Report*, readers will notice maps have been created for all IEC surveys and DEEP surveys. Additionally, maps were created that combine DEEP and IEC data into a single map. The following 13 IEC stations were incorporated in the combined maps: A1, A2M, A3, A4, A5, B1S, B2, B3M, B4, H-A3, H-B, H-C, H-C1. As IEC and DEEP share two stations (A4 and B3), the data from these stations were averaged together to create the new combined maps. IEC stations in embayments (*i.e.,* DI1, DI2, 9-409, 9-412, 9-413, E-12, 8-405, 8-403, and H-D) were not included in the combined maps.

While areal estimates were calculated using these combined hypoxia maps and are presented in this report, they are to be considered for informational purposes only. It is inappropriate to utilize the combined areal estimates as the official hypoxic area for 2016 as they are not comparable to the previous 24 years estimates. DEEP is just beginning the process of updating all the areal estimates from 1991 to the present utilizing historical datasets from IEC. Once completed the datasets would again be comparable.

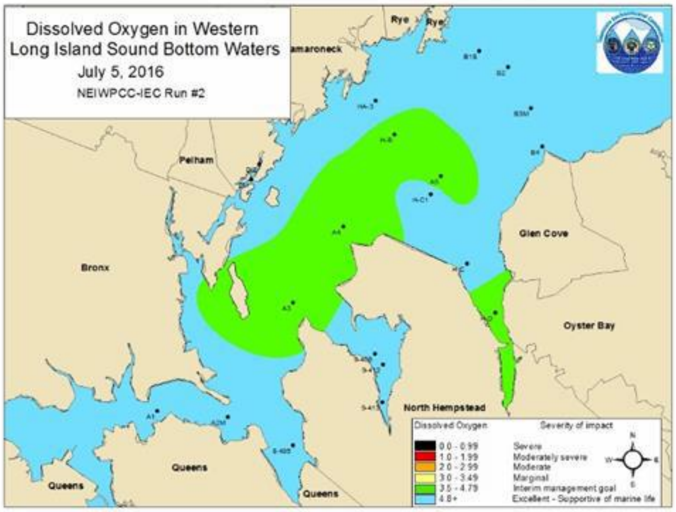
IEC Run #1

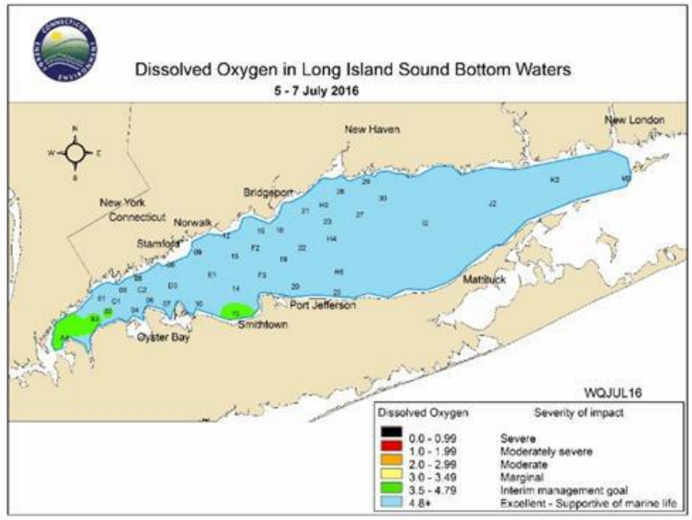


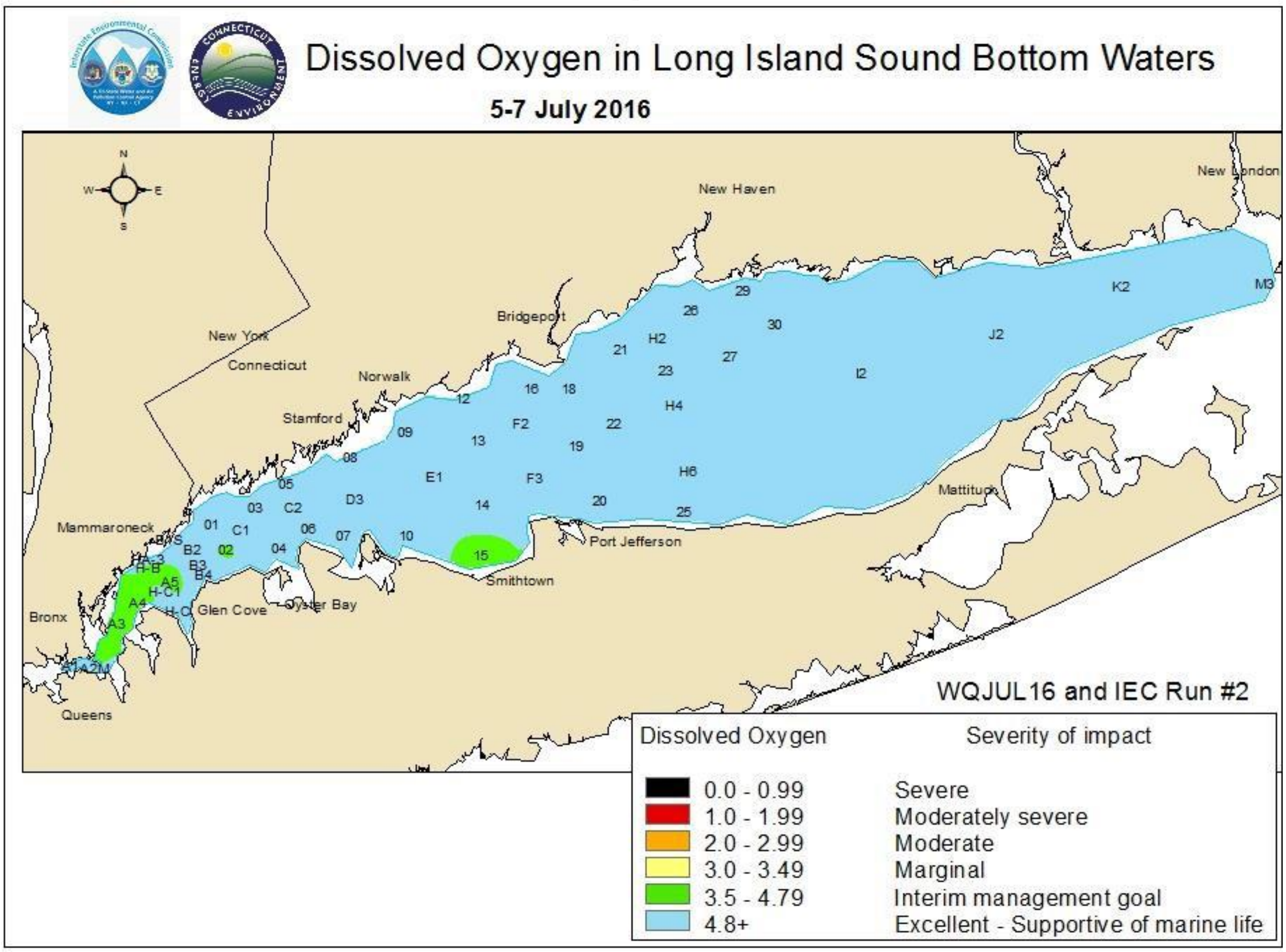
During the WQJUN16 and HYJUN16 surveys all CT DEEP stations had DO concentrations above 4.8 mg/L; therefore, no maps were produced. During IEC's first sampling run on 28 June, four stations had concentrations below 4.8 mg/L, which are represented above.

DEEP WQJUL16 and IEC Run #2

During the WQJUL16 and Run #2 surveys dissolved oxygen concentrations in the bottom waters of LIS were less than 4.8 mg/L at four CT DEEP stations- A4, B3, 02, and 15 and five IEC stations- A3, A4, H-B, A5, and H-D.

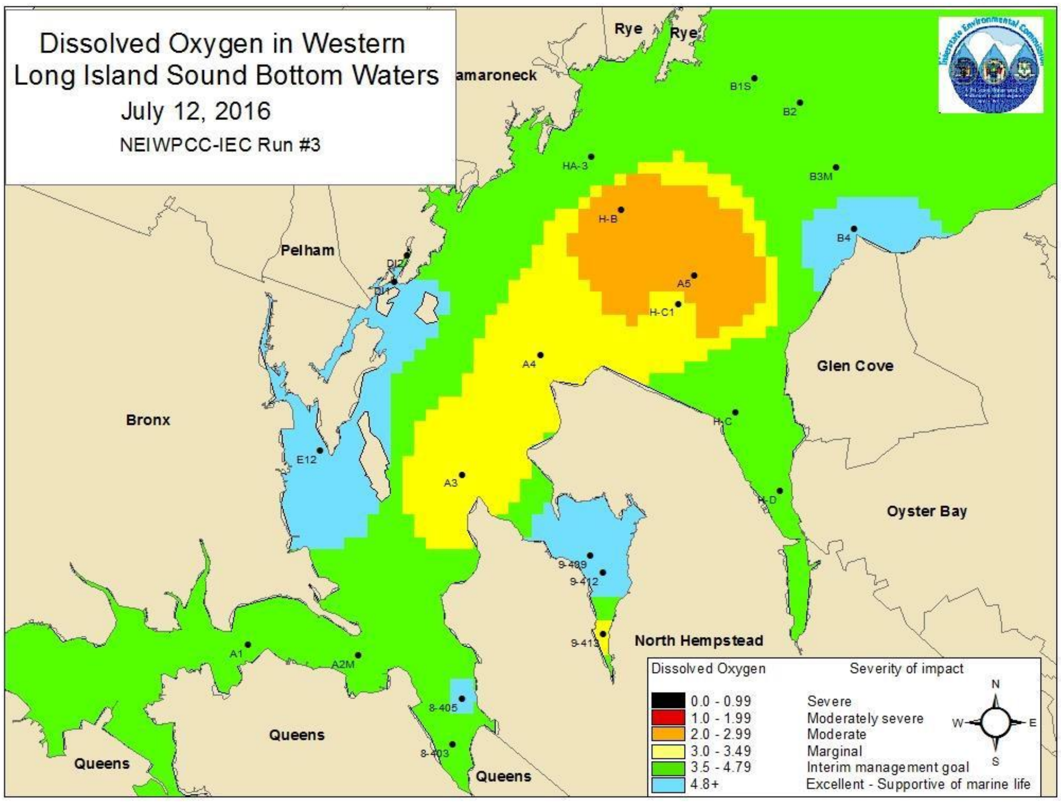






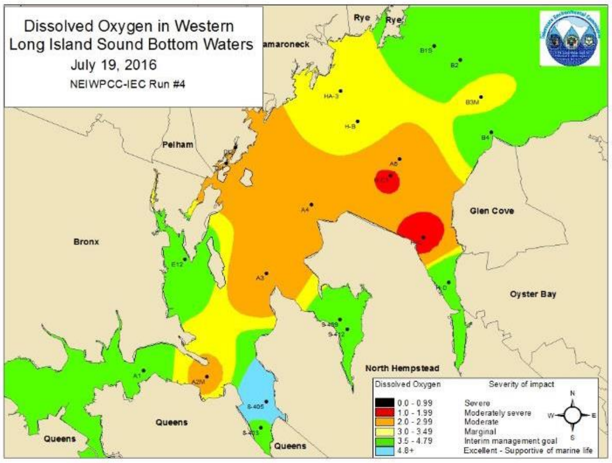
IEC Run #3

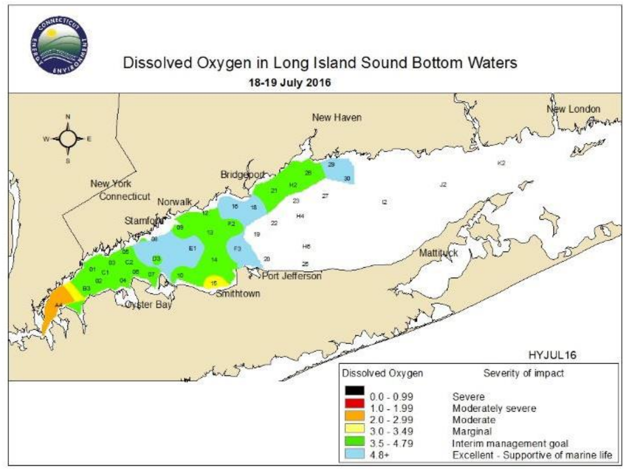
During IEC Run #3 on 12 July, two stations in the far Western Sound exhibited DO concentrations below 3.0 mg/L; four stations were below 3.5 mg/L; and nine stations were below 4.8 mg/L.

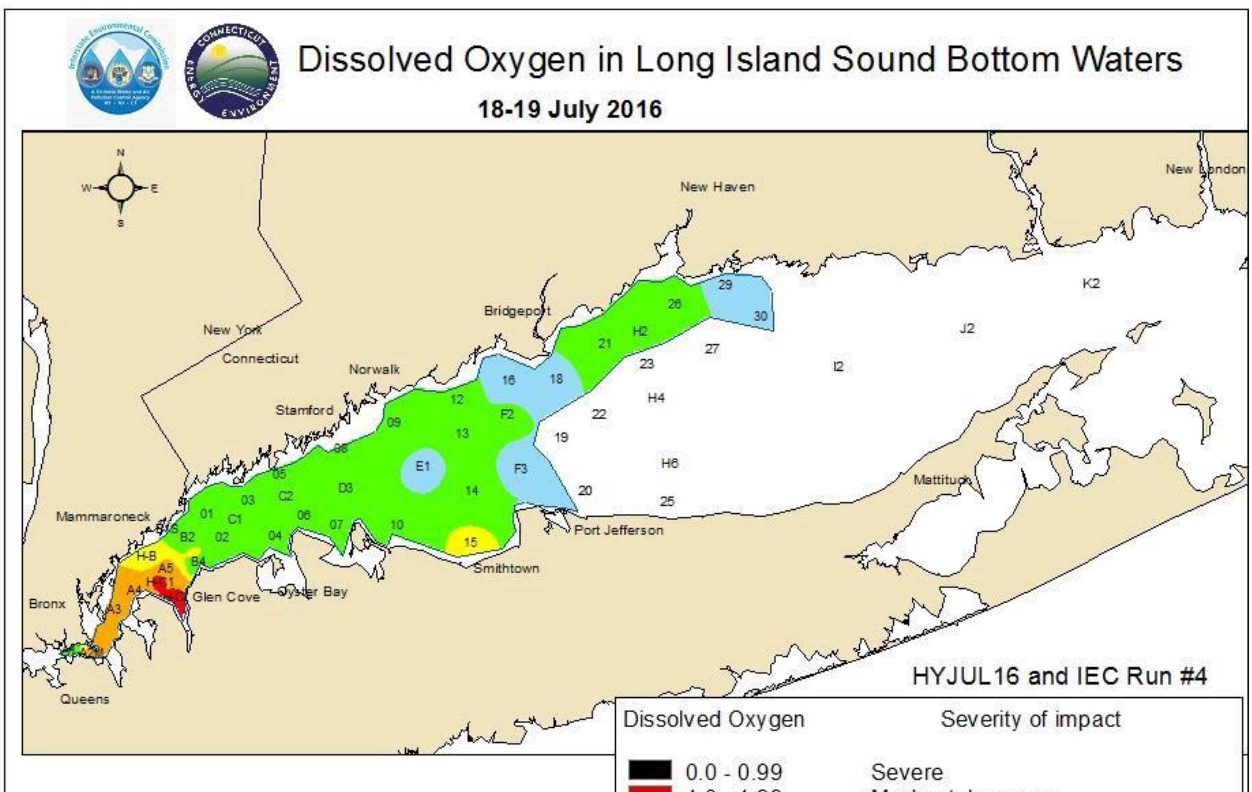


DEEP HYJUL16 and IEC Run #4

During IEC Run #4 on 19 July, only one station exhibited DO concentrations above 4.8 mg/L. Two stations (HC and HC-1) were below 2.0 mg/L, three stations were below 3.0 mg/L and three stations were below 3.5 mg/L. During the DEEP HYJUL16 survey, DO concentrations dropped below 4.8 mg/L at 19 stations with one station below 3.5 mg/L and one station below 3.0 mg/L. DEEP and IEC were coincidentally at Station A4 at the same time on 7/19. Measurements between the two agencies were comparable—DEEP logged a DO concentration of 2.44 mg/L at 34.4 meters (m) while IEC recorded 2.48 mg/L at 36.0 m.



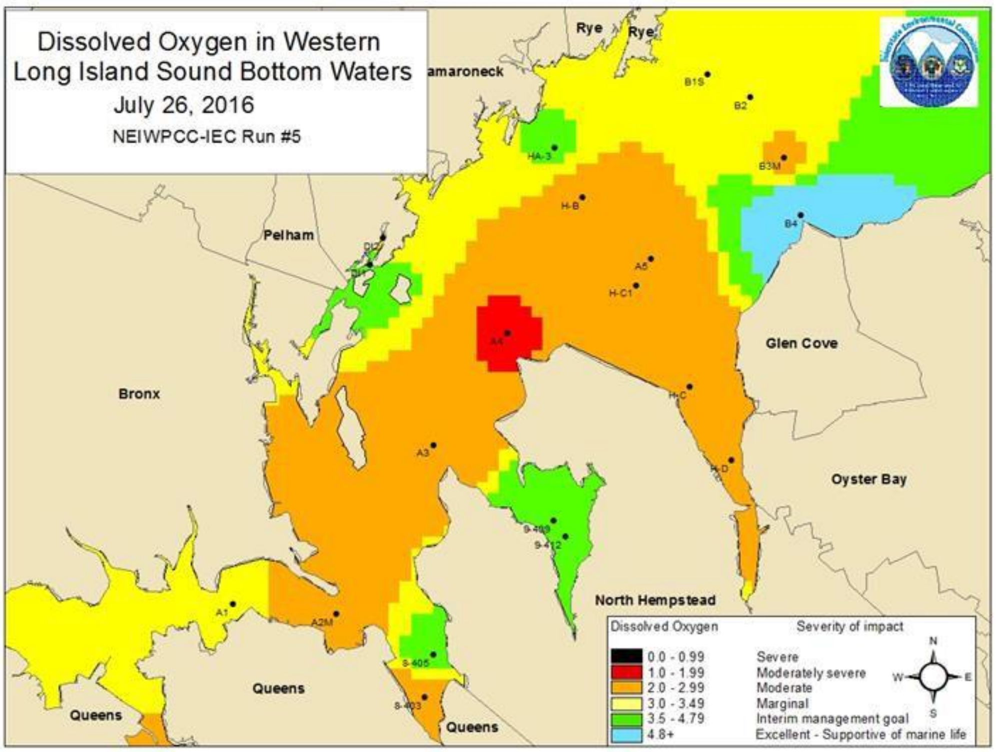




Data from 11 DEEP stations were not available due to CTD battery failure.

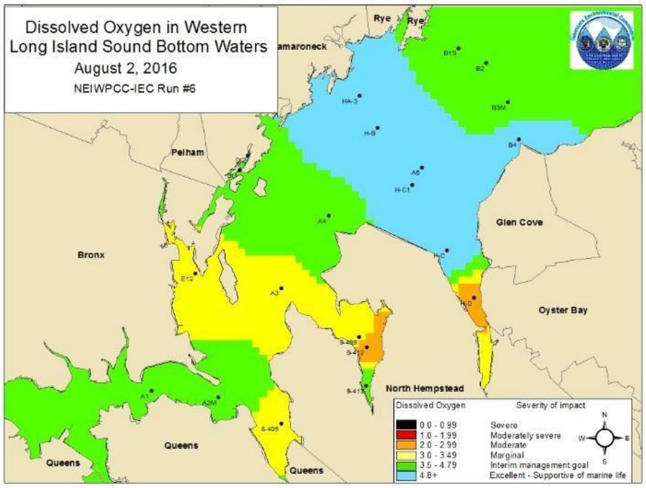
IEC Run #5

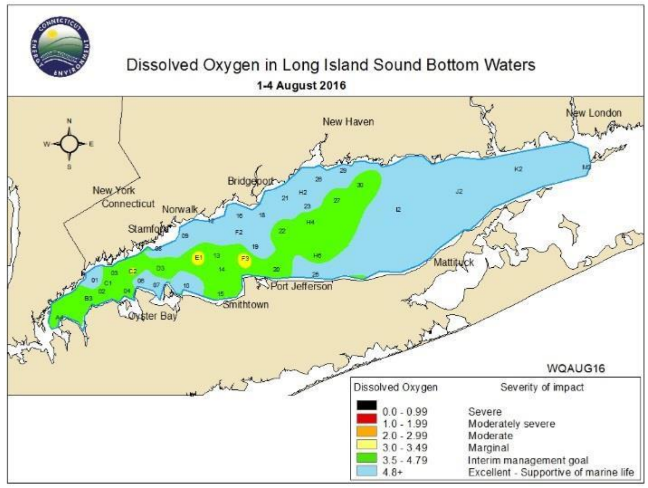
IEC Run #5 occurred on 26 July DO measurements at nineteen (19) stations were less than 4.8 mg/L. Of those, three were less than 3.5 mg/L; nine were less than 3.0 mg/L; and one station, A4, was less than 2.0 mg/L. At Station A4 the DO was 1.96 mg/L. Station B3 was at 2.95 mg/L.

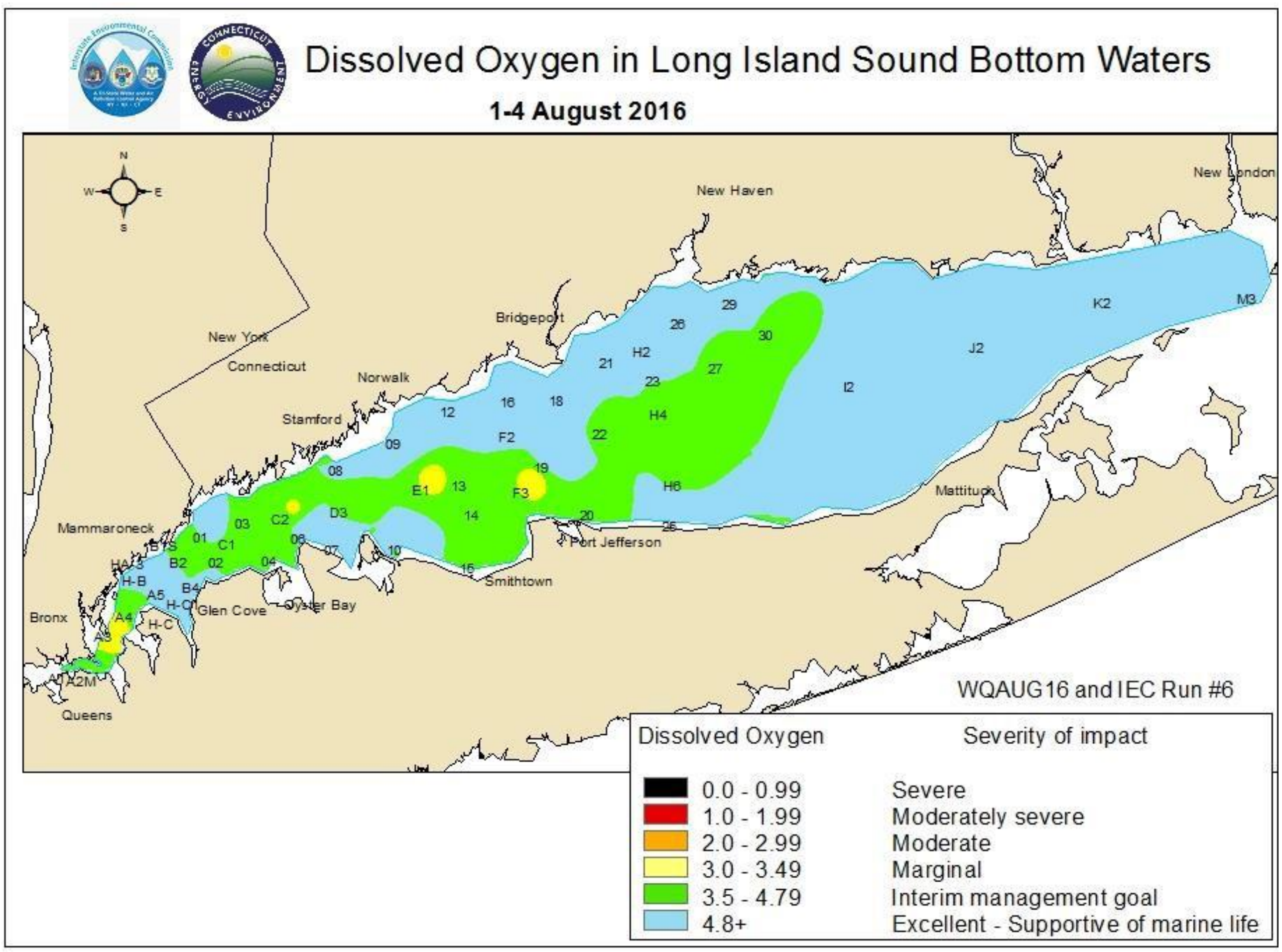


DEEP WQAUG16 and IEC Run #6

During the DEEP WQAUG16 survey, conditions improved with dissolved oxygen concentrations at all stations above 3.0 mg/L. DEEP stations C2, E1, and F3 lingered below 3.5 mg/L. During IEC Run #6 only two embayment stations were below 3.0 mg/L and four stations were less than 3.5 mg/L.

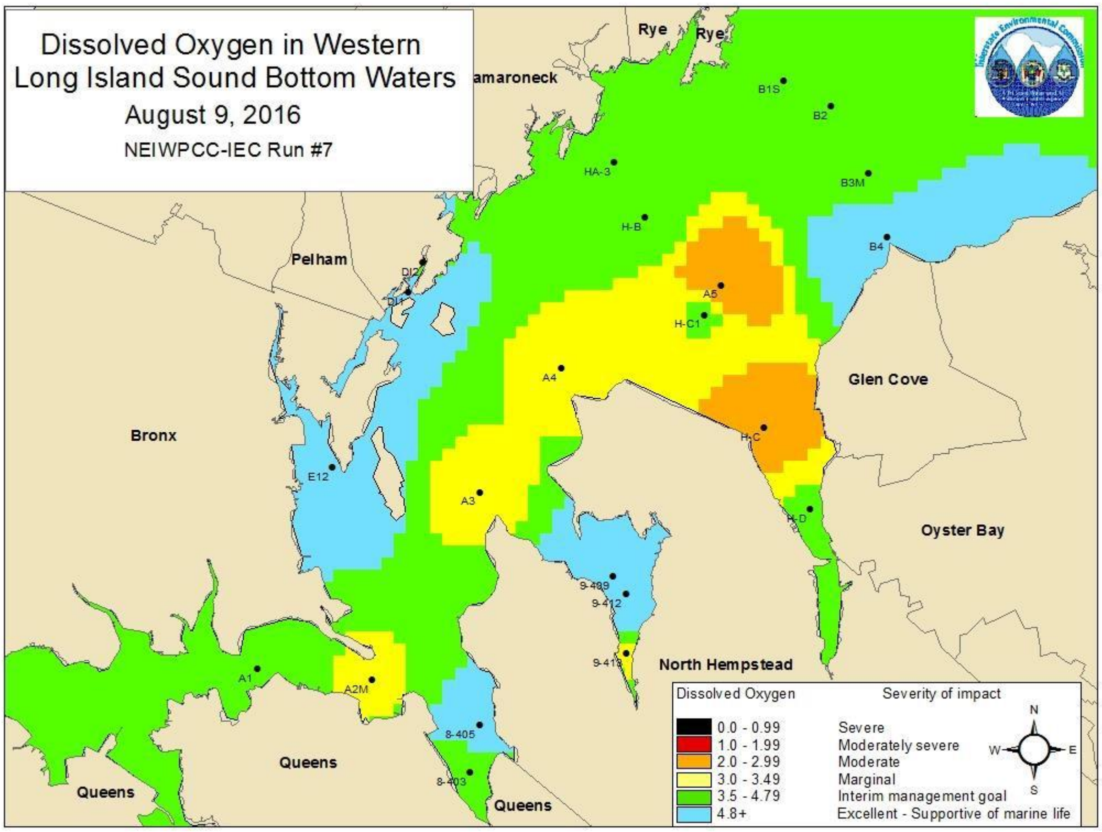






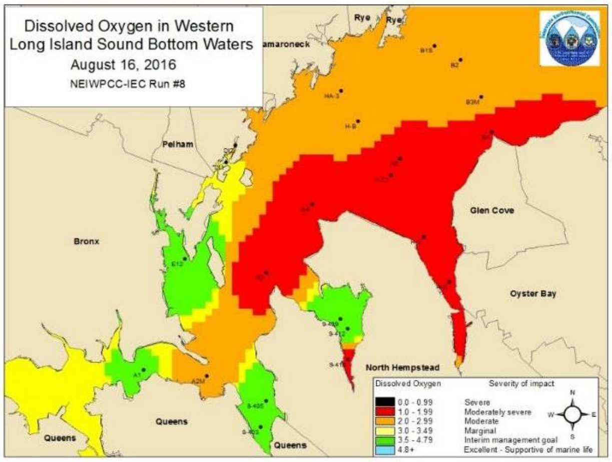
IEC Run #7

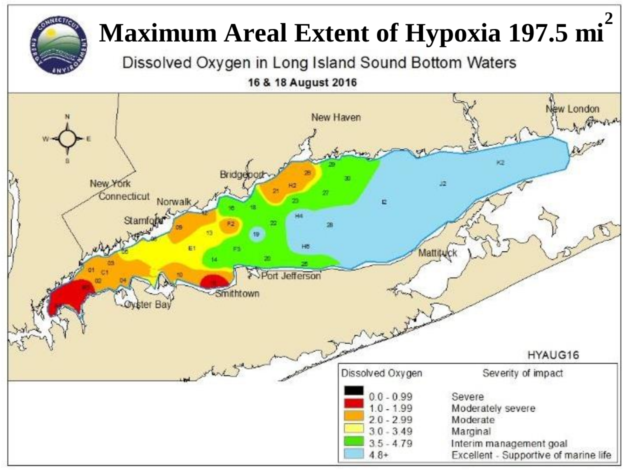
During IEC Run #7 on 9 August, DO concentrations at Stations A5 and H-C dropped below 3.0 mg/L. Four additional stations exhibited DO concentrations below 3.5 mg/L, including Station A4.

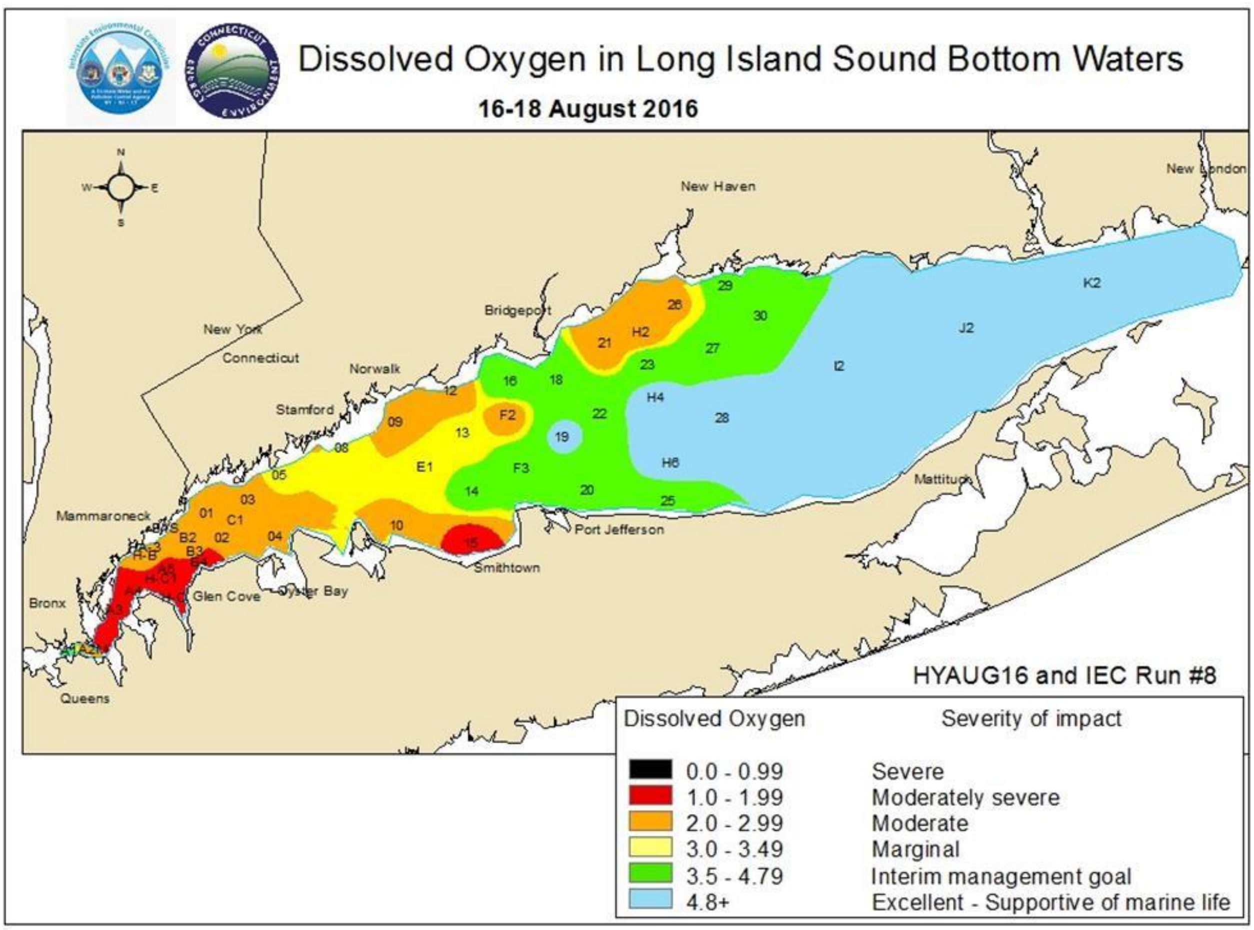


DEEP HYAUG16 and IEC Run #8

During the HYAUG16 survey, DEEP recorded three stations with DO concentrations less than 2.0 mg/L, and IEC documented eight stations below 2.0 mg/L. DEEP also logged 12 stations with concentrations less than 3.0 mg/L, and IEC measured DO's less than 3.0 mg/L at six stations. This would be the height of the hypoxic event. Based on the traditional DEEP map, 197.5 mi^2 of bottom waters were estimated to have DO concentrations below 3.0 mg/L.

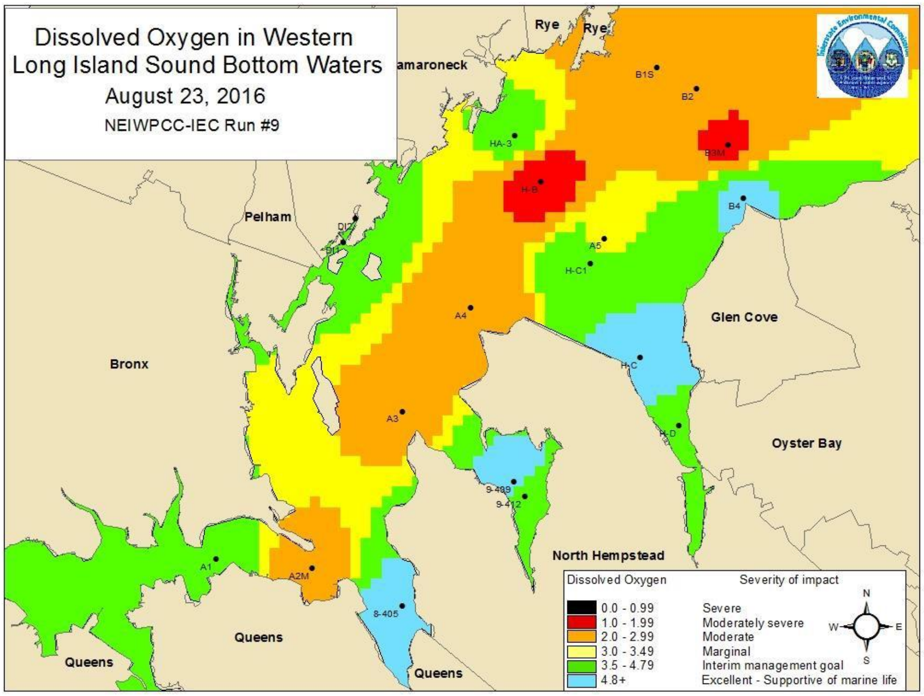






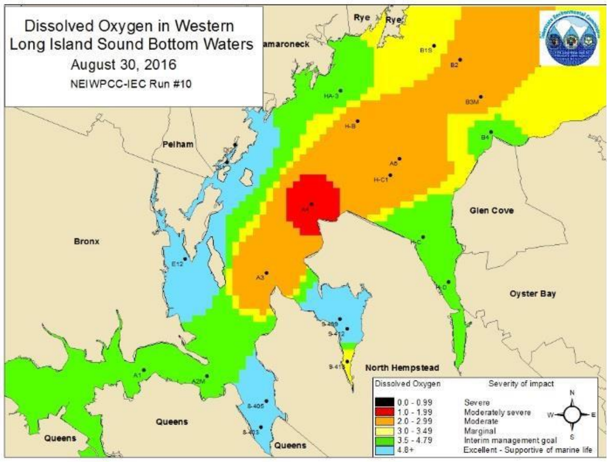
IEC Run #9

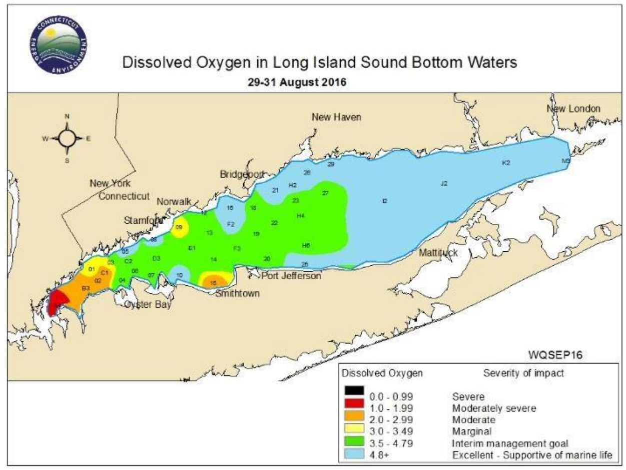
During IEC Run #9 on 23 August, conditions rebounded with only 2 stations exhibiting DO concentrations below 2.0 mg/L, compared to eight stations the week before. Five additional stations remained below 3.0 mg/L.

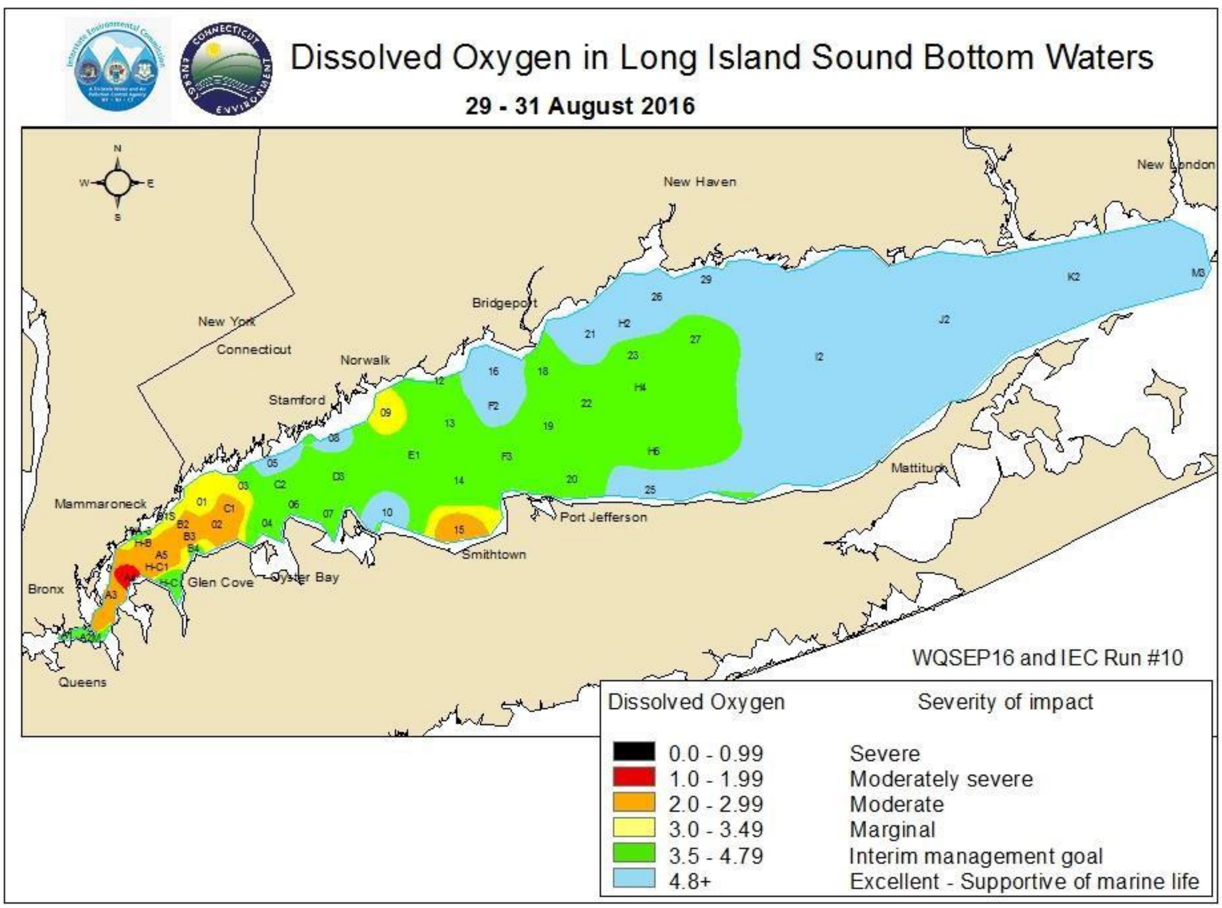


DEEP WQSEP16 and IEC Run #10

Hypoxic conditions were recorded in the Western Sound during the WQSEP16 survey and IEC Run #10. Concentrations at A4 were still below 2.0 mg/L. Four additional stations remained below 3.0 mg/L and two more were less than 3.5 mg/L during the DEEP survey. During the IEC survey six stations remained below 3.0 mg/L and two additional stations were less than 3.5 mg/L.

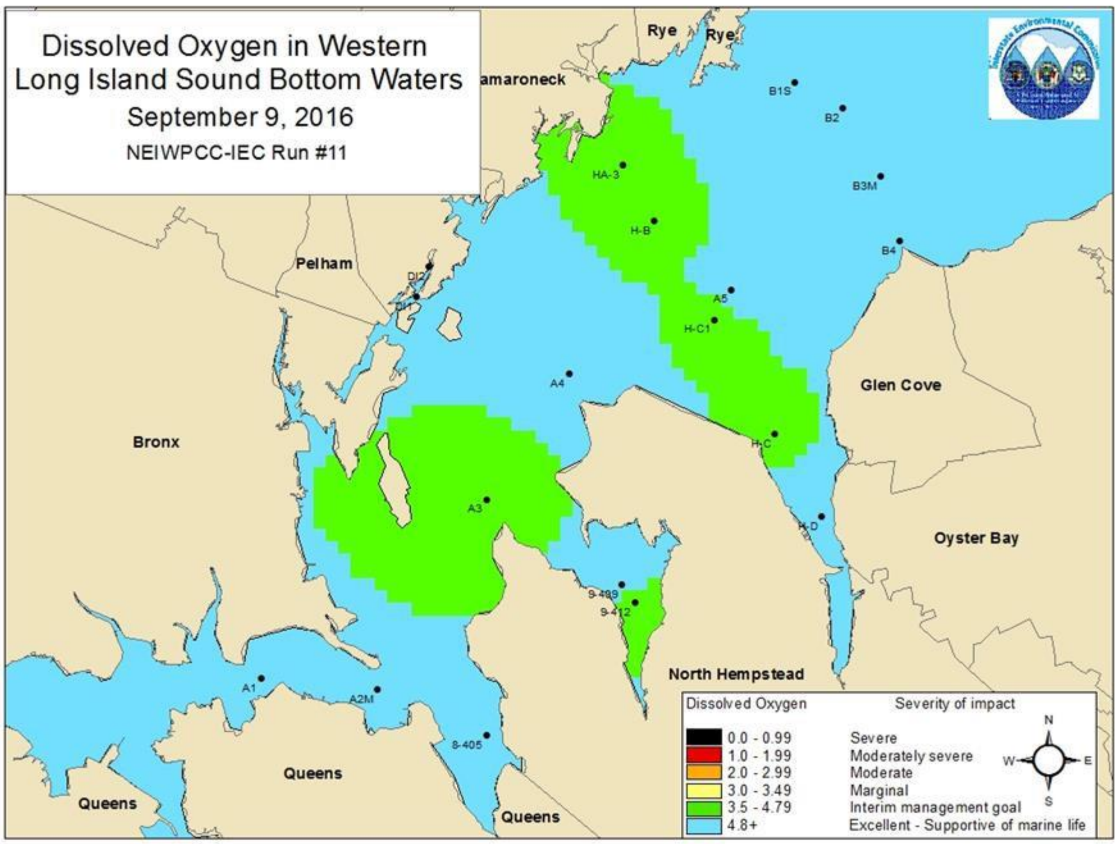






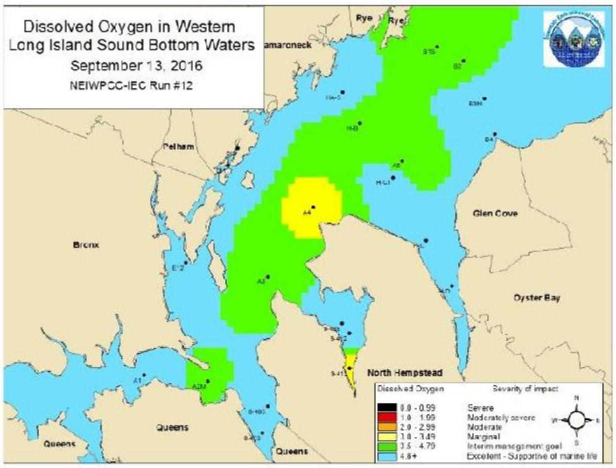
IEC Run #11

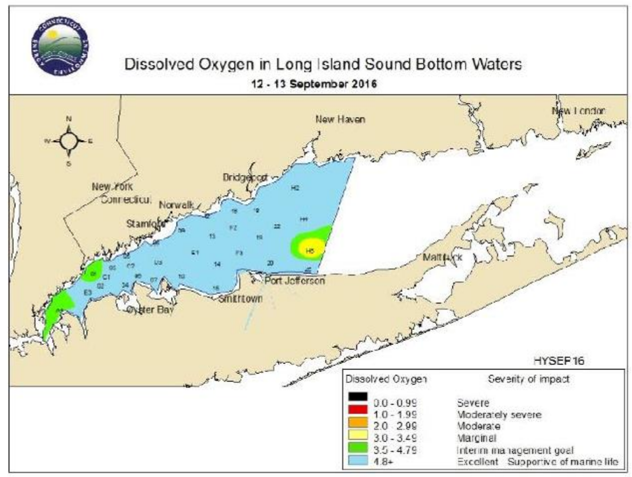
During IEC Run #11 on 9 September, the bottom waters of Western Long Island Sound showed marked improvement with only six stations below 4.8 mg/L.

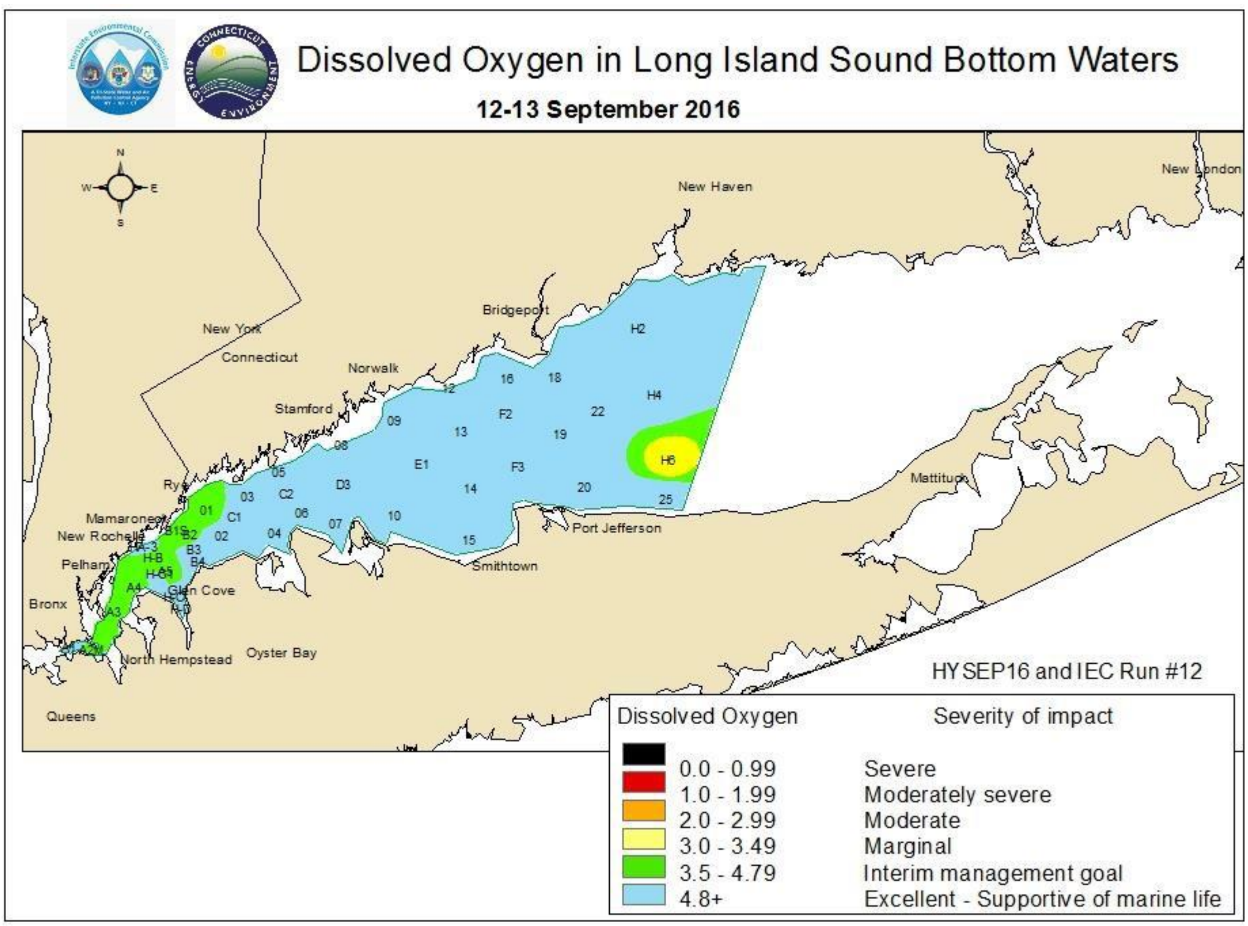


DEEP HYSEP16 and IEC Run #12

The remnants of Hurricane/Tropical Storm Hermine (August 28, 2016 – September 6, 2016) did not bring much precipitation to Long Island Sound, but sustained winds increased mixing and further alleviated hypoxic conditions. The LISICOS Execution Rocks buoy data showed concentrations climbing above 3.0 mg/L and staying above 3 mg/L beginning on or about 3 September. During the IEC Run #12, Station A4 was less than 3.5mg/L. During the DEEP HYSEP16 cruise, only one station, H6, was below 3.5 mg/L. Stations A4 and 01, which were sampled on 13 September, remained below 4.8 mg/L.





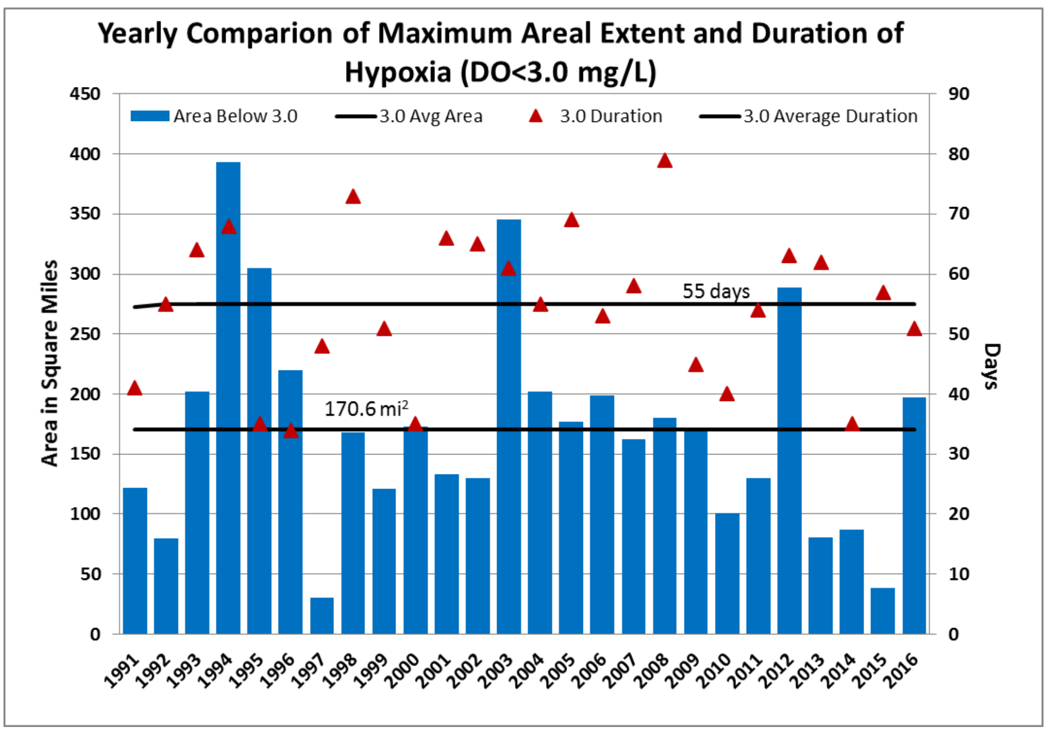


AREA ESTIMATES

The peak hypoxic event occurred during **IEC Run #8 and the HYAUG16** cruises between 16 and 18 August. Based on the *traditional CT DEEP stations only interpolation*, the **maximum area was 197.5 square miles**. Compared to the previous 24-year average, 2016 was slightly above average in area (see figure below). The lowest dissolved oxygen concentration (1.37 mg/L) documented by CT DEEP during 2016 occurred on 8/16/16 at Station A4. The lowest dissolved oxygen concentration (1.42 mg/L) documented by IEC during 2016 occurred on 8/18/16, also at Station A4. The Execution Rock Buoy also recorded its' lowest reading during this time, 0.98 mg/L on 8/17.

The maximum areal estimate is still based on the traditional CT DEEP only data to maintain the continuity of the long-term data set and because the entire previous 24-year dataset has not been re-interpolated using both the CT DEEP and IEC stations.

The tables on the following two pages demonstrate the differences in the areal estimates between using CT DEEP data alone and CT DEEP data combined with IEC data. Differences in areal estimates are attributed to the increase in spatial coverage in the Western Sound. By increasing the spatial coverage, the map interpolation software used to create the maps places less emphasis (weighting) on stations A4 and B3. For example, if one looks at the areal estimates for the peak event, CT DEEP only data provides an estimate of 40.4 square miles of the bottom water with DO concentrations less than 2.0 mg/L. Adding in the IEC data reduces the estimate to 6.8 square miles. Looking at the maps on page 23 helps to further illustrate this. On the IEC only map (top left) one can see that there are 5 stations with concentrations in the 2-2.99 mg/L range. The CT DEEP only map (top right) uses data from stations A4 and B3, and interpolates that area in the 1-1.99 mg/L range.



			Area of hypoxia in Sq mi	
Date	Survey Name	mg/L range	DEEP	IEC & DEEP
7/5-6/2016	WQJUL16 & IEC Survey #2	0 to 1	0	0
	WQJUL16 & IEC Survey #2	1 to 2	0	0
	WQJUL16 & IEC Survey #2	2 to 3	0	0
	WQJUL16 & IEC Survey #2	3 to 3.5	0	0
	WQJUL16 & IEC Survey #2	3.5 to 4.8	36.7	30.5
	WQJUL16 & IEC Survey #2	4.8 to 10	1018.3	1024.5
7/18-19/2016	HYJUL16 & IEC Survey #4	0 to 1	0	0
	HYJUL16 & IEC Survey #4	1 to 2	0	3.63
	HYJUL16 & IEC Survey #4	2 to 3	19	19.54
	HYJUL16 & IEC Survey #4	3 to 3.5	13.44	17.18
	HYJUL16 & IEC Survey #4	3.5 to 4.8	231.82	275.1
	HYJUL16 & IEC Survey #4	4.8 to 10*	790.74	739.55
8/1-4/2016	WQAUG16 & IEC Survey #6	0 to 1	0	0
	WQAUG16 & IEC Survey #6	1 to 2	0	0
	WQAUG16 & IEC Survey #6	2 to 3	0	0
	WQAUG16 & IEC Survey #6	3 to 3.5	9.92	14.75
	WQAUG16 & IEC Survey #6	3.5 to 4.8	333.79	318.03
	WQAUG16 & IEC Survey #6	4.8 to 10	711.29	722.22
8/16-18/2016	HYAUG16 & IEC Survey #8	0 to 1	0	0
	HYAUG16 & IEC Survey #8	1 to 2	40.42	6.8
	HYAUG16 & IEC Survey #8	2 to 3	157.03	167.49
	HYAUG16 & IEC Survey #8	3 to 3.5	100.81	101.97
	HYAUG16 & IEC Survey #8	3.5 to 4.8	236.1	237.14
	HYAUG16 & IEC Survey #8	4.8 to 10	520.64	541.6
8/29-31/2016	WQSEP16 & IEC Survey #10	0 to 1	0	0
	WQSEP16 & IEC Survey #10	1 to 2	11.04	2.86
	WQSEP16 & IEC Survey #10	2 to 3	42.63	45.02
	WQSEP16 & IEC Survey #10	3 to 3.5	31.7	37.8
	WQSEP16 & IEC Survey #10	3.5 to 4.8	366.41	373.36
	WQSEP16 & IEC Survey #10	4.8 to 10	603.22	596.49
9/12-13/2016	HYSEP16 & IEC Survey #12	0 to 1	0	0
	HYSEP16 & IEC Survey #12	1 to 2	0	0
	HYSEP16 & IEC Survey #12	2 to 3	0	0
	HYSEP16 & IEC Survey #12	3 to 3.5	11.85	12.05
	HYSEP16 & IEC Survey #12	3.5 to 4.8	44.09	52.86
	HYSEP16 & IEC Survey #12	4.8 to 10	999.06	990.09

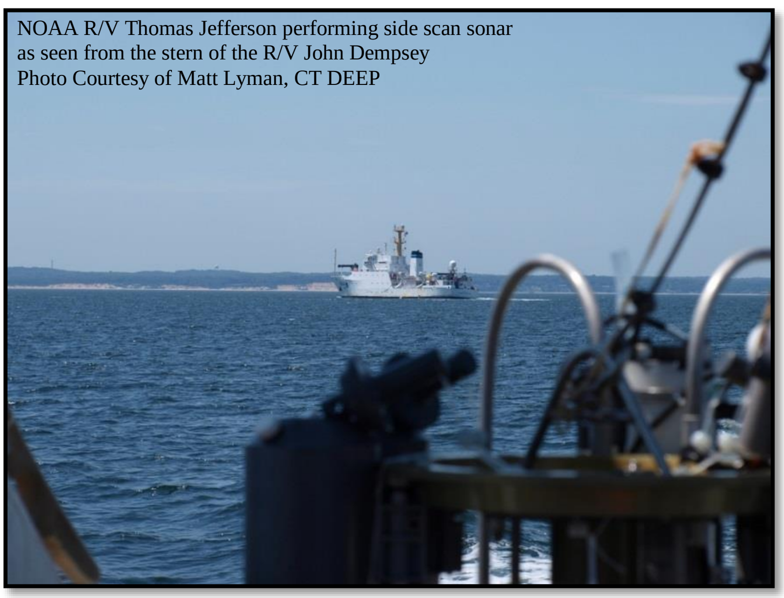
*CTD battery failure resulted in no data for multiple stations. Area under estimated due to no data.

The following table is included to demonstrate the differences in the areal estimates between using DEEP data alone and DEEP data combined with IEC data.

Survey	Area <1.0 mg/L		Area <2.0 mg/L		Area <3.0 mg/L		Area <4.8 mg/L	
	DEEP	IEC & DEEP	DEEP	IEC & DEEP	DEEP	IEC & DEEP	DEEP	IEC & DEEP
WQJUN16	0	0	0	0	0	0	0	0
HYJUN16	0	0	0	0	0	0	0	0
WQJUL16 & IEC Survey #2	0	0	0	0	0	0	36.70	30.50
HYJUL16 & IEC Survey #4	0	0	0	3.63	19.00	23.17	264.25*	315.45*
WQAUG16 & IEC Survey #6	0	0	0	0	0	0	343.71	332.78
HYAUG16 & IEC Survey #8	0	0	40.42	6.80	197.50	174.29	534.37	513.40
WQSEP16 & IEC Survey #10	0	0	11.04	2.86	53.70	47.88	451.78	459.04
HYSEP16 & IEC Survey #12	0	0	0	0	0	0	55.95	64.90

View of Throg's Neck Bridge as seen during an IEC survey.

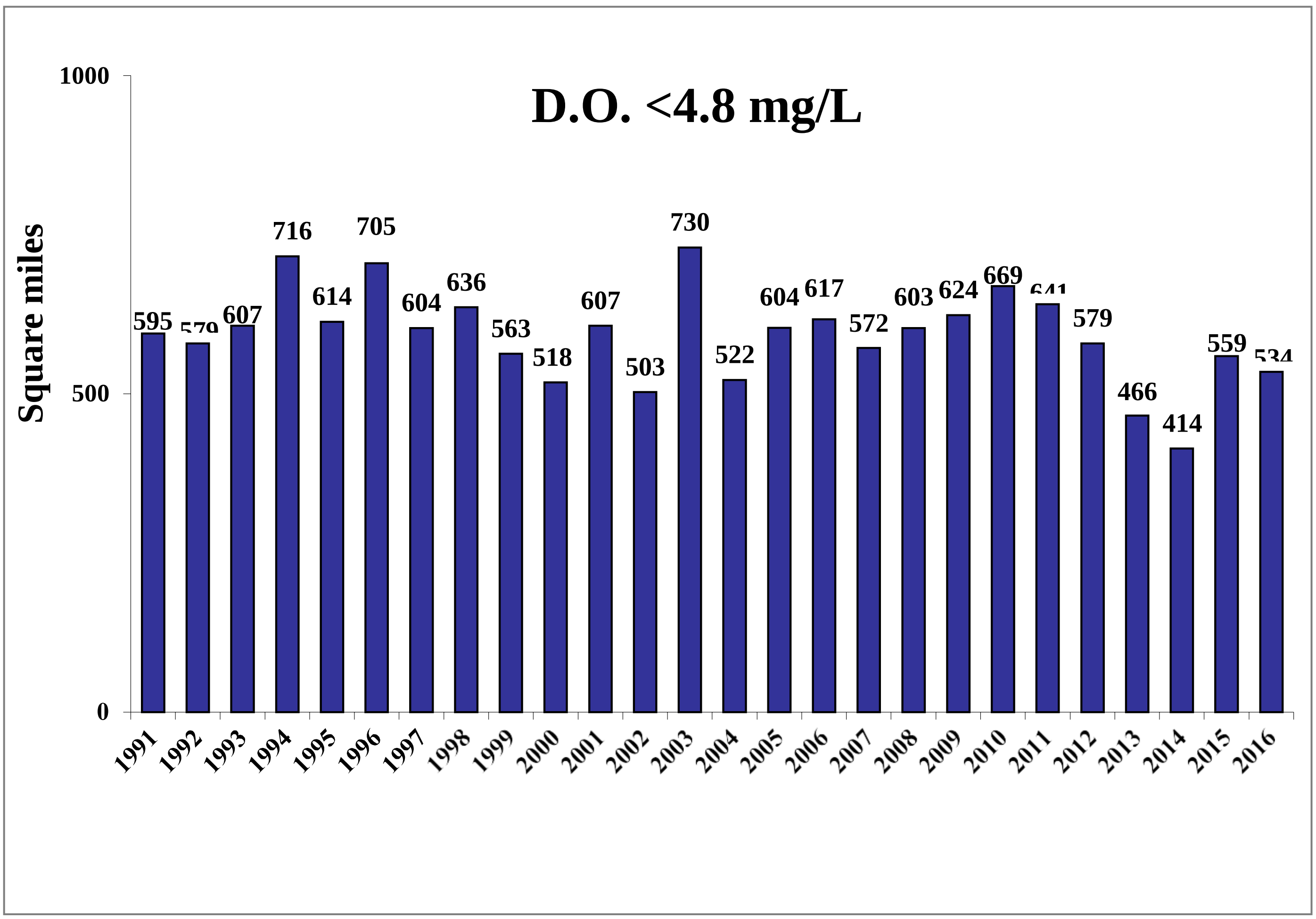
NOAA R/V Thomas Jefferson performing side scan sonar as seen from the stern of the R/V John Dempsey
Photo Courtesy of Matt Lyman, CT DEEP



Area of Dissolved Oxygen Below the Chronic Criterion for Growth and Protection of Aquatic Life for LIS

Aquatic organisms can be impacted by a combination of low dissolved oxygen concentrations, exposure, and extended duration of the low DO events. CT DEEP established Dissolved Oxygen Chronic Exposure Criteria based on research and data collected by the EPA. A DO concentration of 4.8 mg/L meets the chronic criterion for growth and protection of aquatic life regardless of the duration.

This chart illustrates the maximum area of bottom waters within Long Island Sound with DO concentrations less than 4.8 mg/L based on biweekly sampling by CT DEEP. In 2016, the maximum area below 4.8 mg/L occurred during the HYAUG16 survey and was estimated at 534 square miles. From 1991-2016, the area affected by concentrations less than 4.8 mg/L averages 591.6 square miles and varies slightly from 414 to 730 square miles.

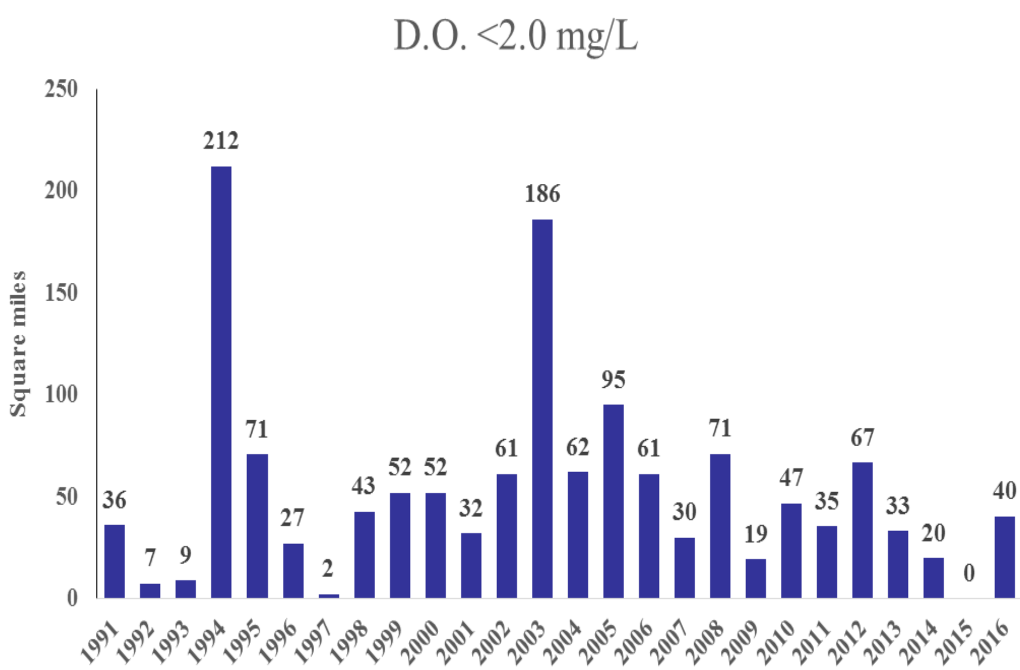


Severe Hypoxia

The Long Island Sound Study provides information on LIS hypoxia for inclusion in EPA's *Report on the Environment* (https://www.epa.gov/aboutepa/about-national-center-environmental-assessment-ncea) which reports on "the best available indicators of information on national conditions and trends in air, water, land, human health, and ecological systems…" The *Report on the Environment* uses 2.0 mg/L as a benchmark to liken conditions in the Gulf of Mexico to LIS. In this report, the term severe hypoxia is used to describe DO < 2.0 mg/L and is discussed below.

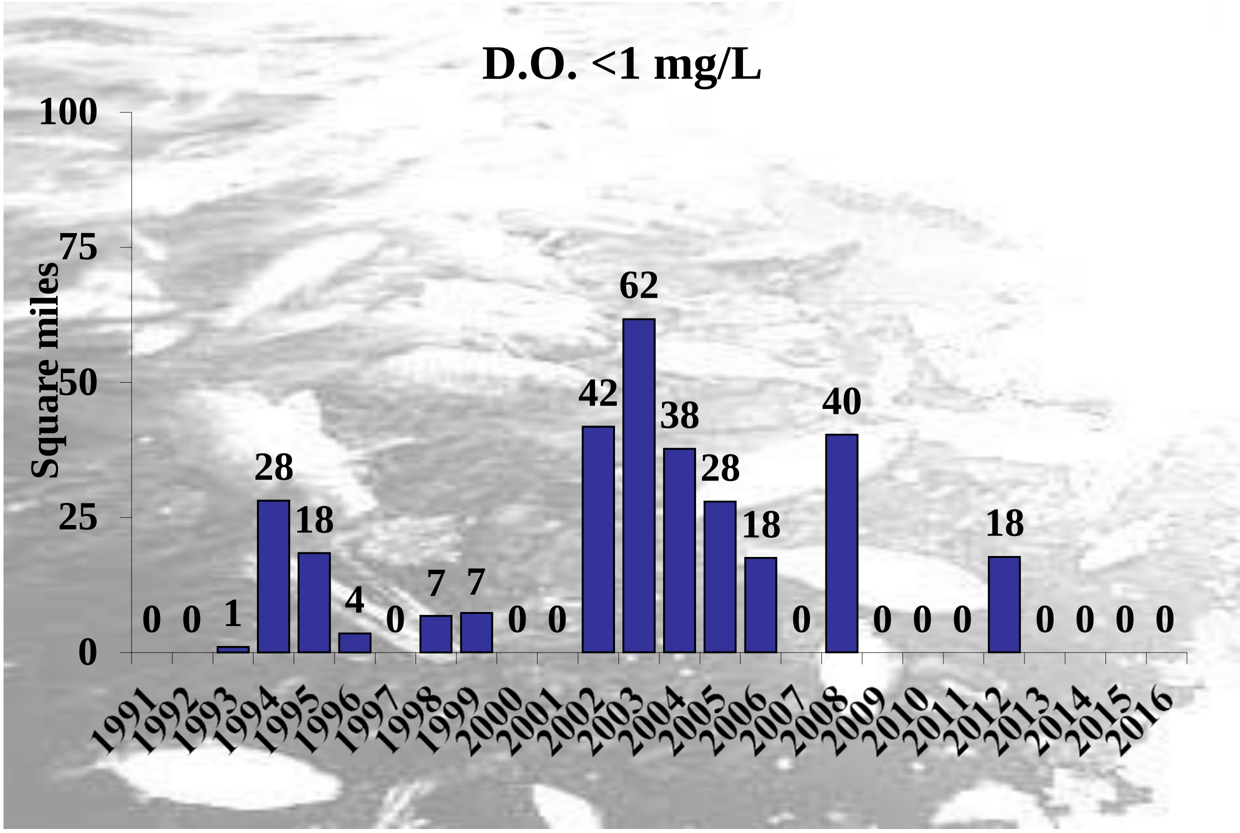
This chart illustrates the maximum area of bottom waters of Long Island Sound with DO concentrations less than 2.0 mg/L. Based on CT DEEP data, in 2016, bottom water dissolved oxygen concentrations were less than 2.0 mg/L over 40.4 square miles. This is an increase over the past three years, especially over last year when concentrations in the bottom waters never dropped below 2.0 mg/L (DEEP data). The average area with concentrations less than 2.0 mg/L, calculated from 1991-2016, is 52.7 mi^2. In 2016, based on CT DEEP estimates, there were 16 days with DO <2.0 mg/L. At the LISICOS Execution Rocks buoy, there were 12.90 cumulative days below 2.0 mg/L.

In comparison, the 30-year average size of the hypoxic zone in the northern Gulf of Mexico is roughly 5,312 mi^2 (larger than the State of Connecticut). The maximum area of the Gulf of Mexico hypoxic zone occurred in 2002 and was estimated at 8,841 mi^2 (22,898 km^2). The 2015 hypoxic zone covered 6474 mi^2 (16760 km^2) and was larger than 2014. The 2016 Gulf of Mexico shelf-wide cruise was cancelled due to major engine problems with the R/V Nancy Foster. Continuously recording dissolved oxygen meters were deployed in the hypoxic zone in mid-June. Following data clean up and QA/QC, these data will be reported on the Gulf of Mexico Hypoxia website at http://www.gulfhypoxia.net/default.asp. The 2016 hypoxia forecast for the Gulf of Mexico released in June predicted the hypoxic zone would cover 6,824 mi^2 (Turner and Rabalais, 2016).



In LIS, 1994 and 2003 appear to be years when severe hypoxia (DO <2.0 mg/L) was especially prevalent. 1994 had cold winter bottom water temperatures and an unusually warm June which led to strong stratification. The highest average Delta T in July 1994 was 8.54°C. 2003 was the second hottest summer since 1895 and the 28th wettest which also led to the Sound being strongly stratified. Strong stratification (Delta T greater than 4°C) lasted for four months in 1994 (May-August) and only one month (July) in 2003.

Anoxia



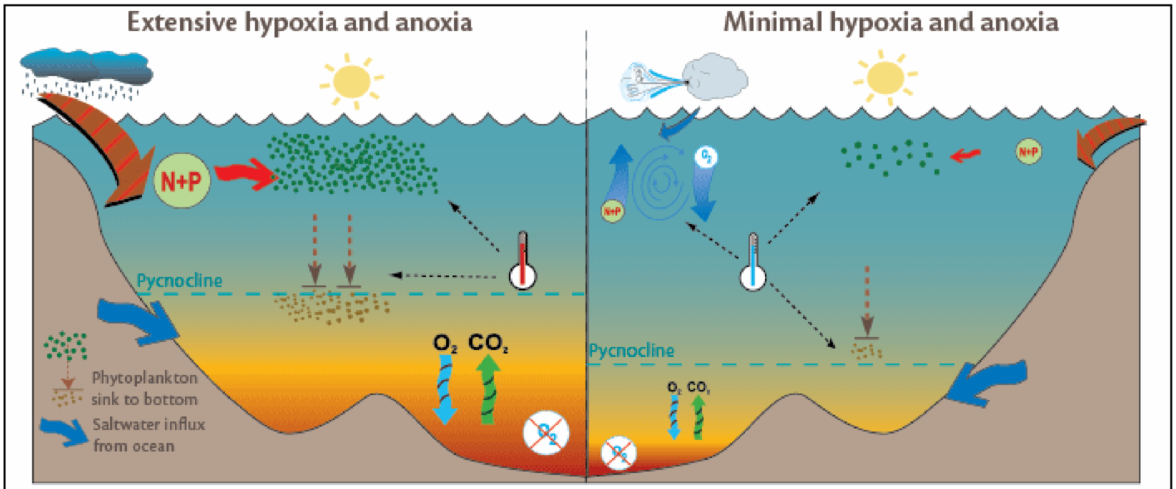
For management purposes, the Long Island Sound Study defines anoxia as DO concentrations less than 1 mg/L. This chart illustrates the maximum area of bottom waters in LIS with DO concentrations less than 1.0 mg/L based on biweekly sampling by CT DEEP.

In 13 of the past 26 years, there was no anoxia reported by CT DEEP. It is important to note that IEC and LISICOS have documented anoxic conditions during years when CTDEEP has not. In 2009 and 2010, IEC documented two stations that were anoxic. In 2011, the LISICOS Execution Rocks buoy (Station A4) captured a minimum DO of 0.61 mg/L.

Prior to 2002, the average area of bottom waters affected by anoxia was 5.9 mi^2. From 2002-2008 the average area affected was 32.4 mi^2. From 2009 to 2016, the average area affected was 2.2 mi^2. The overall average area affected from 1991-2016 is 12.4 mi^2. The greatest area with DO below 1 mg/L (62 square miles) was during the summer of 2003.

WATER TEMPERATURE AND HYPOXIA

In LIS, water temperature plays a major role in the ecology of the Sound especially in the timing and severity of the summer hypoxia event. IEC's monitoring program records water temperature and salinity data weekly from June to September while CT DEEP's monitoring program records water temperatures and salinity year-round. Data collected during IEC's weekly summer surveys and CT DEEP's hypoxia monitoring cruises are used to help estimate the extent of favorable conditions for the onset, extent, and end of the hypoxic event. The conceptual diagram below, while developed for Chesapeake Bay, applies to Long Island Sound. In LIS, there are two key contributors to hypoxia: nutrient enrichment and stratification. (Stratification is discussed more on page 24.) Nutrients, especially nitrogen, flow into the Sound from numerous sources including point sources like wastewater treatment plants and nonpoint sources such as stormwater runoff. This enrichment leads to excessive growth of phytoplankton, particularly in the spring. Temperature can stimulate or impede phytoplankton growth. As the plankton die, they begin to decay and settle to the bottom. Bacterial decomposition breaks down the organic material from the algae, using up oxygen in the process.



	Loads	Phytoplankton	Decomposition	Temperature	Wind event
Large amount of low dissolved oxygen	Large nitrogen and phosphorus loads	Elevated nutrients cause large phytoplankton blooms	High oxygen consumption by decaying phytoplankton	Warm water a) Stimulates decomposition b) Stratifies water column c) Stimulates phytoplankton	No wind event: water column remains stratified
Little amount of low dissolved oxygen	Small nitrogen and phosphorus loads	Less nutrients lead to small phytoplankton blooms	Low oxygen consumption by decaying phytoplankton	Cool water: a) Slow decomposition b) Mixed water column c) Slow phytoplankton growth	Wind events destratifies water column: a) Bottom water aerated b) Nutrients move to surface

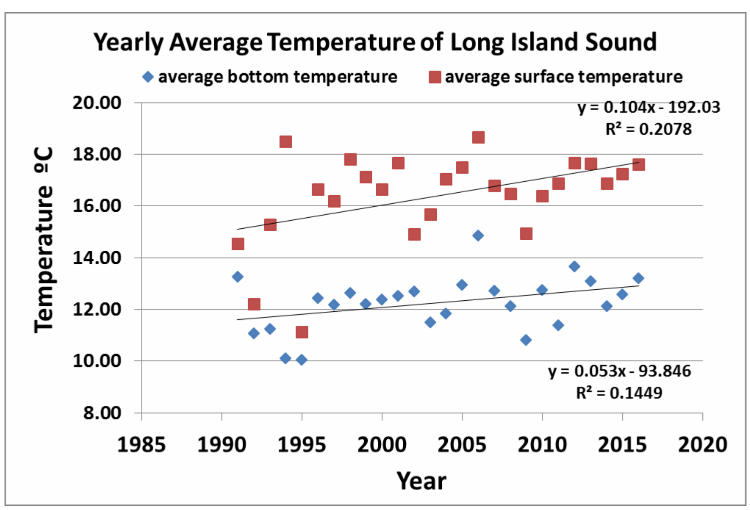
Conceptual diagram detailing the factors that determine the dissolved oxygen content of the tidal waters of Chesapeake Bay
Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Ecocheck

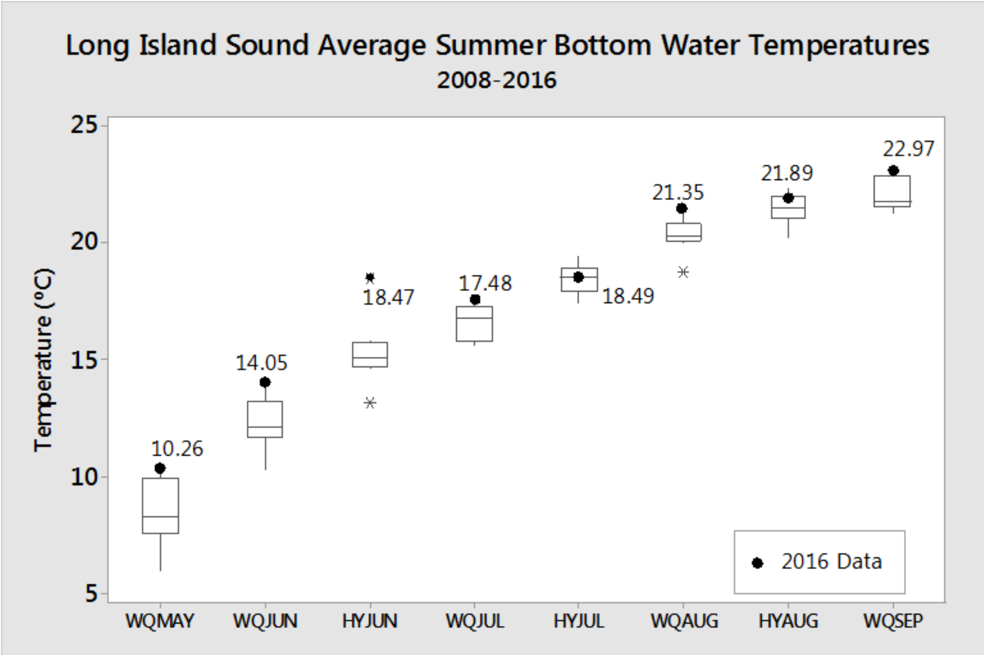
DEEP Water Temperature Data

2016 maximum, minimum, and average water temperature (ºC) data are summarized below. Data are integrated across Long Island Sound (*i.e.*, all stations and all depths) and are displayed by cruise. Data were obtained using the CT DEEP Sea Bird Sea Cat Conductivity, Temperature, Depth (CTD) profiler. The Sound is coldest during February and March and warmest during August and September.

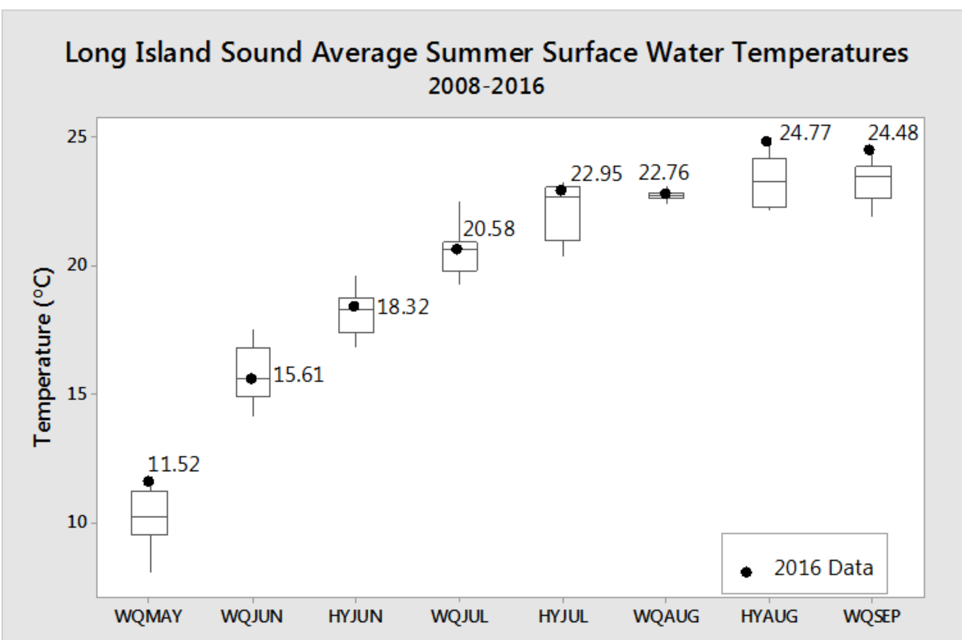
Cruise	2016 Max	1991-2016 Max	2016 Min	1991-2016 Min	2016 Average	1991-2016 Average
WQJAN	8.876	9.311	4.956	0.500	7.353	4.559
WQFEB	5.998	6.748	3.154	-1.325	4.253	2.154
CHFEB	2.611	4.464	1.526	-0.288	2.151	2.217
WQMAR	5.698	6.611	3.342	-1.189	3.878	2.267
CHMAR	6.279	6.575	4.905	-0.109	5.539	3.404
WQAPR	7.624	10.072	5.716	0.650	6.367	4.693
WQMAY	14.458	14.458	9.175	4.517	10.582	8.582
WQJUN	17.361	21.436	12.329	8.027	14.616	12.770
HYJUN	20.089	22.458	14.186	11.116	16.175	15.831
WQJUL	23.160	25.336	16.341	11.639	18.440	17.435
HYJUL	25.239	27.493	17.662	15.038	20.023	19.340
WQAUG	24.099	29.985	11.666	14.018	22.409	20.530
HYAUG	27.261	27.261	19.959	18.678	22.999	21.738
WQSEP	25.797	25.857	20.318	16.390	23.809	21.841
HYSEP	24.330	24.330	22.862	19.533	23.431	21.939
WQOCT		21.571		14.161		19.201
WQNOV		16.601		10.467		13.964
WQDEC		12.712		4.655		9.201

The yearly average surface and bottom temperature of the Sound show slight increases over the period 1991-2016





These box and whisker plots show the median water temperature, range, interquartile range, and outliers by cruise from 2008-2016 compared to the 2016 cruise. Water temperatures during the summer of 2016 mimicked air temperatures and were generally above the 2008-2016 medians.



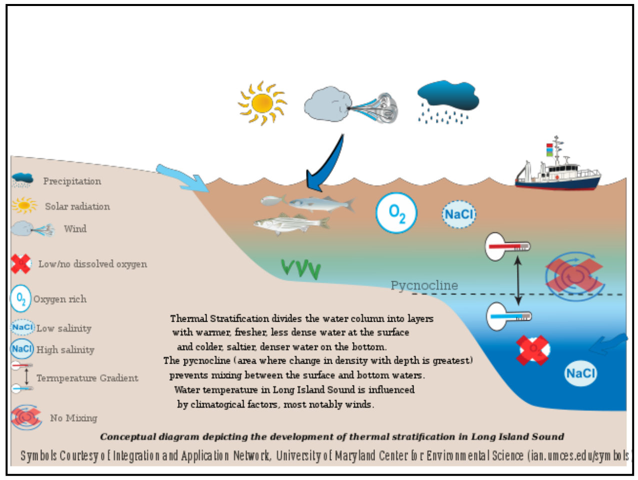
Historical IEC Water Temperature and Hypoxia Data

1991-2016 average summer (June-September) temperatures (ºC) for surface and bottom depths in Western Long Island Sound are summarized below in addition to percentage of hypoxic measurements.

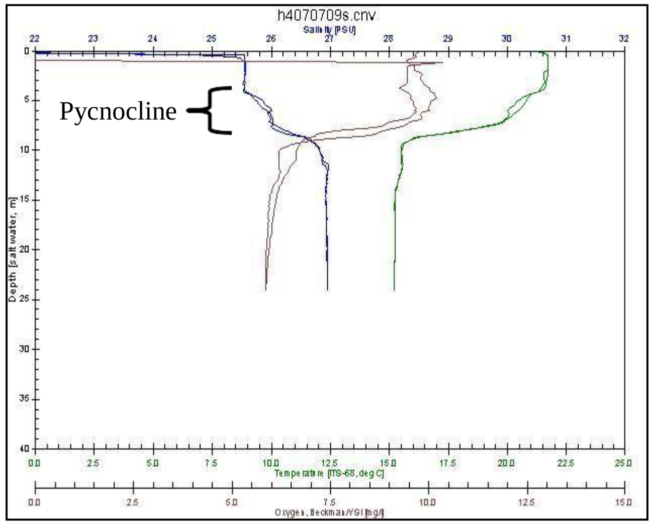
Year	Mean Summer Temp. (ºC)		Mean ΔT (ºC)	Mean Summer DO (mg/L)		% Hypoxic Measurements (DO<3.0 mg/L)	
	Surface	Bottom		Surface	Bottom	Surface	Bottom
1991	22.2	21.5	0.65	6.47	4.21	0	24.2
1992	21.1	19.9	1.22	7.10	4.72	0	6.8
1993	21.8	20.3	1.49	6.88	4.19	0.93	24.1
1994	21.5	19.8	1.62	6.49	4.09	4.17	33.3
1995	22.3	20.8	1.46	6.85	5.24	0	3.5
1996	21.4	20.0	1.36	6.52	4.09	1.44	17.8
1997	21.5	19.8	1.63	6.97	5.15	1.55	19.3
1998	21.9	20.7	1.13	6.27	4.21	0	17.5
1999	22.6	21.2	1.32	6.40	3.91	0	25.4
2000	21.4	20.5	0.84	7.82	4.55	0	15.0
2001	22.0	20.8	1.12	6.59	3.19	3.83	47.0
2002	22.6	21.2	1.45	6.10	3.46	5.33	43.8
2003	21.1	19.2	1.85	6.81	3.50	2.89	37.8
2004	21.4	20.1	1.36	5.37	2.65	9.13	68.9
2005	22.9	20.9	2.00	7.36	3.50	3.31	44.1
2006	21.6	19.8	1.81	6.27	3.53	4.62	40.7
2007	21.2	19.7	1.51	7.10	4.10	2.23	19.1
2008	22.0	20.7	1.26	6.07	2.97	4.31	60.4
2009	22.0	20.3	1.70	8.28	4.25	1.59	27.5
2010	22.9	21.5	1.47	6.25	3.84	11.3	28.2
2011	22.3	21.0	1.33	5.95	4.05	1.14	21.5
2012	23.3	22.1	1.21	5.98	3.53	4.53	36.4
2013	22.4	21.0	1.37	6.58	4.10	0.40	24.7
2014	21.3	20.3	0.99	6.92	5.62	4.35	13.6
2015	22.8	21.5	1.20	5.71	4.27	2.25	17.4
2016	23.1	21.9	1.39	6.42	4.23	1.52	21.0

Delta T and Stratification

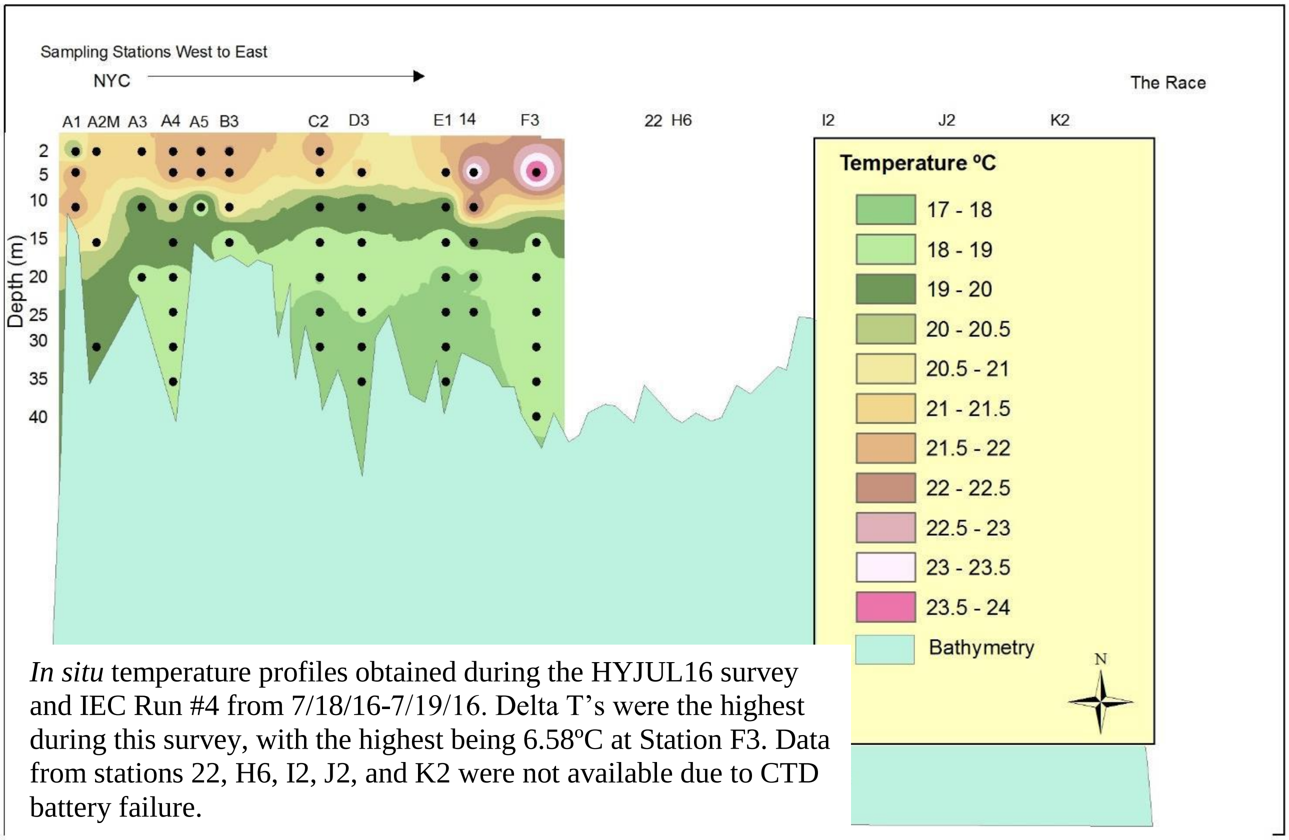
The temperature difference between the bottom waters and the surface waters is known as "Delta T". This Delta T, along with salinity differences, creates a density difference, or density gradient, resulting in a separation or stratification, of water layers. Stratification hinders the oxygenated surface waters from circulating downward and mixing with the oxygen starved bottom waters. The pycnocline, or zone where water density increases rapidly with depth due to the changes in temperatures and salinity, inhibits oxygenated surface waters from mixing with oxygen depleted bottom waters, exacerbating the hypoxia. The pycnocline typically develops in LIS in late spring/early summer when rapid surface water warming exceeds the rate of warming in the bottom waters. The pycnocline generally persists into early fall when it is disrupted by strong winds associated with storms which lead to mixing or cooling air temperatures. With the dissolution of the pycnocline, hypoxic conditions are alleviated or eliminated. The smallest Delta Ts occur during the winter when the water column is well mixed. The largest Delta T's occur during the early summer. The greater the Delta T the greater is the potential for hypoxia to be more severe.



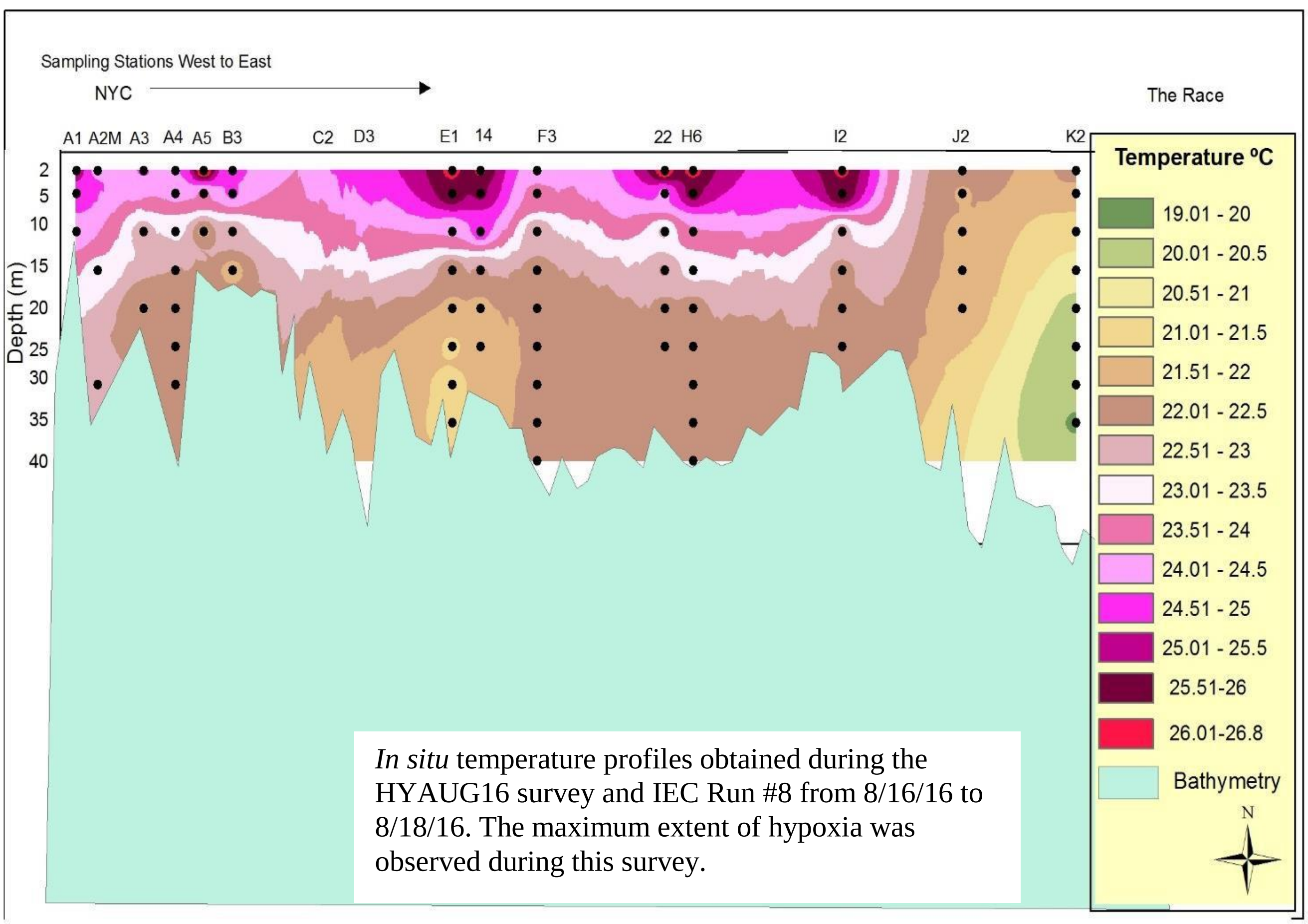
Conceptual diagram depicting the development of thermal stratification in Long Island Sound



The temperature graphs on page 38 show computer interpolations along the west-east axis of LIS generated from profile data collected during two surveys by CT DEEP and IEC. During the mid-July IEC and DEEP surveys, surface water temperatures had warmed to an average of 22.5ºC while the bottom water remained cooler around an average of 18.7ºC. This set up the largest differences in temperatures between the surface and bottom waters with Delta T's between 1.6 and 6.58ºC. The second graph shows how the water column was thermally stratified during the HYAUG16 survey when hypoxic conditions were at their worst. The temperature area maps on page 39 show how the Delta T's varied over the course of the summer sampling season. Delta T's increased from the WQAPR16 survey through the HYJUL16 survey, setting up the stratification and leading to the maximum extent of hypoxia in late August. By the September survey, Delta T's decreased to around 1.1ºC over much of the Sound. Delta T's continued to decrease during the HYSEP16 survey to around 0.3ºC, allowing the oxygenated surface waters to mix through to the bottom, leading to the end of the hypoxic event. The maps also show how the Delta T varies spatially. The Western Sound typically has higher Delta T's due to the limited flushing capacity, bathymetry, and geology. In the east where cooler, oxygen rich, off-shore ocean water mixes with the Sound water, Delta T's are much lower and hypoxia rarely occurs. This year the Central Sound had the highest Delta T's.

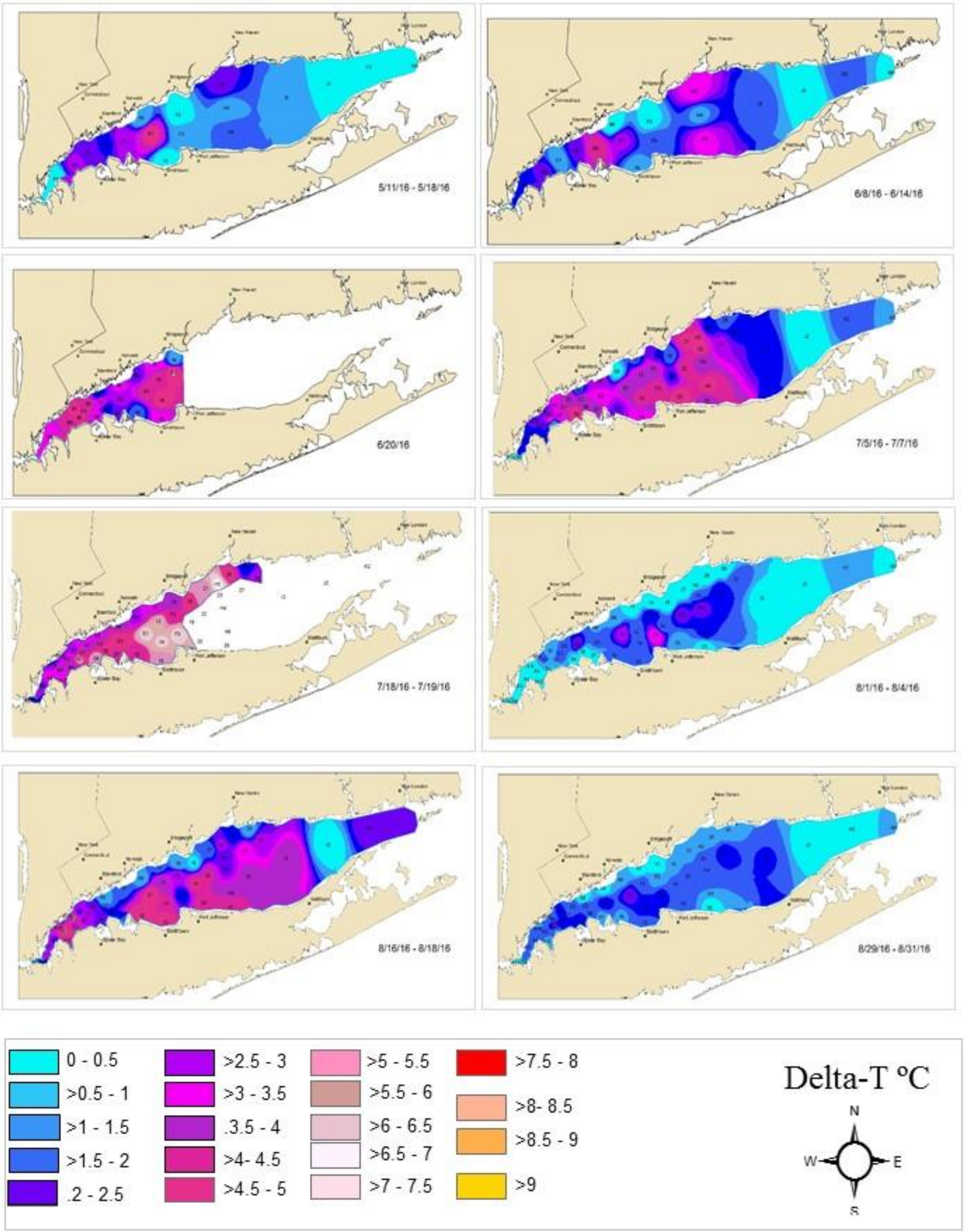


In situ temperature profiles obtained during the HYJUL16 survey and IEC Run #4 from 7/18/16-7/19/16. Delta T's were the highest during this survey, with the highest being 6.58ºC at Station F3. Data from stations 22, H6, I2, J2, and K2 were not available due to CTD battery failure.



In situ temperature profiles obtained during the HYAUG16 survey and IEC Run #8 from 8/16/16 to 8/18/16. The maximum extent of hypoxia was observed during this survey.

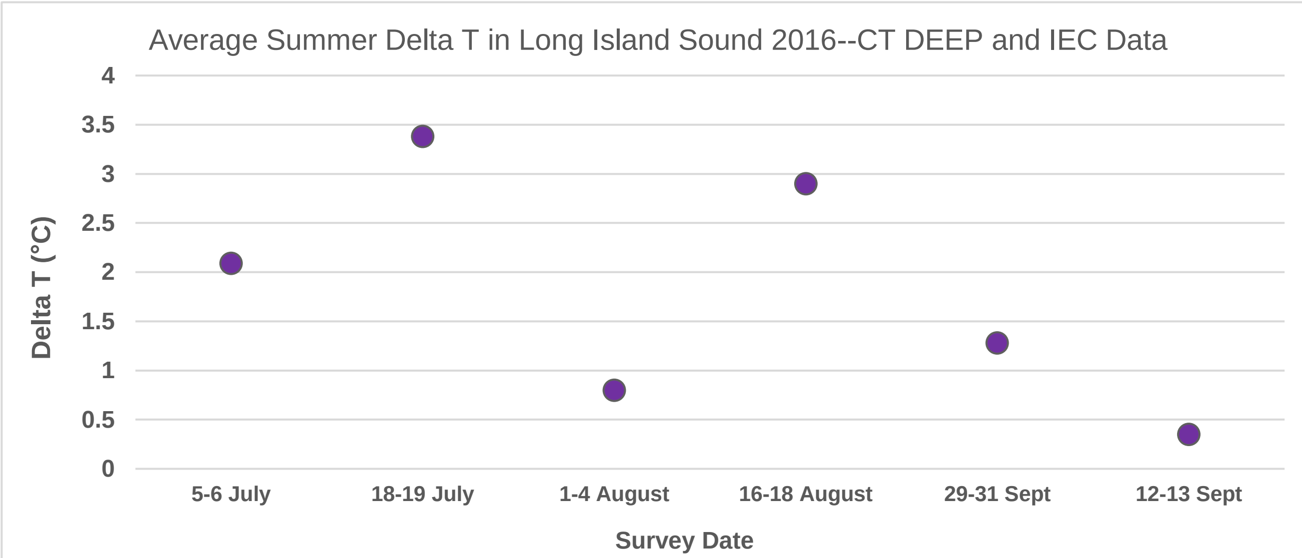
2016 Delta-T Maps

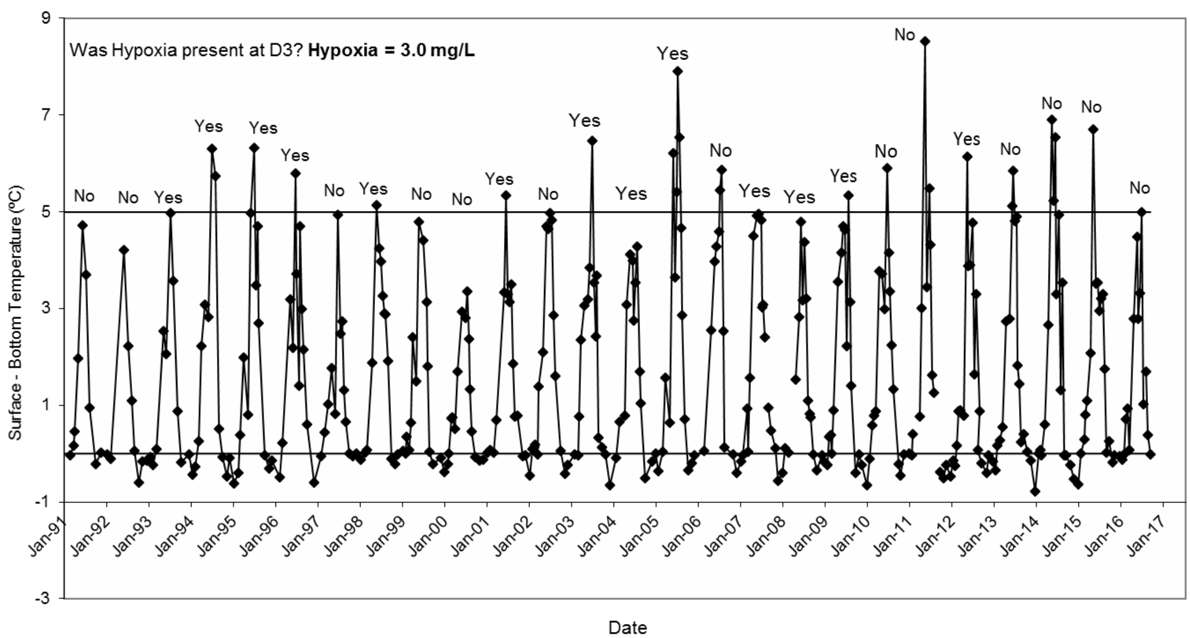


This table summarizes the minimum winter temperatures (January, February, and March), the maximum summer temperatures (June, July, August, and September), the maximum Delta T, and maximum hypoxic area at **Station D3**. Station D3 is located in the eastern-most and deepest portion of the Narrows (see map on page 1). The CT DEP 1991-1998 Data Review report (Kaputa and Olsen, 2000) found a positive correlation between the maximum Delta T observed at D3 and the maximum area of hypoxia in the same year. Delta T was not correlated to the duration of hypoxia. 2012 had the warmest minimum winter temperature, 2015 had the lowest winter temperature recorded, 2014 had the highest summer temperature, 2011 had the highest Delta T max, and 1994 had the largest area of hypoxia as indicated in bold.

Year	Minimum Winter Temp (ºC)	Maximum Summer Temp (ºC)	Maximum ΔT (ºC)	Maximum Area of Hypoxia (mi^2) DO<3.0 mg/L
1991	2.69	22.23	4.75	122
1992	1.86	20.89	4.83	80
1993	1.06	22.68	5.33	202
1994	-0.68	24.08	6.33	**393**
1995	0.95	23.78	6.33	305
1996	-0.19	23.78	5.91	220
1997	1.87	21.81	4.96	30
1998	3.40	23.20	5.22	168
1999	2.67	23.41	5.51	121
2000	0.57	21.99	6.02	173
2001	1.67	23.20	5.38	133
2002	4.03	23.47	5.52	130
2003	-0.52	22.88	6.74	345
2004	-0.93	23.09	4.33	202
2005	0.53	25.10	8.19	177
2006	2.17	25.11	6.72	199
2007	0.83	23.03	5.12	162
2008	2.45	22.47	4.91	180.1
2009	0.72	24.31	5.90	169.1
2010	1.35	24.91	6.36	101.1
2011	0.66	22.32	**8.34**	130.3
2012	**4.09**	24.85	6.13	288.5
2013	2.00	24.23	5.85	80.7
2014	0.07	**25.86**	6.90	87.1
2015	**-1.1**	24.23	6.71	38.3
2016	2.54	24.98	5.00	197.5

A compilation of CT DEEP and IEC water temperature data and Delta T calculations indicate that summer stratification in Long Island Sound was most prevalent during the middle of July and August. Stratification broke during the middle of September, as expected, in response to cooler air temperatures and storm-induced mixing.





Time series of ΔT (surface water temperature - bottom water temperature) at station D3, 1991 through 2016.

Station D3 is located in the eastern-most and the deepest portion of the Narrows. Station D3 does not experience hypoxia every year. This station is used as an example to show how stratification and the development of hypoxia in the Sound relate. Kaputa and Olsen (2000) found that there was a strong correlation between the maximum Delta T at D3 and the maximum area of hypoxia in the same year. Prior to 2004, when Station D3 became hypoxic the observed maximum Delta T was greater than 5ºC. Since 2004, this trend does not seem to hold. Over the period of record, 2011 had the highest observed Delta T at Station D3 (>8ºC) but the lowest dissolved oxygen concentration recorded in 2011 at D3 was 3.22 mg/L. In 2015, the maximum Delta T at D3 was 6.71ºC and the station was not hypoxic (lowest DO 3.5 mg/L). In 2016, the maximum Delta T at D3 was 5.00ºC and the station again was not hypoxic (lowest DO 3.84 mg/L).

DEEP Salinity Data

Salinity is a measure of the concentration of dissolved salts in seawater. During the summer months, Long Island Sound waters stratify and bottom waters become cool, dense, and more saline while surface waters are warmer, less dense, and have lower salinity.

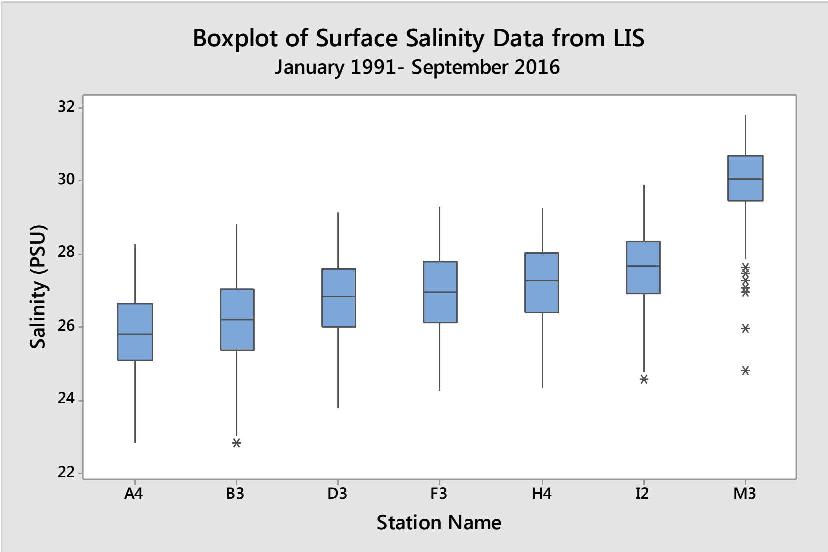
DEEP measures salinity in practical salinity units (PSU). Salinity levels across Long Island Sound vary from 23 PSU in the Western Sound at Station A4 to 33 PSU in the eastern Sound at Station M3. The Thames, Connecticut, and Housatonic rivers are the major sources of freshwater entering the Sound. Summary statistics for salinity data collected from seven stations across the Sound from 1991- 2016 are presented in the tables. Data collected this year are also presented separately.

		1991-2016 Bottom Water Statistics						
Station Name	Count	Minimum	Maximum	Mean	Median	SE Mean	Standard Deviation	Variance
A4	335	23.82	28.73	26.47	26.53	0.05	0.94	0.88
B3	382	24.26	28.93	26.72	26.76	0.05	0.93	0.87
D3	359	24.91	29.22	27.34	27.46	0.05	0.88	0.77
F3	333	25.15	29.43	27.70	27.79	0.05	0.86	0.74
H4	291	25.51	29.70	27.85	27.95	0.05	0.84	0.70
I2	310	25.76	29.99	28.14	28.23	0.05	0.83	0.70
M3	261	28.61	32.62	30.65	30.64	0.05	0.74	0.54

		2016 Bottom Water Statistics						
Station Name	Count	Minimum	Maximum	Mean	Median	SE Mean	Standard Deviation	Variance
A4	15	26.55	28.23	27.45	27.39	0.14	0.53	0.29
B3	14	26.76	28.53	27.67	27.57	0.16	0.61	0.37
D3	14	27.22	28.92	28.11	28.16	0.14	0.52	0.27
F3	12	27.53	29.24	28.48	28.55	0.17	0.60	0.35
H4	11	27.48	29.45	28.60	28.79	0.19	0.62	0.39
I2	9	27.66	29.66	28.62	28.83	0.24	0.73	0.54
M3	8	29.45	31.53	30.72	30.73	0.26	0.74	0.55

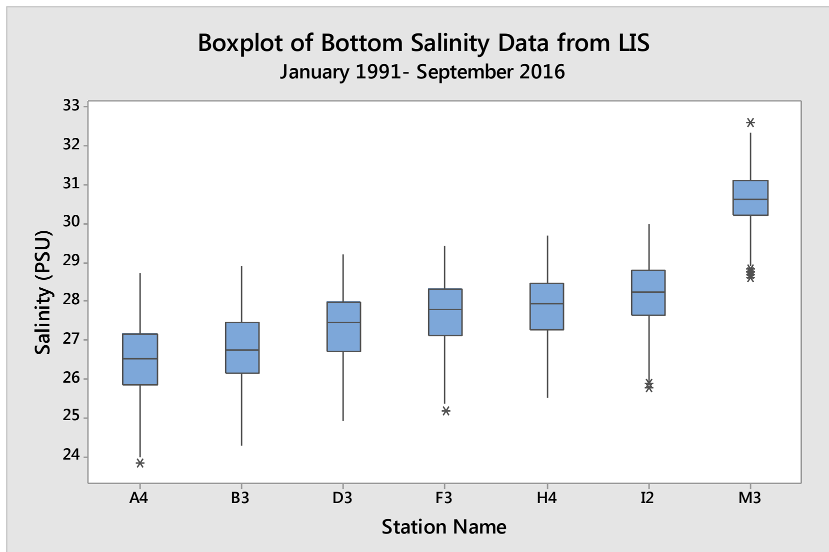
		1991-2016 Surface Statistics						
Station Name	Count	Minimum	Maximum	Mean	Median	SE Mean	Standard Deviation	Variance
A4	324	22.83	28.28	25.79	25.82	0.06	1.07	1.14
B3	365	22.80	28.84	26.17	26.19	0.06	1.08	1.17
D3	341	23.77	29.15	26.79	26.83	0.06	1.06	1.13
F3	312	24.25	29.31	26.93	26.98	0.06	1.09	1.18
H4	270	24.32	29.26	27.20	27.28	0.07	1.07	1.15
I2	278	24.56	29.91	27.59	27.68	0.06	1.03	1.06
M3	221	24.79	31.84	29.99	30.05	0.07	1.04	1.08

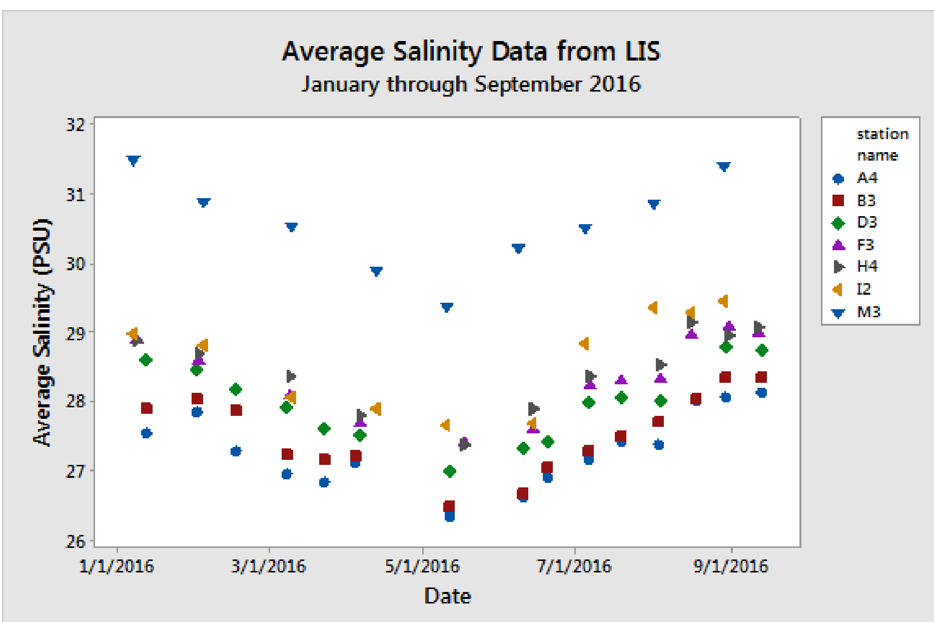
		2016 Surface Statistics						
Station Name	Count	Minimum	Maximum	Mean	Median	SE Mean	Standard Deviation	Variance
A4	14	25.90	27.96	26.96	26.90	0.16	0.61	0.37
B3	15	26.06	28.28	27.24	27.24	0.16	0.62	0.38
D3	13	26.79	28.67	27.79	27.70	0.18	0.65	0.42
F3	10	27.19	28.89	28.08	27.93	0.20	0.64	0.40
H4	11	27.19	29.09	28.21	28.22	0.19	0.62	0.38
I2	9	27.20	29.32	28.43	28.58	0.24	0.73	0.54
M3	8	28.97	31.13	30.00	30.00	0.27	0.77	0.59



This box plot, based upon data collected during CT DEEP surveys from January 1991 – September 2016, shows the median surface salinity, range, interquartile range, and outliers by station. Surface in this case refers to data collected two meters below the air/water interface. Salinity increases from west to east across the Sound.

This box plot, based upon data collected during CT DEEP surveys from January 1991- September 2016, shows the median bottom salinity, range, interquartile range, and outliers by station. Bottom in this case refers to data collected five meters above the sediment/water interface. The bottom waters are generally saltier than the surface waters.





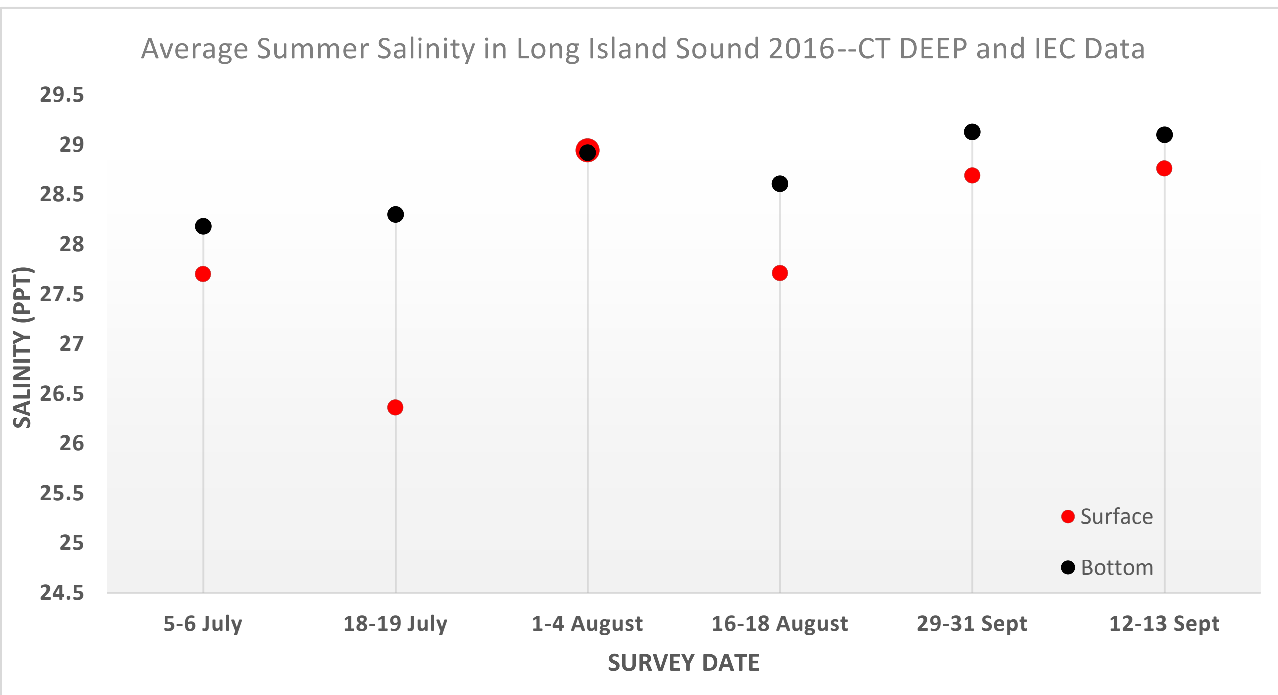
This plot illustrates the temporal variability of the mean salinity values by station from January-September 2016.

IEC 2016 Summer Salinity Data

Summer 2016 IEC Surface Salinity Statistics—Western Long Island Sound								
Station Name	Count	Minimum	Maximum	Mean	Median	SE Mean	Standard Deviation	Variance
A3	12	27.16	29.50	28.34	28.38	0.22	0.75	0.57
A2M	12	26.65	28.75	27.77	27.70	0.19	0.66	0.44
A1	12	26.32	28.56	27.56	27.80	0.21	0.72	0.52
B3M	12	27.52	30.23	28.79	28.79	0.25	0.85	0.72
A5	12	22.08	30.14	28.17	28.60	0.60	2.08	4.33
A4	12	22.03	29.90	27.96	28.27	0.58	2.02	4.07

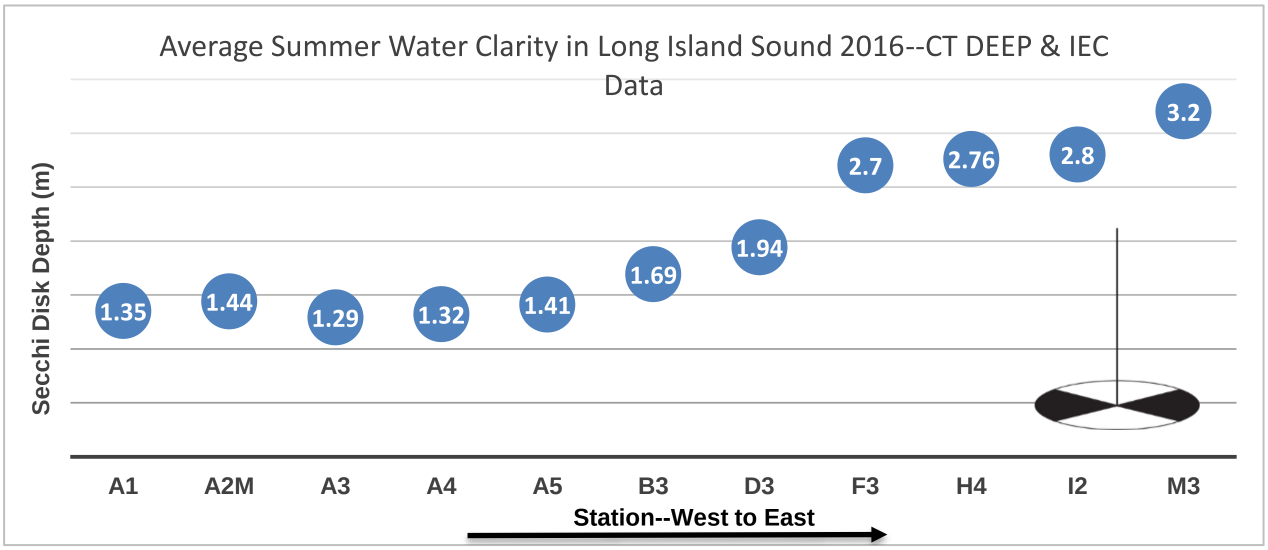
Summer 2016 IEC Bottom Salinity Statistics—Western Long Island Sound								
Station Name	Count	Minimum	Maximum	Mean	Median	SE Mean	Standard Deviation	Variance
A3	12	23.72	30.07	28.48	28.76	0.48	1.65	2.73
A2M	12	27.35	29.50	28.47	28.49	0.18	0.61	0.37
A1	12	25.66	29.41	27.79	27.97	0.27	0.95	0.91
B3M	12	28.11	30.29	29.28	29.21	0.20	0.70	0.49
A5	12	28.06	30.12	29.06	28.88	0.20	0.70	0.49
A4	12	28.06	30.05	29.00	28.81	0.19	0.65	0.43

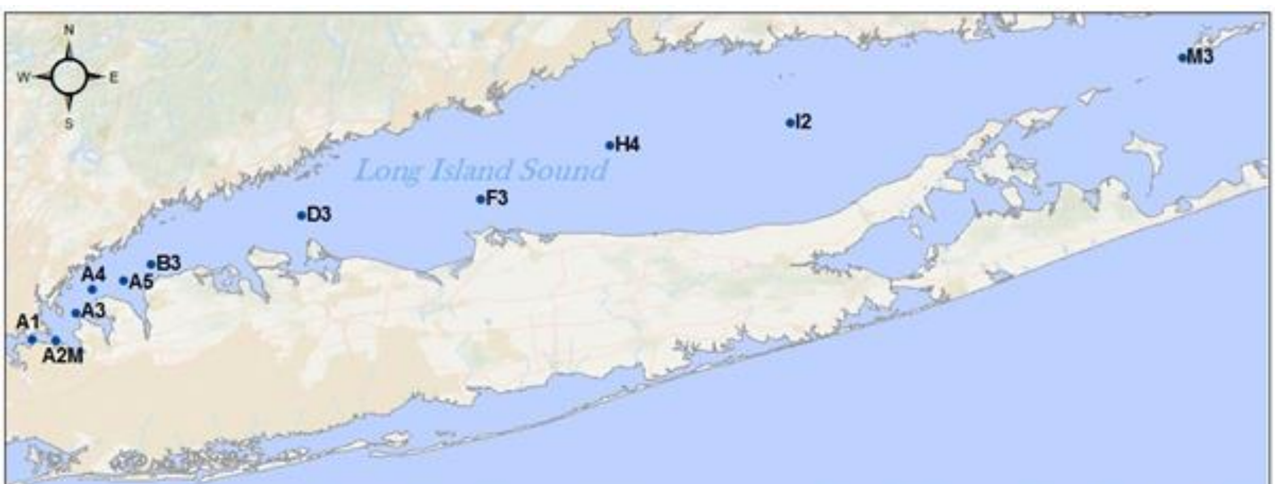
During the summer months, Long Island Sound waters stratify. Bottom waters become cool, dense, and more saline; surface waters are warmer, less dense, and have lower salinity. IEC salinity statistics for surface and bottom waters in the Western Sound are in the above tables. IEC measures salinity in parts per thousand (ppt). Salinity differences between surface and bottom waters are represented in the graph below.



Water Clarity

Water clarity is measured by lowering a Secchi disk into LIS until it disappears. It is then raised until it reappears. The depth where the disk vanishes and reappears is the Secchi disk depth. The depth to disappearance is related to the transparency of the water. Water clarity in Long Island Sound follows a west to east gradient, with clarity improving as you move eastward. The graph below highlights this gradient present in Long Island Sound. In 2016, the Western-most axial station (A1 near the Whitestone Bridge) had an average summer Secchi disk depth of 1.35 meters, whereas the eastern-most axial station (M3 near Fisher's Island) had an average summer Secchi disk depth of 3.2 meters. The eastern portion of Long Island Sound is a wide and deep channel with considerable influx from the Atlantic Ocean. This exchange of waters increases water clarity in the Eastern Sound. The Western Sound is more narrow and shallow compared to the Eastern Sound and its surrounding land is densely populated and developed. This results in less of an exchange of waters and also increases the concentrations of pollutants in the water that may affect water clarity.

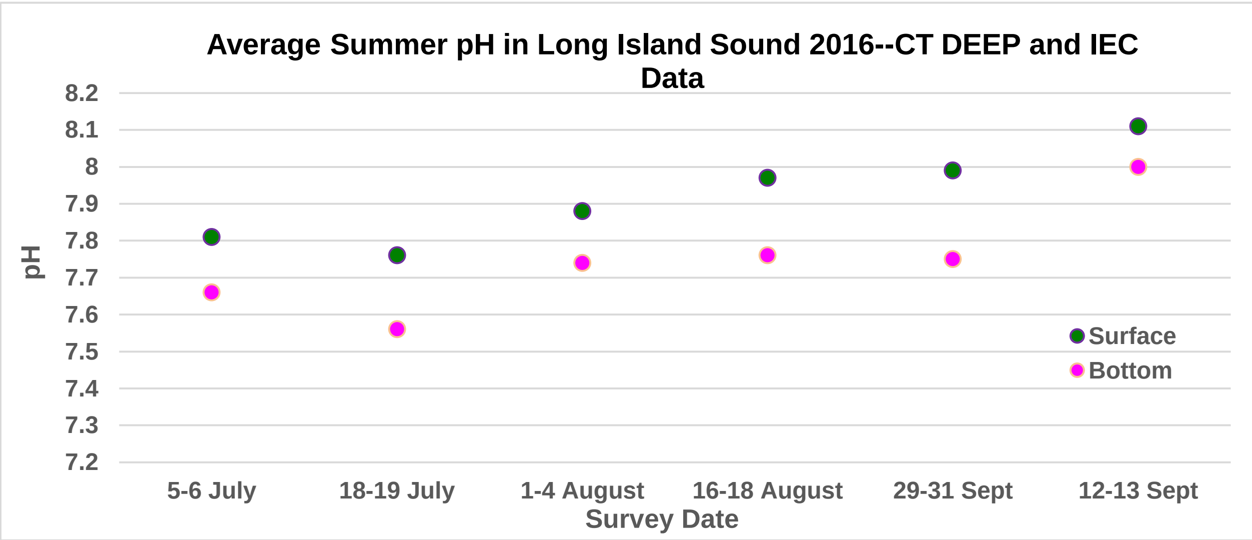


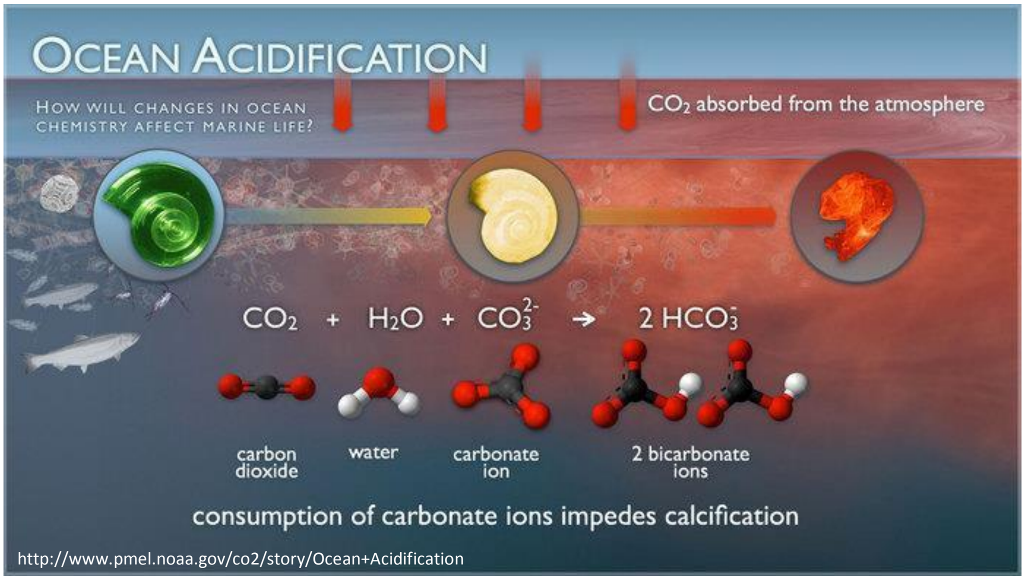


This map of IEC and CT DEEP LIS monitoring locations visually represents the stations in the above graph.

pH and Ocean Acidification

Human activities have resulted in increases in atmospheric carbon dioxide (CO_2). The ocean absorbs CO_2, greatly reducing greenhouse gas levels in the atmosphere and minimizing the impact on climate. When CO_2 dissolves in seawater, carbonic acid is formed. This acid formation reduces the pH of seawater and reduces the availability of carbonate ions. This process is depicted in the image below from NOAA. Carbonate ions are utilized by marine organisms in shell and skeletal formation. According to the NOAA Pacific Marine Environmental Laboratory Ocean Acidification, the pH of the ocean surface waters has already decreased from an average of 8.21 Standard Units (SU) to 8.10 SU since the beginning of the industrial revolution. The Intergovernmental Panel on Climate Change predicts a decrease of an additional 0.3 SU by 2100. Additional information specific to the Northeast region is available on the North East Coastal Acidification Network's website (http://www.necan.org/).

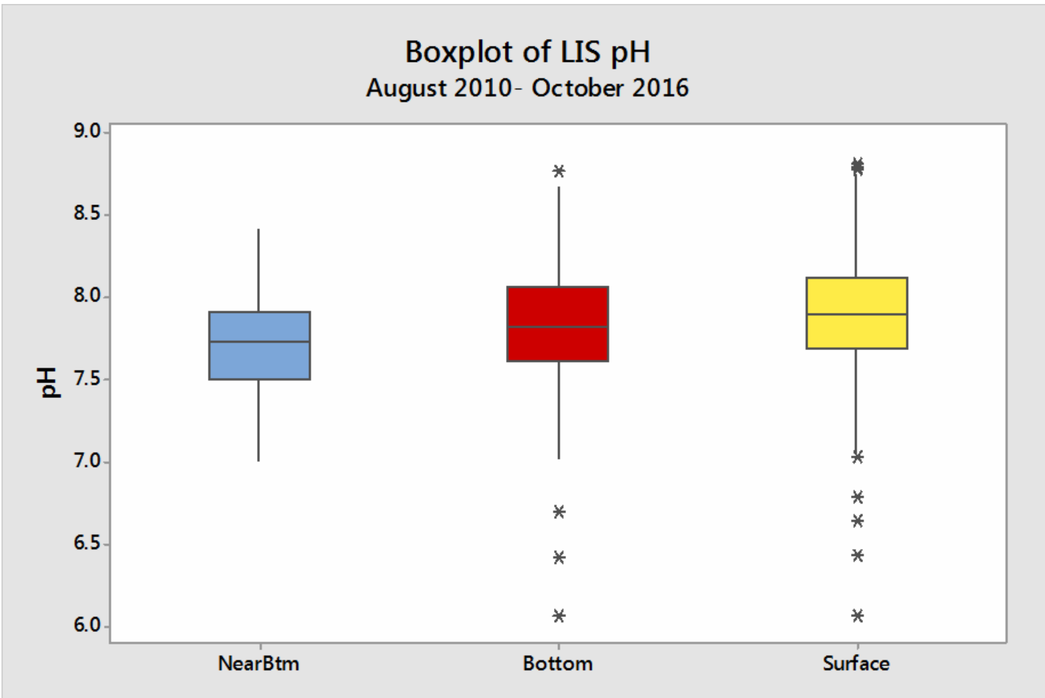




Data from the 2016 monitoring season, depicted in the graph above, show that the pH of bottom waters is lower than pH of surface waters. Surface and bottom waters followed a similar pattern in 2016 becoming increasingly less acidic at the end of the summer, when compared to the start of summer.

In August 2010, CT DEEP upgraded its SeaCat Profilers and began collecting and reporting pH data. Year round data collected through the WQOCT16 survey are summarized below.

	n	Maximum	Minimum	Mean	Median	SE Mean	StDev	Variance	Q1	Q3
Near Btm	1394	8.42	7.00	7.71	7.73	0.01	0.27	0.07	7.50	7.91
Bottom	1484	8.76	6.06	7.83	7.82	0.01	0.30	0.09	7.61	8.06
Surface	2224	8.81	6.07	7.90	7.90	0.01	0.28	0.08	7.69	8.12



Chlorophyll a

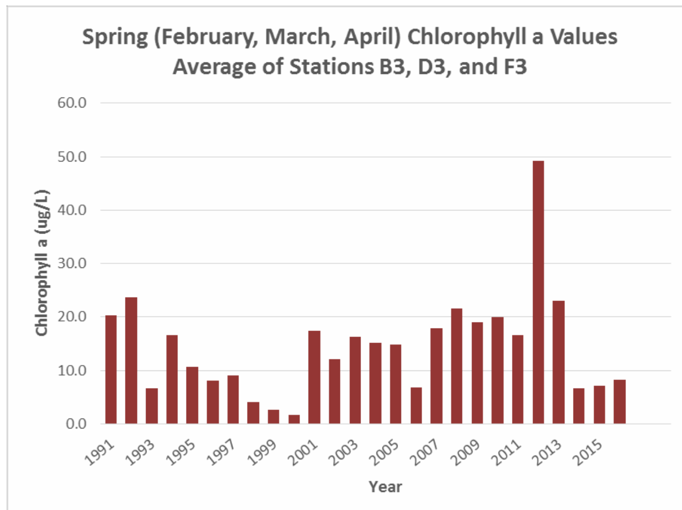
Chlorophyll is a pigment found in plants that gives them their green color. It allows plants to absorb light from the sun and convert it to chemical energy during photosynthesis. In photosynthesis, carbon dioxide and water are combined to produce sugar giving off oxygen as a byproduct. Microscopic plants, called phytoplankton, form the basis of the food web in Long Island Sound. Water temperature, nutrient concentrations, and light availability all factor into the amount of phytoplankton biomass found in the Sound.

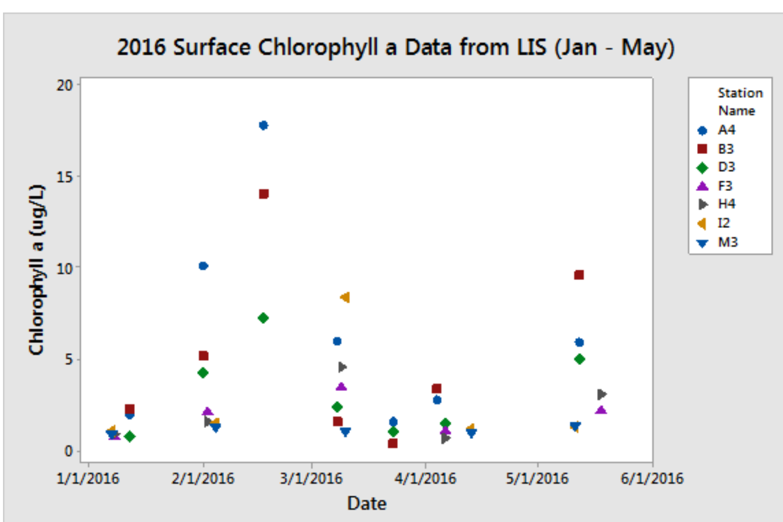
The concentration of chlorophyll a is used as a measure to estimate the quantity of phytoplankton biomass suspended in the surface waters. It is most commonly used because it is easy to measure and because photosynthetic production is directly proportional to the amount of chlorophyll present.

Chlorophyll a concentrations are measured year-round by CT DEEP using the CTD fluorometer for measurement as well as through the collection of grab samples using Niskin bottles. The grab samples are brought back into the onboard laboratory, filtered, and then sent to University of Connecticut for analysis.

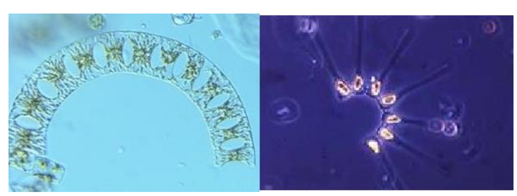
IEC collects grab samples during the summer months and analyzes them for chlorophyll a content in their own in-house laboratory.

The spring phytoplankton bloom occurs in Long Island Sound between February and April. Historically high levels of chlorophyll a in the Western Sound during this time have been linked to summertime hypoxia conditions.



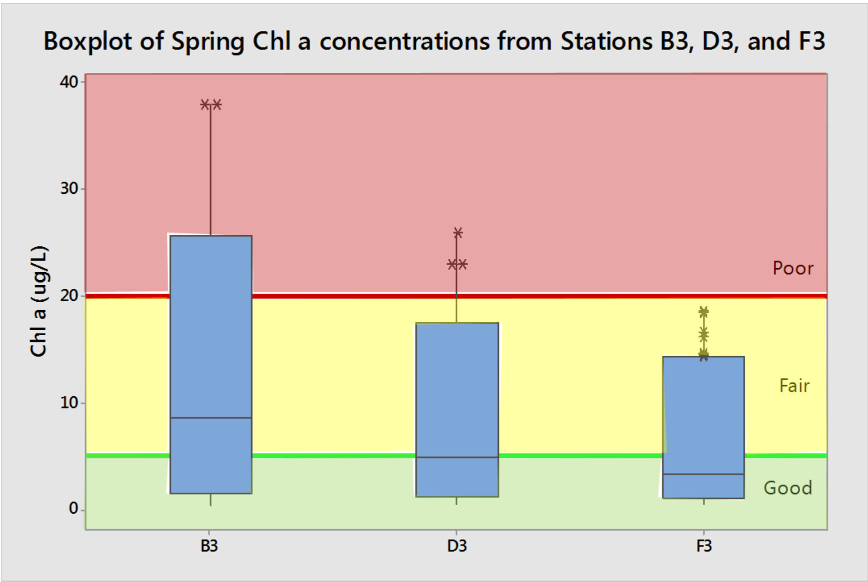


This plot illustrates the temporal variability of the surface chlorophyll a values (grab samples) by station from January- May 2016. The spring bloom was captured during the CHFEB16 (2/17) survey.



Microscopic images of phytoplankton.
Judy Li, NOAA, formerly of CT DEEP

The Integration and Application Network at the University of Maryland Center for Environmental Science released the first report card for Long Island Sound to the public in 2015. Chlorophyll a thresholds were set at 5 ug/L and 20 ug/L. The National Coastal Condition Report also uses these thresholds and ranks data in three categories: poor, fair, and good. Chlorophyll a concentrations less than 5 ug/L are good; concentrations between 5 and 20 ug/L are fair; and concentrations greater than 20 ug/L are poor.

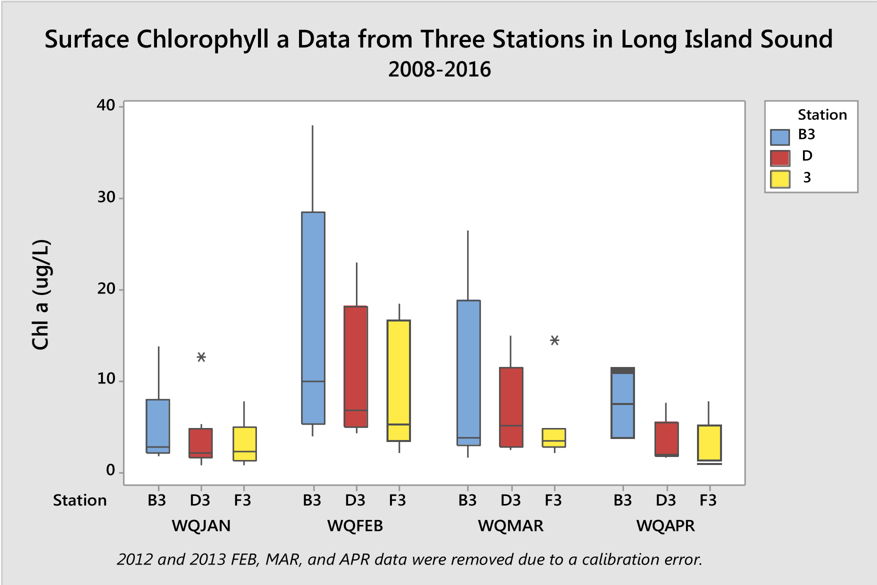


This boxplot examines spring (February-April) surface chlorophyll a data from three stations (B3, D3, and F3) in the Western/central portion of LIS from 1991 to 2016. Data from February, March, and April 2012 and 2013 are not included due to a lab calibration error.

At stations D3 and F3, 90% of the individual data are less than 20 ug/L and 75% of the data at B3 are less than 20 ug/L. This would place these stations in the fair category. The average concentration at each station is less than 20 ug/L but at or above 5 ug/L.

	n	Min	10th %	25th %	Median	75th %	90th %	Maximum	Mean	St Dev
B3	84	0.40	1.57	3.43	8.65	16.05	25.65	38.00	10.86	9.01
D3	83	0.50	1.24	2.37	4.90	10.00	17.47	26.00	6.97	6.28
F3	68	0.50	1.10	1.50	3.40	6.53	14.32	18.60	4.98	4.57

This boxplot examines recent data by survey.



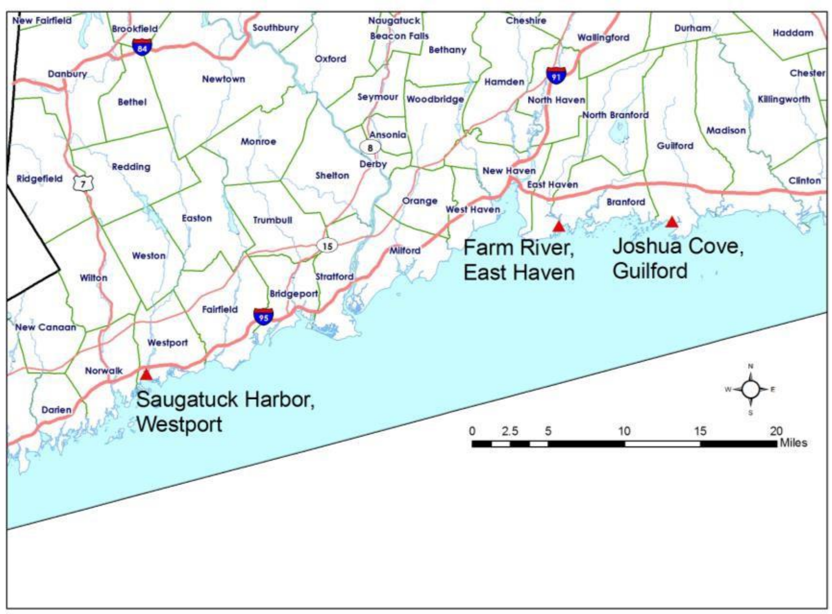
Embayment Pilot Project Sampling 2016

In 2016, CTDEEP began a pilot project to increase capacity for volunteer monitoring. The project is aimed at developing standard operating procedures for bacteria and water quality sampling in the near shore coastal waters of Connecticut.

Prior to engaging potential volunteer groups, CT DEEP conducted sampling in the Farm River in East Haven and Joshua Cove/Island Bay in Guilford. CT DEEP enlisted the Harbor Watch to sample a third embayment, Saugatuck Harbor in Westport.

Stations were sampled approximately monthly between July and September for bacteria, nutrients, and *in situ* parameters. Protocols were reviewed for macroalgae sampling and benthic macroinvertebrate sampling. One data loggers was deployed for a minimum of two weeks in both the Farm River and Joshua Cove to record continuous dissolved oxygen concentrations.

Additional data collection and SOP refinement will continue in 2017.



References Cited

Kaputa, N.P. and Olsen, C.B., 2000. Long Island Sound Summer Hypoxia Monitoring Survey 1991-1998 Data Review. CT DEP Bureau of Water Management, Planning and Standards Division, 79 Elm Street, Hartford, CT 06106, p. 45.

Latimer, J.S., Tedesco, M.A., Swanson, R.L., Yarish, C., Stacey, P., and Garza, C., eds., 2014. *Long Island Sound—Prospects for the Urban Sea*: New York, Springer, p. 558.

NRRC. 2016a. [Online] *Eastern Region Quarterly Climate Impacts and Outlook. September 2016* Northeast Regional Climate Center Accessed 20 January 2017 from http://www.nrcc.cornell.edu/services/reports/reports/2016-09.pdf

NRRC. 2016b. [Online] *Northeast Drought Forum Overview. October 2016*. Northeast Regional Climate Center. Accessed 20 January 2017 from http://www.nrcc.cornell.edu/services/special/reports/drought_oct2016.pdf

Simpson, David G., Gottschall, K., and Johnson, M. 1995. Cooperative interagency resource assessment (Job 5). In: A study of marine recreational fisheries in Connecticut, CT DEP Marine Fisheries Office, PO Box 719, Old Lyme, CT 06371, p. 87-135.

Simpson, D.G., Gottschall, K., and Johnson, M. 1996. Cooperative interagency resource assessment (Job 5). In: A study of marine recreational fisheries in Connecticut, CT DEP Marine Fisheries Office, PO Box 719, Old Lyme, CT 06371, p. 99-122.

Turner, E. and Rablais, N. 2016. [Online] *2016 Forecast: Summer Hypoxic Zone Size Northern Gulf of Mexico.* Accessed 18 January 2017 from http://www.gulfhypoxia.net/news/default.asp?year=2016

US EPA. 2000. Ambient aquatic life water quality criteria for dissolved oxygen (saltwater): Cape Cod to Cape Hatteras. EPA-822-R-00-012. Office of Water, Washington, DC. p. 49.

US EPA. 2015. [Online] *Letter to State Commissioners on Proposed EPA Nitrogen Reduction Strategy* United States Environmental Protection Agency. Region 1. Boston, Massachusetts and Region 2, New York, NY. Accessed 19 January 2017 from http://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Cover-Letter-final-12-23-15.pdf

Photos taken by Lloyd Langevin for CT DEEP, June 2007. Photo credit also to Jessica Haley, IEC, 2016

Acknowledgements

Funding for the CT DEEP Long Island Sound Water Quality Monitoring Program is provided through a grant from the EPA through the Long Island Sound Study.

IEC's monitoring program was partially funded by an agreement (LI96144501) awarded by the Environmental Protection Agency to the New England Interstate Water Pollution Control Commission in partnership with the Interstate Environmental Commission. Although the information in this document has been funded wholly or in part by the United States Environmental Protection Agency under agreement LI96144501 to NEIWPCC, it has not undergone the Agency's publications review process and therefore, may not necessarily reflect the views of the Agency and no official endorsement should be inferred. The viewpoints expressed here do not necessarily represent those of the Interstate Environmental Commission, NEIWPCC, or EPA nor does mention of trade names, commercial products, or causes constitute endorsement or recommendation for use.