STATE OF CONNECTICUT
DEPARTMENT OF ENVIRONMENTAL PROTECTION
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Hartford, CT 06106-5127
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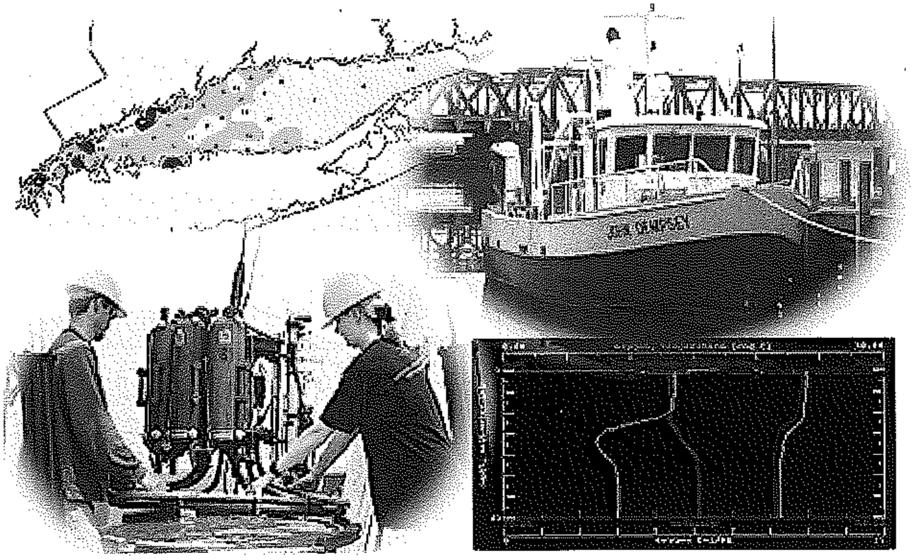
Arthur J. Roque, Jr., Commissioner

Bureau of Water Management

LONG ISLAND SOUND AMBIENT WATER QUALITY MONITORING PROGRAM:



Summer Hypoxia Monitoring Survey
1991-1998 Data Review

**Funding provided by the
U. S. Environmental Protection Agency
Long Island Sound Study**

LONG
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STUDY
A Partnership to Restore and Protect The Sound

September 2000

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Summer Hypoxia Monitoring Survey 1991-1998 Data Review

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Cover photos: Matthew Lyman

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Visit the Long Island Sound Water Quality Monitoring Program web page, with Program information and data. Under construction at:
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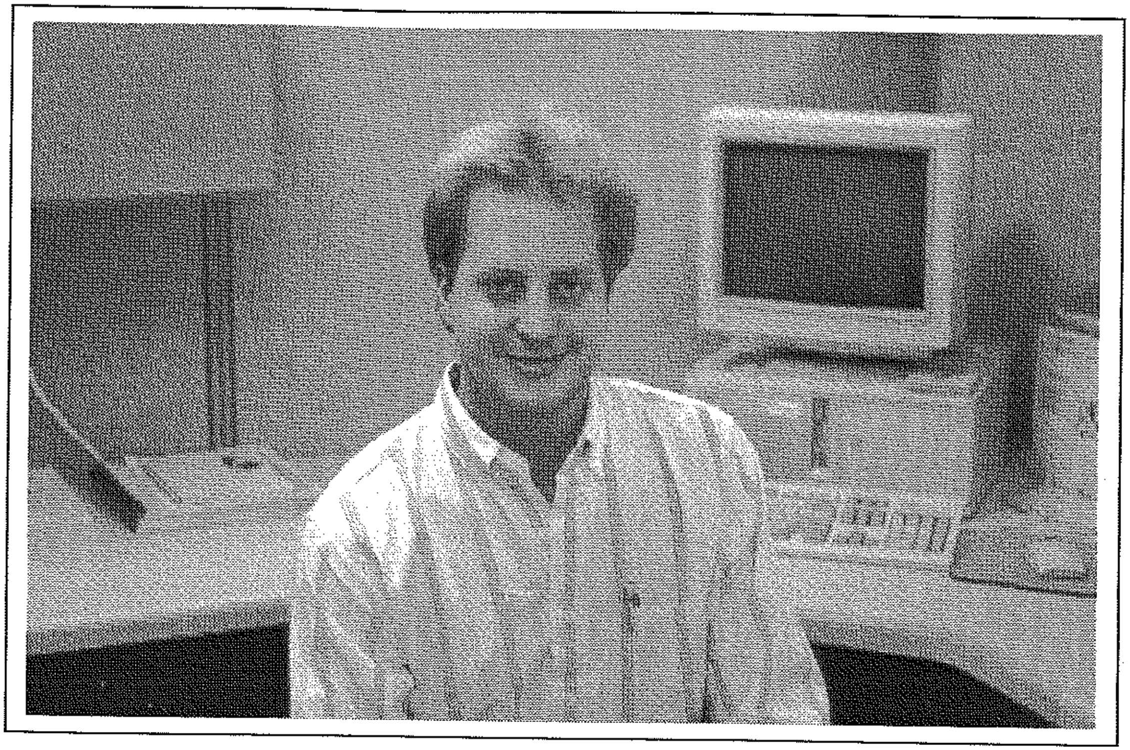

IN MEMORY

Nicholas P. Kaputa, Environmental Analyst 2 with the CTDEP Bureau of Water Management's Long Island Sound Water Quality Monitoring Program since January 1995, lost a year and half battle with cancer on June 20, 1999. Nick's history with the Department goes back to 1989 when he began his association with the Inland Fisheries Division, working as a seasonal employee, and, as a graduate student at the University of Connecticut, performing his Master's thesis work on the fishes of the lower Housatonic River. We mourn the loss of a hard-working colleague who took on an extensive field sampling program with apparent ease. Through a conscientious effort to make it the best it could be and a high level of personal initiative he has left us with high quality data, an efficient and organized data handling and database system, and the information and training we need to keep it all going. We miss his capable mind and hands in charge of the monitoring effort - fixing equipment and cables, organizing, analyzing and interpreting a cumbersome data set. We miss his ready smile, his sense of humor, and his honesty. We miss our very capable friend.

The following is Nick's effort, his report, that he never had the pleasure of seeing in this final form.

Christine Olsen and Paul Stacey
CTDEP Bureau of Water Management
Hartford, Connecticut
January 2000

ACKNOWLEDGMENTS

We would like to acknowledge the work of numerous past and present employees of the CTDEP Bureau of Water Management's Long Island Sound Water Quality Monitoring Program whose time both in the field and the office contributed significantly to this data collection and reporting effort: Christopher Bellucci, Daniel Biron, Nathan Denslow, Mark Fallon, Carla Farris, Jason Flaherty, Mark Foreman, Matthew Gates, Douglas Jann, Michael Kovacs, John Lake, Matthew Lyman, Julie Millus, Amy O'Neal, and George Smith. Additionally we would like to thank the staff of the Bureau of Natural Resources Fisheries Division for their previous and continued support in our sampling efforts, especially: Mark Alexander, Kurt Gottschall, Mark Johnson, and David Simpson. We also give great thanks to the crew of the R/V *John Dempsey*, Miles Peterle and Peter Simpson, for their considerable efforts in the logistics of the operation of the research vessel and the substantial task of assisting our program's biweekly monitoring of Long Island Sound during the summer months for the eight years of this survey.

We would also like to acknowledge the cooperation and assistance provided by the Interstate Sanitation Commission, especially Peter Sattler, and the New York City Department of Environmental Protection Marine Sciences Section, especially Bernadette Boneicki, for their ongoing water quality sampling efforts and their contribution of data to this effort. Thanks also to the Environmental Research Institute of the University of Connecticut, especially Jan Heitert and the nutrient laboratory staff, for their cooperation and commitment to fulfilling all of our analytical needs.

This work was partially funded by the U.S. Environmental Protection Agency, through the Long Island Sound Study, under sections 320 and 119 of the federal Clean Water Act.

Long Island Sound Summer Hypoxia Monitoring Survey
1991 - 1998 Data Review

EXECUTIVE SUMMARY

The Connecticut Department of Environmental Protection, Bureau of Water Management, initiated the Long Island Sound Ambient Water Quality Monitoring Program in January of 1991 to establish a chemical and biological database necessary to monitor trends in water quality throughout the Sound. The purposes of this report are to: 1) describe the summer dissolved oxygen monitoring survey; 2) provide a review of the 1991 through 1998 summer dissolved oxygen and hydrographic data collected; 3) depict trends in observed summer dissolved oxygen concentrations and other observed parameters over the first eight years of monitoring (1991 through 1998); 4) establish and provide baseline statistics that can be used to evaluate the course of future trends in dissolved oxygen; and 5) provide data for research and modeling activities in the region.

Annual summer dissolved oxygen monitoring surveys consisted of sampling approximately every other week from mid-June through September each year. In the first three years of this study (1991-1993), sampling was conducted as part of a cooperative intra-agency effort with CTDEP Fisheries Division to evaluate dissolved oxygen (DO) conditions and coincident fish abundance. This effort was supplemented by monthly water quality monitoring at seven axial master stations from Throgs Neck in the west to Fishers Island in the east. Beginning in 1994, forty-eight permanent stations were established and six to seven sampling cruises were conducted each summer season. Stations were sampled for dissolved oxygen, temperature, salinity, photosynthetically-active radiation (beginning in May 1992), and chlorophyll *a*.

The duration, area and severity of low dissolved oxygen conditions varied annually in Long Island Sound. Although hypoxia (defined as DO less than 3.0 mg/L) was typically present in the Sound by early July, the observed onset ranged from July 1 in 1994 to August 10 in 1996. Additionally, the duration of hypoxic conditions ranged from a low of 34 days in 1996 to a high of 78 days in 1993. The maximum area of hypoxia occurred in 1994 with an area of 1022 km^2 impacted. In 1997, only 77 km^2 of the Sound's bottom waters were hypoxic. Short and long-term weather patterns, particularly those that affected water temperatures, stratification and mixing in the Sound had an important influence on the extent of hypoxia.

The survey results revealed an increasing (improving) trend in summertime bottom water DO concentrations throughout most of the Sound. Five stations, one in the Narrows, one in the Western Basin, two in the Central Basin, and one in the Eastern Basin, experienced significantly increasing DO levels ($p<0.05$). Thirty-three additional stations also showed trends of increasing DO, although these were not statistically significant ($p>0.05$).

This work was partially funded by the United States Environmental Protection Agency's Long Island Sound Study. Questions regarding this report and requests for additional data or information from the Long Island Sound Ambient Water Quality Monitoring Program should be brought to the attention of the Planning and Standards Division of the Bureau of Water Management.

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INTRODUCTION

Background

Initiated in 1985, the Long Island Sound Study (LISS) is a partnership of federal, state, and local governments agencies, private organizations, and citizens formed to develop and implement a comprehensive conservation and Management Plan (CCMP) for Long Island Sound. Funding support for the LISS is provided by the EPA through the National Estuary Program and by the states of Connecticut and New York. One of the primary missions of the LISS is to collect data and assess the environmental conditions of the Sound. During 1988, 1989 and 1990, a series of comprehensive field surveys was conducted to complement the development of a coupled hydrodynamic-water quality model being prepared as part of the federal National Estuary Program's Long Island Sound Study (LISS) by the National Oceanic and Atmospheric Administration (NOAA) and HydroQual, Inc. These surveys provided physical, chemical, and biological water column data essential to calibrate and verify the Long Island Sound model. Surveys were conducted by the Marine Sciences Institute (MSI) of the University of Connecticut, the Marine Sciences Research Center (MSRC) of the State University of New York at Stony Brook, and the New York City Department of Environmental Protection (NYCDEP), and were supported by the Environmental Protection Agency□s (EPA) National Estuary Program. The 1988-1990 work significantly expanded the database developed during the preceding two years of the LISS, detailing water temperature-salinity structure throughout the Sound and providing the first comprehensive set of synoptic current and water quality data. The data were essential to modeling efforts and to the management strategy development and implementation activities that followed.

In January of 1991 the Connecticut Department of Environmental Protection (CTDEP) initiated a water quality and hydrographic survey to provide continuity to the LISS data set and to ensure that data would be available as the LISS progressed into the implementation phase. This survey continues in an expanded form with EPA support as the Department's Long Island Sound Ambient Water Quality Monitoring Program (the "Program").

Over the long-term, the data from this Program are essential to assess trends in water quality, especially responses to implementation of the LISS *Comprehensive Conservation and Management Plan* (CCMP) recommendations (LISS 1994). Nitrogen enrichment in particular has been determined to be a primary cause of low dissolved oxygen conditions in the Sound. Reducing the loading of this nutrient is a major goal in the management actions being taken by the LISS and participating jurisdictions to improve the health of the Sound. In particular, the data will allow the Department and the LISS to assess the effectiveness of management actions taken to reduce nutrient inputs to the Sound. The purpose of this survey is to document summer dissolved oxygen conditions throughout Long Island Sound.

Goals and Objectives

The goals of the Department's Long Island Sound Ambient Water Quality Monitoring Program are:

- ☐ to monitor water quality parameters year round on a monthly schedule at stations throughout Long Island Sound
- ☐ To monitor the temporal and spatial extent of summertime hypoxia through Sound-wide sampling every other week from late June through mid-September
- ☐ To maintain a long-term database of the information collected

The objectives of the Program are:

- ☐ To review the data periodically, in combination with available historical data, for trends
- ☐ To assess the long-term results of specific management actions such as the "no-net increase" nutrient (nitrogen) policy adopted in 1990 and the nutrient reduction strategy implemented in 1994
- ☐ To provide state and federal managers and policy-makers with information on existing conditions and trends that can be used in the development, implementation and assessment of strategies to control and improve water quality in the Sound
- ☐ To make the data available for related efforts such as research and water quality model development and calibration
- ☐ To make data available to other interested individuals/groups

Hypoxia

The Long Island Sound Study has defined hypoxia as low concentrations of dissolved oxygen, less than 3.0 milligrams per liter (mg/L), in water. Specifically, "hypoxia" refers to the low dissolved oxygen condition that develops each summer in the bottom waters of Long Island Sound (LISS 1994). Hypoxia has been identified as the most pressing problem affecting the health of the Sound in the *Comprehensive Conservation and Management Plan* (LISS 1994). In general, the key factor that promotes the development of hypoxia in the Sound is the presence of excess nutrients, especially nitrogen. Nitrogen is a natural and necessary nutrient for a healthy estuarine ecosystem, but is found in Long Island Sound in concentrations much higher than would naturally occur. These high concentrations are due to inputs from anthropogenic sources such as sewage treatment plants, industry, land runoff, and atmospheric pollution. Excess nitrogen contributes to the excessive growth of phytoplankton, the microscopic plants that are abundant in the Sound's waters. When the phytoplankton die, they sink to the bottom where natural decomposition of this organic matter takes place, consuming oxygen in the process. During the summer months, stratification of the water column restricts the mixing of oxygen-rich surface waters with bottom waters. Consequently, dissolved oxygen becomes depleted in the bottom waters as reoxygenation through the action of winds, waves, currents, and photosynthesis is absent or insufficient. Hypoxia stresses fish and other marine organisms, reducing feeding and growth and decreasing the amount of suitable habitat available to them. In severe cases, hypoxia can result in mortality of exposed organisms.

Excess nitrogen and the abundant phytoplankton blooms it supports are key factors in the development of low dissolved oxygen (or hypoxic) conditions in LIS. However, the characteristics of each year's occurrence, including annual variability in the timing, duration, spatial extent, and severity of the hypoxic event, are largely driven by weather conditions. The timing and strength of summer stratification, which is important to the development of hypoxia, depend on winter, spring, and summer weather patterns and conditions. Stratification is the result of a density differential between surface and bottom waters. This density difference in Long Island Sound is primarily a function of temperature differences between surface and bottom waters, with salinity differences contributing only slightly. The stratification of the water column sets up in the late spring or early summer and restricts the mixing of highly oxygenated surface waters with the oxygen depleted bottom waters. The larger the temperature and salinity differences between surface and bottom waters, the stronger the barrier to oxygen movement.

Weather conditions, patterns and events that are important to the development and characteristics of hypoxia include air temperatures, precipitation, and wind events. These weather patterns and events are responsible for water temperatures, salinity patterns, the timing and volume of runoff, including spring snowmelt, and the timing of water column mixing events. The variability in weather patterns contributes to the annual variability in hypoxia through its effects on nutrient delivery and water column mixing.

METHODS

Study Area

Long Island Sound is a semienclosed estuary located in the eastern United States with openings to the Atlantic Ocean at both its western and eastern ends (Figure 1). The western end connects to the Atlantic Ocean via a tidal strait, the East River, which connects to the lower Hudson River at New York Bay. The connection to the Atlantic Ocean at the eastern end of the Sound is larger and more direct, contributing most of the volume and tidal flow that control circulation and tidal patterns. The Sound is approximately 200-km long and 40 km at its widest point. It is bordered by the states of Connecticut (to the north) and New York (to the west and south) with 90% of its freshwater inputs coming from the Connecticut, Housatonic, and Thames Rivers (LISS 1994). With a surface area of approximately 3,366 square kilometers (including embayments) and a variety of habitat types, Long Island Sound has diverse marine faunal and floral assemblages including important recreational and commercial fisheries (LISS 1994). Its value to the region, which has more than five million people living within twenty-five kilometers of its coast, is both

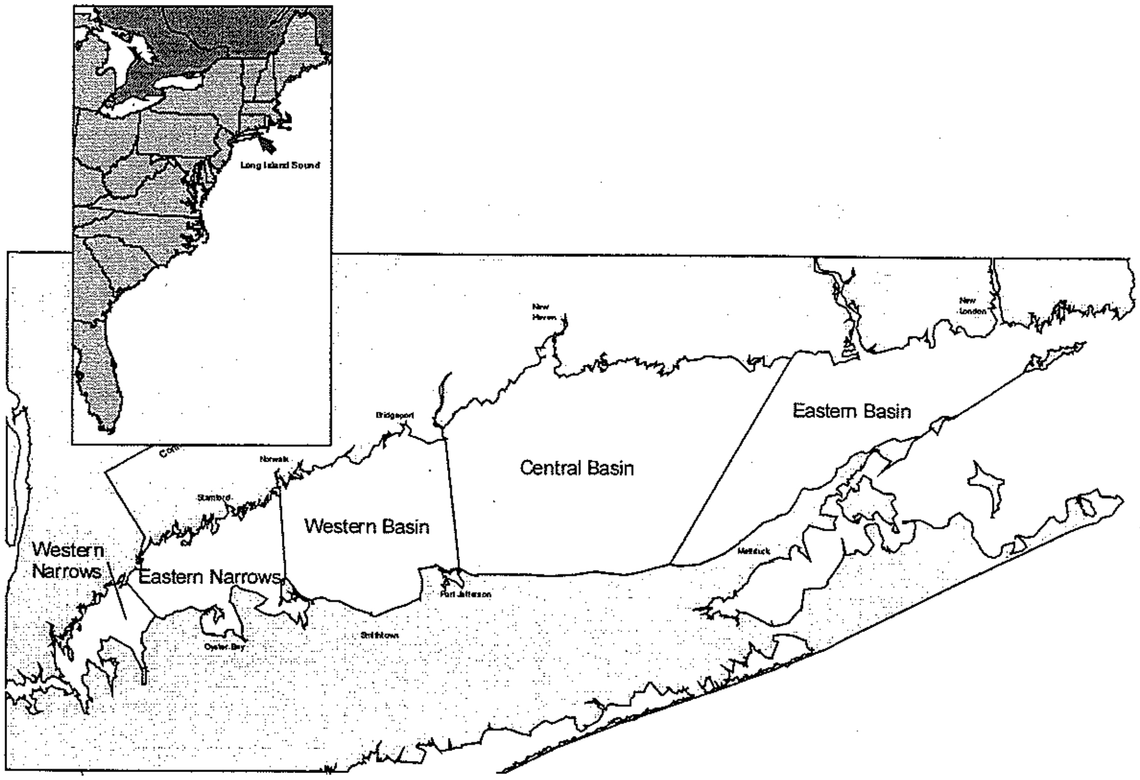


Figure 1. Long Island Sound study area showing basins. Inset shows location along the U.S. east coast.

economic and aesthetic. With so many people living in close proximity to its shores and with a drainage basin of 41,000 km^2, Long Island Sound has been the recipient of a wide range of anthropogenic pollutants. There are forty-four Publicly Owned Treatment Works (POTWs) discharging directly into the Sound and more than eighty throughout the Connecticut portion of the watershed alone. These POTWs, or sewage treatment plants, are significant sources of nutrients to LIS.

Area/Stations Sampled

1991-1993

CTDEP began intensive summer dissolved oxygen monitoring in June of 1991. During the summers of 1991-1993 most of the summer dissolved oxygen sampling was conducted as part of a cooperative intra-agency effort between the Bureau of Natural Resources and the Bureau of Water Management. This sampling was designed to evaluate the effects of dissolved oxygen concentrations on fish abundance as well as to determine the temporal and spatial extent of hypoxia. Sampling sites were randomly selected within defined areas that extended from the middle of the Western Narrows to the southwestern corner of the Eastern Basin, with a higher

Table 1. Summer dissolved oxygen monitoring 1991-1993.

Year	Cruise	Dates	# Stations Sampled
1991	WQJUL91	7/08-7/18	40
	WQAUG91	7/29-8/13	46
	HYAUG91	8/21-8/28	36
	WQSEP91	9/04-9/12	16
1992	HYJUN92	6/29-7/02	33
	WQJUL92	7/07-7/20	42
	HYJUL92	7/27-7/30	41
	WQAUG92	8/05-8/13	40
	HYAUG92	8/17-8/28	56
	WQSEP92	9/01-9/09	12
1993	HYJUN93	6/28-7/02	42
	WQJUL93	7/07-7/15	48
	HYJUL93	7/26-7/29	46
	WQAUG93	8/02-8/12	58
	HYAUG93	8/17-8/26	55
	WQSEP93	9/07-9/09	12

concentration of sampling sites per area in the west where hypoxia was generally more severe (Simpson et al. 1994). Sampling effort was also divided between two depth strata. Trawling was combined with water quality data collection for 226 samples and 294 additional samples for water quality alone were taken. A further discussion of this sampling design and the results of the living resource trawling component can be found in Simpson *et al.* (1994). The trawling surveys were supplemented by sampling conducted as part of the LIS Monthly Ambient Water Quality Monitoring Program at an additional seven stations each month (Figure 2). Some of these sampling events were combined into "cruises" for purposes of data analysis, in particular for calculating the area of hypoxia where coverage from two consecutive sampling events improved data interpretation and analysis. In total, combining both the trawl surveys and the water quality surveys, four to six sampling cruises were conducted each of these years, with from 12 to 58 stations being sampled each cruise (Table 1).

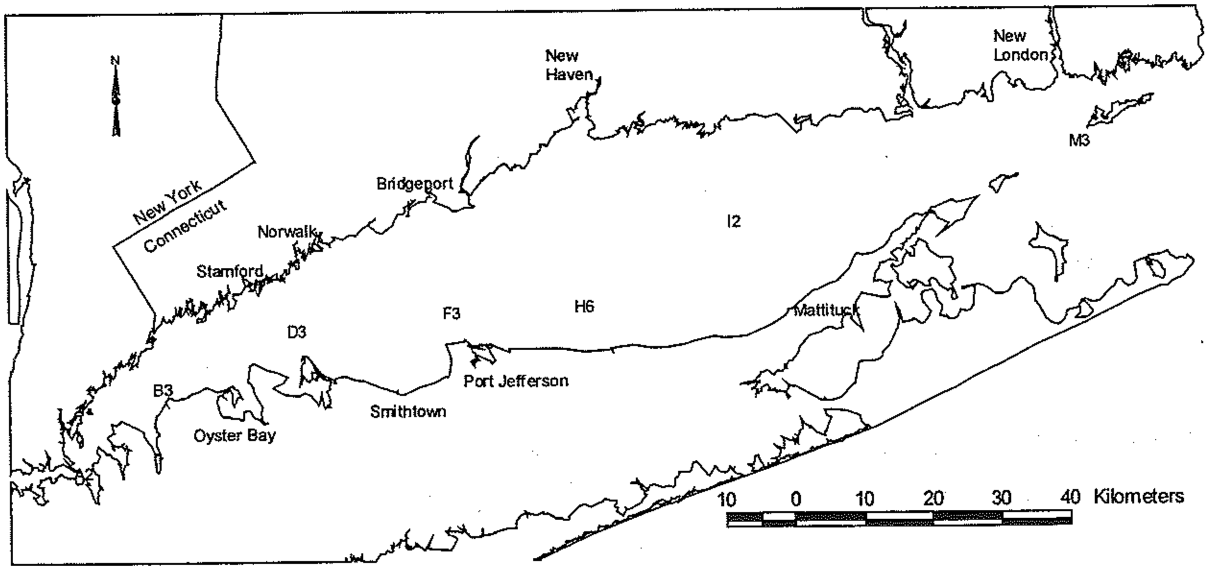


Figure 2. Connecticut DEP monthly water quality sampling stations in Long Island Sound for the years 1991 through 1994.

1994 – 1998

In 1994, 48 permanent sampling stations were established to monitor hypoxia. Eighteen of these permanent stations were also sampled as part of the monthly water quality monitoring program, which was expanded from seven to eighteen stations in December 1994. In 1998 one additional station was added in the Eastern Basin (Station J4). From 1994 through 1998 summer dissolved oxygen monitoring was conducted at these 48 (or 49) stations (Figure 3 and Table 2). These stations were concentrated in the western Sound, where low dissolved oxygen conditions have typically been most severe. Stations ranged in depth from 9 to more than 40 meters, and included a variety of physical characteristics. Six to seven cruises were conducted each summer, with from 6 to 48 stations being sampled each cruise for a total of 1,170 station profiles (Table 3). An effort was made to sample as many stations as possible given constraints of time and weather conditions. In some cases, when no hypoxia was observed in the western Sound or when the pattern of dissolved oxygen concentrations was evident from stations sampled (*e.g.*, a large area of western or central LIS with dissolved oxygen concentrations above 5.0 mg/L), stations in the far eastern part of the Sound, where dissolved oxygen concentrations generally do not fall below 5.0 mg/L, were not sampled.

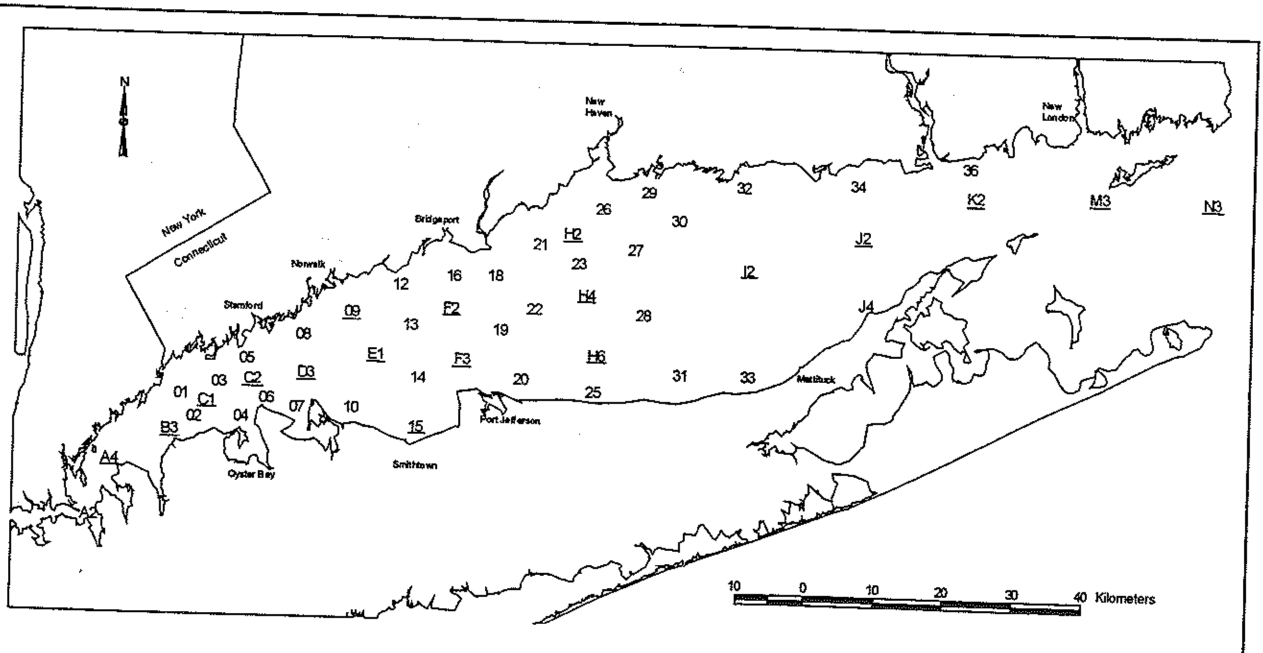


Figure 3. Summer dissolved oxygen monitoring stations for the years 1994 through 1998. Eighteen underlined stations also served as monthly water quality monitoring stations beginning in December 1994.

Table 2. Station information for all fixed stations sampled since June 1994 (see Figure 3).

Station	Station Depth (meters)	Latitude	Longitude	General Schedule	Sampling Dates	Notes
Narrows						
A2	29.2	40 48.05N	73 47.24W	Year round	4/91 - 11/94	sampled by NYCDEP
A4	32.6	40 52.35N	73 44.05W	Year round	8/94 - present	
B3	18.0	40 55.10N	73 38.57W	Year round	2/91 - present	
01	14.8	40 57.80N	73 37.42W	Summer	6/94 - present	
02	15.8	40 56.08N	73 36.04W	Summer	6/94 - present	
C1	19.8	40 57.35N	73 34.82W	Year round	12/94 - present	
03	24.1	40 58.76N	73 33.64W	Summer	6/94 - present	
04	12.3	40 56.27N	73 31.16W	Summer	6/94 - present	
C2	32.4	40 59.06N	73 30.13W	Year round	12/94 - present	
05	13.0	41 00.56N	73 30.82W	Summer	6/94 - present	
06	18.2	40 57.67N	73 28.60W	Summer	6/94 - present	
07	12.7	40 57.02N	73 25.52W	Summer	6/94 - present	
08	12.9	41 02.45N	73 25.08W	Summer	6/94 - present	
D3	40.9	40 59.63N	73 24.68W	Year round	2/91 - present	
Western Basin						
09	9.1	41 04.25N	73 20.17W	Year round	6/94 - present	
10	17.3	40 57.10N	73 19.95W	Summer	6/94 - present	
E1	38.1	41 01.16N	73 17.48W	Year round	12/94 - present	
12	10.5	41 06.52N	73 15.18W	Summer	6/94 - present	
13	22.3	41 03.50N	73 14.06W	Summer	6/94 - present	
14	25.4	40 59.49N	73 13.13W	Summer	6/94 - present	
15	15.3	40 55.88N	73 13.27W	Year round	6/94 - present	
16	8.9	41 07.22N	73 09.75W	Summer	6/94 - present	
F2	19.7	41 04.82N	73 09.92W	Year round	12/94 - present	
F3	40.9	41 01.07N	73 08.67W	Year round	1/91 - present	
Central Basin						
18	12.6	41 07.34N	73 05.40W	Summer	6/94 - present	
19	25.5	41 03.32N	73 04.85W	Summer	6/94 - present	
20	22.5	40 59.64N	73 02.54W	Summer	6/94 - present	
21	14.3	41 09.84N	73 00.89W	Summer	6/94 - present	
22	26.9	41 04.94N	73 01.37W	Summer	6/94 - present	
H2	13.9	41 10.68N	72 57.63W	Year round	6/94 - present	
23	19.0	41 08.41N	72 56.93W	Summer	6/94 - present	
H4	23.7	41 06.10N	72 56.04W	Year round	6/94 - present	
H6	41.4	41 01.56N	72 54.81W	Year round	1/91 - present	
25	10.7	40 58.86N	72 55.09W	Summer	6/94 - present	
26	11.2	41 12.55N	72 54.51W	Summer	6/94 - present	
27	20.2	41 09.52N	72 50.97W	Summer	6/94 - present	
28	30.1	41 04.69N	72 50.01W	Summer	6/94 - present	
29	9.4	41 13.89N	72 49.78W	Summer	6/94 - present	
30	15.3	41 11.78N	72 46.52W	Summer	6/94 - present	
31	25.8	41 00.25N	72 46.10W	Summer	6/94 - present	
32	10.7	41 14.49N	72 39.94W	Summer	7/94 - present	
I2	27.3	41 08.25N	72 39.30W	Year round	1/91 - present	
Eastern Basin						
33	20.2	41 00.23N	72 39.07W	Summer	6/94 - present	
34	16.7	41 14.76N	72 28.10W	Summer	6/94 - present	
J2	21.8	41 10.92N	72 27.46W	Year round	6/94 - present	
J4	18.5	41 05.85N	72 27.00W	Summer	6/98 - present	
36	6.6	41 16.23N	72 16.53W	Summer	7/94 - present	sampled infrequently
K2	37.7	41 14.06N	72 15.95W	Year round	7/94 - present	
M3	72.6	41 14.23N	72 03.20W	Year round	1/91 - present	
N3	52.9	41 14.00N	71 51.46W	Year round	1/95 - present	

Table 3. Summer dissolved oxygen monitoring 1994-1998.

Year	Cruise	Dates	# Stations Sampled
1994	HYJUN94	6/21-6/23	38
	WQJUL94	7/05-7/11	44
	HYJUL94	7/20-7/22	34
	WQAUG94	8/01-8/04	42
	HYAUG94	8/16-8/18	37
	WQSEP94	8/29-9/01	37
	HYSEP94	9/07-9/08	9
1995	HYJUN95	6/22-6/27	28
	WQJUL95	7/06-7/11	38
	HYJUL95	7/18-7/20	42
	WQAUG95	7/31-8/04	48
	HYAUG95	8/14-8/16	39
	WQSEP95	9/05-9/12	18
1996	HYJUN96	6/25-6/27	29
	WQJUL96	7/08-7/11	39
	HYJUL96	7/23-7/25	40
	WQAUG96	8/05-8/08	42
	HYAUG96	8/20-8/22	39
	WQSEP96	9/03-9/06	28
	HYSEP96	9/20	11
1997	HYJUN97	6/27-6/30	21
	WQJUL97	7/08-7/09	20
	HYJUL97	7/22-7/24	33
	WQAUG97	8/04-8/07	46
	HYAUG97	8/19-8/22	42
	WQSEP97	9/02-9/05	35
	HYSEP97	9/17	6
1998	HYJUN98	6/24-6/26	35
	WQJUL98	7/06-7/09	46
	HYJUL98	7/21-7/23	43
	WQAUG98	8/03-8/06	48
	HYAUG98	8/17-8/21	46
	WQSEP98	8/31-9/03	46
	HYSEP98	9/15-9/17	21

Equipment

Water sampling was conducted with the cooperation of CTDEP's Bureau of Natural Resources' Fisheries Division aboard the 50-ft R/V *John Dempsey.* Conductivity-temperature-depth (CTD) water column profiles were taken with a Sea-Bird model SBE-19 SeaCat Profiler, further equipped with dissolved oxygen (YSI model 5739) and photosynthetically-active radiation (PAR) (Licor spherical underwater model 193SA) sensors. The profiler unit had an internal memory to store temperature, conductivity, pressure, dissolved oxygen, and PAR data at a rate of twice per second as the unit was lowered through the water column. The instrument calculated secondary parameters of salinity, depth, and density and generated these data values as well. The data were generally reviewed in real-time (*i.e.,* as the profile was taking place) via the onboard computer and were uploaded to the computer during or after cast completion. Generally, the CTD unit was mounted on a rosette water sampling device (General Oceanics model 1015 Rosette Multi-Bottle Array) which could also hold up to nine, 5-liter Niskin water sampling bottles. These bottles were open as the rosette was deployed and were closed to collect a water sample when the real-time readout from the CTD indicated that the desired water sampling depth had been reached on the upcast. The rosette triggering device was powered through an electromechanical hydrocable attached to a deck command unit in the onboard laboratory, allowing remote actuation of the water sampling bottles.

A Turner Designs Model 10 Field Fluorometer was used to estimate chlorophyll *a* concentrations (an estimate of phytoplankton biomass) from whole water samples.

Measurements

The CTD unit described above provided measurements of salinity, temperature, dissolved oxygen, and light throughout the water column from the surface to the bottom at each station. These measurements were recorded twice per second by the instrument as it was lowered through the water column at a rate of approximately 0.2 meters/second. Water samples collected at selected depths via the Niskin bottles were analyzed for chlorophyll *a* and chemical dissolved oxygen concentration. These chemical and physical measurements are fundamental indicators of water quality, with specific relevance to hypoxia. These measurements provide:

- Evidence of changing conditions in the Sound
- Baseline information for the interpretation of related biological measurements from monitoring and research
- A Sound-wide baseline that localized monitoring and research programs can use for the purpose of comparing and corroborating their data

Chemical

Water samples were collected at a minimum of two depths. Surface water samples were collected approximately two meters below the surface; near-bottom water samples were generally collected between one and two meters off the bottom. Mid-water samples were regularly taken at one, two, or three additional depths, depending on the station depth.

Water samples were filtered in the onboard laboratory and filters were delivered to the analytical laboratory of the Environmental Research Institute (ERI) at the University of Connecticut for analyses of chlorophyll *a* using a standard fluorometric method, described in ERI□s Standard Operating Procedures for the Long Island Sound Study (ERI 1991). Whole (unfiltered) water samples were analyzed in the field using the field fluorometer for chlorophyll *a* estimations. These chlorophyll data will be reviewed in a future report. Winkler titration (azide modification) for determining the dissolved oxygen content of the water (AWWA 1992) were performed in the onboard laboratory as a quality assurance check of the CTD dissolved oxygen sensor performance. Dissolved oxygen sensor calibrations were performed at least monthly, usually prior to each cruise, using methods recommended by the manufacturer. All field procedures for sample collection and handling followed strict protocols detailed in the Program's Water Quality and Hydrographic Surveys Standard Operating Procedures (SOP) Manual (CTDEP 1991).

Physical

Physical parameter measurements (salinity, temperature, and density) were made with the use of the CTD water column profiling instrument, described above. The profiler was lowered through the water column at a rate of approximately 0.2 meters per second. Factory calibrations were conducted approximately annually on the conductivity and temperature sensors. Field procedures for instrument handling are detailed in the Program's SOP (CTDEP, 1991).

Cruise Identification

For purposes of hypoxic area calculations and trend analyses all samples were associated with a particular cruise. Each summer month (June through September) had two cruises: an early "water quality" cruise and a later "hypoxia" cruise (Tables 1 and 3). Cruise names include a 2-letter prefix, either "WQ" for "Water Quality" indicating sampling was conducted as part of, or, in the case of 1991-1993 sampling, close in time to the monthly water quality cruise. Monthly water quality cruises were generally conducted during the first week of each month. "HY" at the beginning of the cruise name is short for "Hypoxia", indicating the special summer cruises conducted approximately midway between monthly water quality cruises during the summer months. The "WQ" or "HY" prefix is followed by a 3-letter month identifier (JUN, JUL, AUG, or SEP) and then by a 2-digit year (91, 92, etc). Water Quality cruises included additional sampling for dissolved and particulate nutrient concentrations (data reported separately) at master stations (18 since December 1994) whereas Hypoxia cruises did not include such sampling. 1991-1993 cruise data was from two surveys (Water Quality and Fisheries Resource/Hypoxia Surveys) so that most of the cruise sampling periods were of longer duration than during 1994-1998 (Table 4).

Table 4. Range of dates during which sampling was conducted for each cruise ID.

Cruise ID	Range of Dates 1991-1998	Range of Dates 1994-1998
HYJUN	June 21 – July 2	June 21 – June 30
WQJUL	July 5 – July 20	July 5 – July 11
HYJUL	July 18 – July 30	July 18 – July 25
WQAUG	July 29 – August 13	July 31 – August 8
HYAUG	August 14 – August 28	August 14 – August 22
WQSEP	August 29 – September 12	August 29 – September 12
HYSEP	September 7 – September 20	September 7 – September 20

Data Presentation

Time series of bottom water dissolved oxygen concentrations are organized and presented by basin and station (Appendix A). Where available, data are included from the year-round monthly monitoring to give a complete record of the annual bottom water DO cycle. In addition, data from the Interstate Sanitation Commission (ISC) are included to supplement the data set. Appendix B, also organized by basin and station, provides a summary of data from all fixed sampling stations. Mean minimum DO for each summer cruise (HYJUN, WQJUL, HYJUL, etc.) is plotted showing the general seasonal trend at each station. Also plotted are the highest and lowest minima for each cruise ID (i.e. the range) and the standard deviation associated with the mean. Appendix C is a series of maps, organized by year and cruise, showing the stations sampled and the estimated area of Long Island Sound with a) minimum dissolved oxygen concentrations less than 3.0 mg/L (area of hypoxia, in black), b) minimum DO concentrations between 3.0 and 5.0 mg/L (areas in gray), and c) minimum DO concentrations of 5.0 mg/L or greater (white areas).

Timing, Duration, and Area of Hypoxia

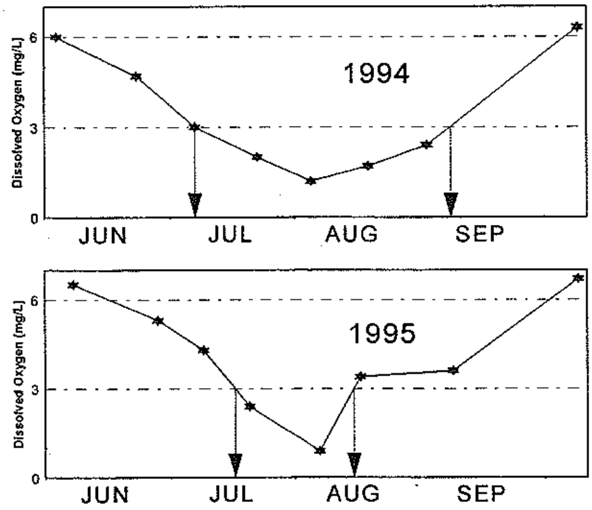


Figure 4. Bottom water dissolved oxygen observations at station B3, June through October 1994 (top) and 1995 (bottom). Arrows indicate approximate date (Julian date scale) of start and end of hypoxic event at this station.

The beginning and end dates of each annual hypoxic event in Long Island Sound were estimated using time series of bottom water dissolved oxygen concentrations at each station (Appendix A and Figure 4). Figure 4 shows two time series examples for station B3 from the summers of 1994, when duration of hypoxia was relatively long at 68 days, and 1995, when duration was short, at 35 days. Start and end dates were approximated for each station by determining the intersection of the time series line (drawn with straight lines connecting sequential observations) with the 3.0-mg/L grid line (Figure 4). The earliest start date and the latest end date derived by this method, regardless of station, provided the preliminary start and end date estimates for the year. Data available from other programs and agencies, as well as daily wind and precipitation records were then considered. Such supplementary data improved the date estimates by filling in gaps between sampling events and accounting for substantial wind or storm events that would likely have provided the energy necessary to mix the water column when such events occurred between an actual sampling date and an estimated date. The duration of hypoxia was then estimated as the number of days from the earliest estimated start date to the latest estimated end date.

The minimum dissolved oxygen concentration and the location of each station sampled during each cruise was entered into a Geographic Information System (ArcView) database and plotted on a map of Long Island Sound. The Spatial Analyst extension in ArcView was used to interpolate DO values between stations using the inverse distance weighted (IDW) method. In this way a grid of minimum DO values for the entire sound was generated. The area within each dissolved oxygen interval (0.0-0.99 mg/L, 1.0-1.99 mg/L, 2.0-2.99 mg/L, etc) was estimated by counting the number of cells in the grid with values in each interval then multiplying the number of cells by the area of each cell (approximately 0.1 square km). The estimated total area included in this analysis was based on a line drawn at approximately the 4.0 meter depth contour, with the exception of the western and eastern boundaries of the Sound and where the line crossed the mouth of large bays, harbors and rivers into which our sampling did not extend. This area boundary line can be seen on all of the maps in Appendix C. The total calculated study area was 2723 square kilometers (km^2).

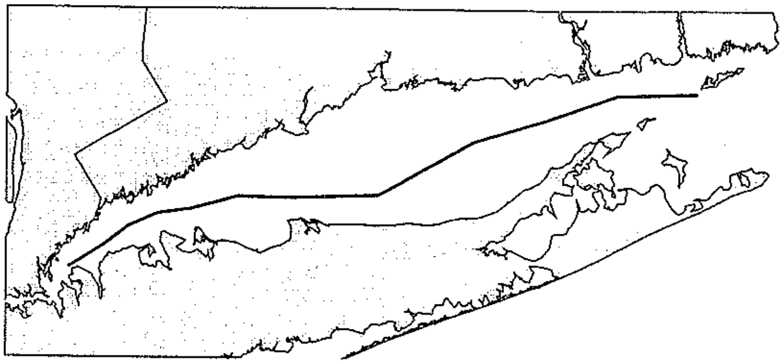


Figure 5. Map of Long Island Sound showing axial transect used for evaluating west to east distributions of dissolved oxygen, temperature, and salinity.

Axial Profiles

To review temperature, salinity, and dissolved oxygen data along the length of the Sound, a west-to-east axial transect was created by connecting twelve deep-water axial stations (Figure 5). A bathymetric profile of LIS was produced along this axial transect by identifying the maximum depth along each of a series of north-to-south transects drawn from points along the axial transect and separated by one nautical mile. The maximum depth at each of these points was determined from a 1983 NOAA 1:80,000 scale nautical chart using the mean low water depths. The resulting path of the west-to-east axial transect through Long Island Sound is shown in Figure 5 and approximates the thalweg of the Sound. This axial transect cross-section allows a graphical display of data to show surface-to-bottom and east-to-west differences in the water column throughout the length of Long Island Sound. By plotting temperature (isotherms), salinity, and dissolved oxygen data in this manner, differences in the pycnocline depth between stations and over time can be seen. Additionally, differences in the volume of water affected by hypoxia, between stations and over time, can be graphically represented. This report includes only a small number of these distribution plots by way of example (see *Vertical Dissolved Oxygen Distribution* and *Axial Profiles* sections of Results and Discussion).

Trend Analyses

Data from 1994 through 1998 were analyzed for significant trends in summer dissolved oxygen concentrations. Summer DO data from earlier years (pre-1994) were not included in this trend analysis because of the difference in sample design, in particular the use of random versus fixed station locations. The minimum dissolved oxygen concentrations observed for each station during each sampling event were first deseasonalized to remove the effects of serial correlation in the data (Bauer et al. 1984). A cruise mean and associated sample standard deviation were calculated for each station. To deseasonalize the data, the cruise mean was subtracted from each of the individual observations (measurements) to obtain the "deseasonalized" data. It was these data that were used for statistical trend analysis.

The deseasonalized data for dissolved oxygen concentrations from each station were put into a frequency distribution and were evaluated using a Chi-square test to determine whether they fit the normal distribution model. If the data set fit the normal distribution model, a seasonal linear regression (parametric method) was plotted, and a Student's t-distribution used to determine the significance of the slope (and thus whether a statistically significant trend existed). If the deseasonalized data set did not fit the normal distribution model a seasonal Kendall's test (nonparametric method) was used to determine whether a statistically significant trend existed. In such cases the Kendall slope estimator was used to estimate the rate of change. Trends were considered significant if the p-value was less than 0.05 (significance level of 95%).

The above-described analyses were applied to the 1994-1998 summer DO data from fixed stations sampled where sufficient data was available. In addition, data collected by the Interstate Sanitation Commission (ISC) (Interstate Sanitation Commission 1991 – 1998) were used to supplement CTDEP dissolved oxygen data in the western portions of Long Island Sound. An explanation of the stations sampled and the methods used in the ISC special survey, Ambient Water Quality Monitoring in Long Island Sound to Document Dissolved Oxygen Conditions, is available in ISC Annual Reports (ISC 1992 – 1999).

RESULTS/DISCUSSION

Schedule

Over the eight-year period from 1991 through 1998, and during the three-month period from mid-late June through mid-late September (*i.e.*, summer months), a total of 50 sampling cruises were conducted by the CTDEP (Tables 1 and 3). From 1991 through 1993, cruises conducted as a cooperative intra-agency effort to evaluate both the temporal and areal extent of hypoxia as well as the effect of dissolved oxygen concentrations on living resource abundance as estimated from trawl catches were included (Simpson et al. 1994). Beginning in 1994, the intensive summertime dissolved oxygen monitoring no longer included a living resource trawling component. The Department's Bureau of Water Management focused the intensive effort on observing dissolved oxygen concentrations throughout the Sound, with coincident measurements of additional chemical and physical water quality parameters.

CTD Profiles

Over all eight years a total of 1752 station profiles were taken. Figure 6 provides examples of the water column profile data obtained with the CTD, showing results from nine consecutive surveys from May through October 1996 at station D3. These profile data, in their entirety, are available for those wishing to pursue additional analyses.

General Dissolved Oxygen Observations

Generally, the patterns observed concerning dissolved oxygen concentrations in LIS were consistent from year to year and included:

- Stations exhibited a distinct seasonal pattern with respect to DO concentrations

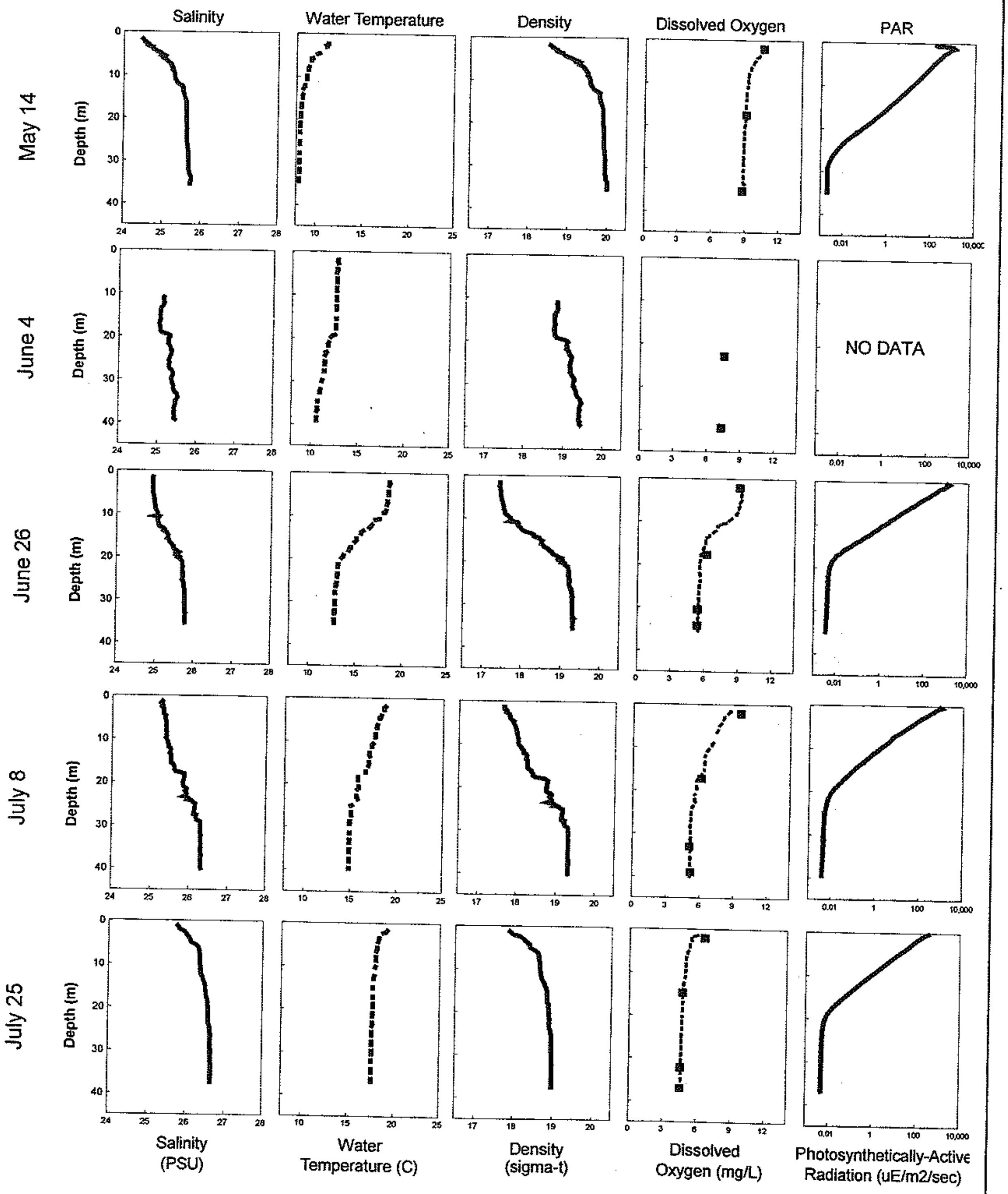


Figure 6. Continuous water column profiles at station D3, May through October 1996. Part 1: May through July. "■" shows the result of chemical titrations for dissolved oxygen on discrete water samples plotted over CTD profiling results.

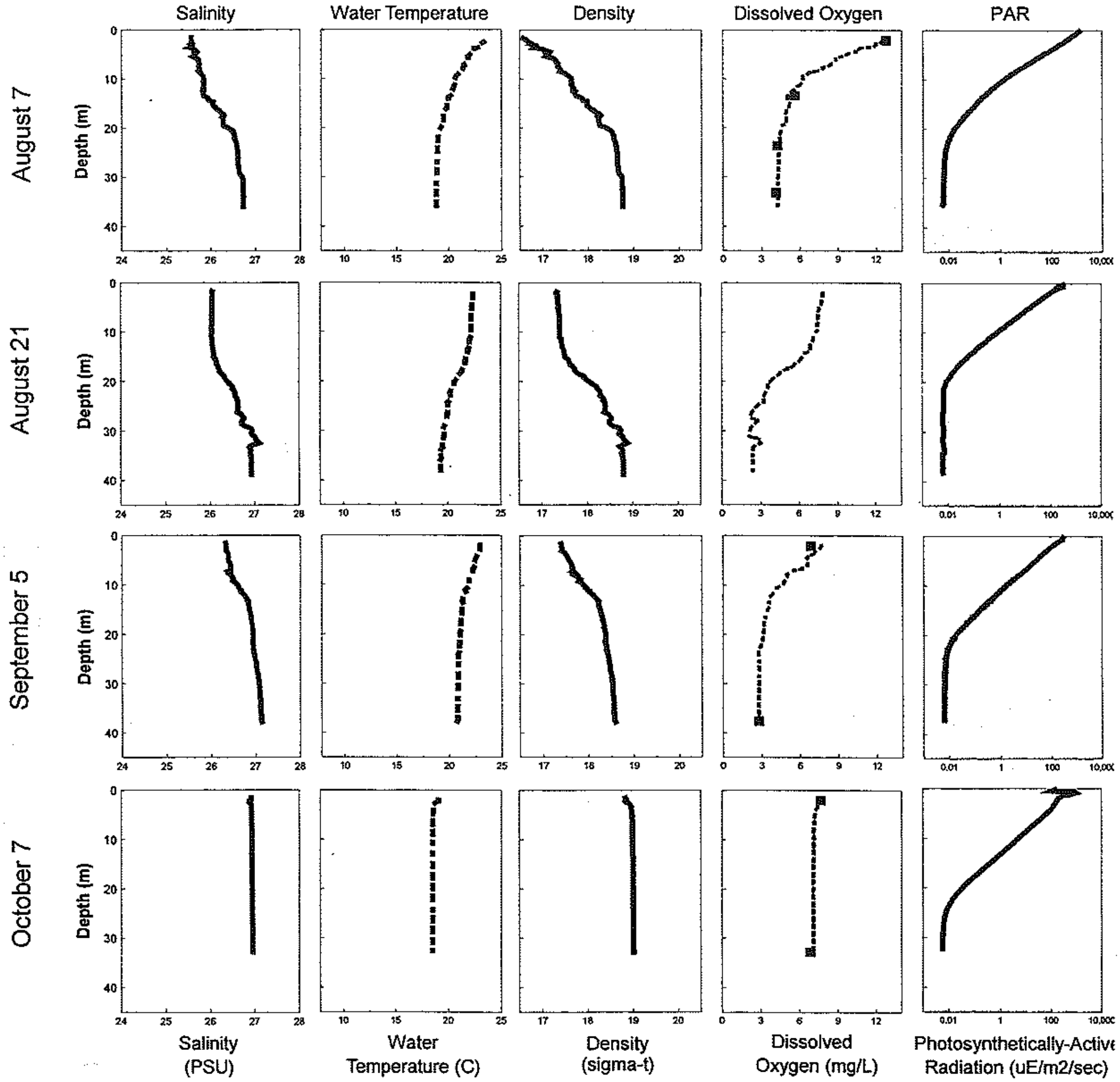


Figure 6 (continued). Continuous water column profiles at station D3, May through October 1996. Part 2: August through October.

- Lowest DO concentrations of the year were most often observed during August
- Maximum area of hypoxia was observed during August in all but one year (1998)
- The Narrows - hypoxic conditions were observed every year
- The Western Basin - hypoxic conditions were observed in all but one year (1997)

- Lowest DO concentrations were observed in western LIS and concentrations increased to the east

- The Central Basin - hypoxic conditions were observed in all but two years (1991 and 1997)

- The Eastern Basin – DO concentrations consistently at or above 5.2 mg/L at all but one station; hypoxia was observed only once, at Station 33, in 1994

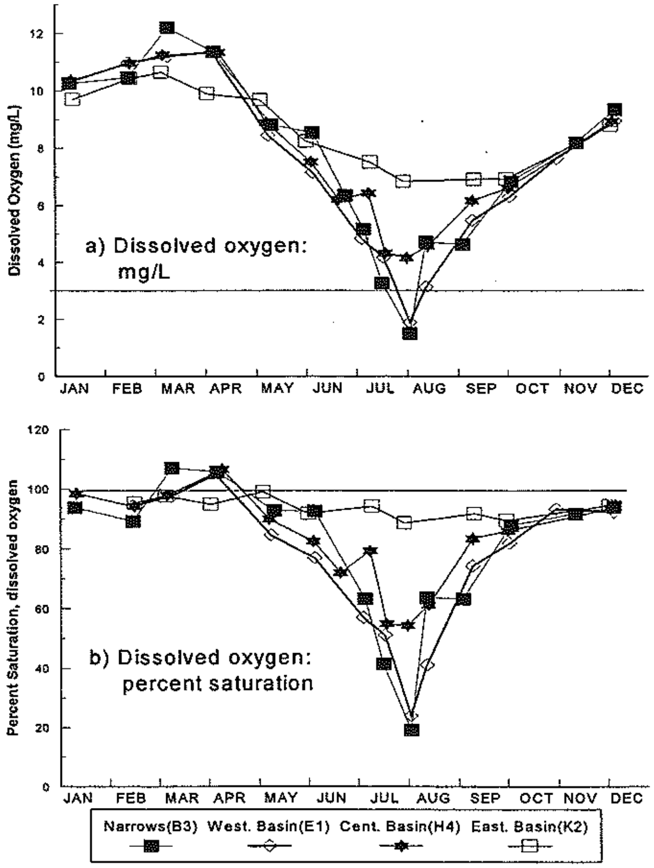


Figure 7. Bottom water dissolved oxygen a) concentration in mg/L, and b) percent saturation observed during 1995 at four stations, one from each basin in Long Island Sound.

Dissolved oxygen exhibited distinct seasonal patterns in LIS. Maximum DO concentrations were observed during the winter months and minimum concentrations were observed during the summer throughout the Sound (Figure 7a and Appendix A). Figure 7 shows annual bottom water DO patterns using 1995 data from four stations as examples. Evident from these data is the difference in bottom water DO between the western and eastern Sound. The western Sound (the Narrows) had somewhat higher DO concentrations during the late winter/early spring, when production was generally at its peak, and significantly lower DO concentrations than the eastern sound (the Eastern Basin) during the summer months. This pattern was repeated each year of the study. During the winter months concentrations of DO in both surface and bottom waters were near or above 100% saturation (Figure 7b). During the summer months percent saturation generally declined, especially in the bottom waters of the western and central Sound (Figure 7b).

The annual range in bottom water DO concentrations was larger at western stations than at eastern stations. Higher levels of nutrients in the western Sound support higher phytoplankton production and higher DO concentrations during the late winter/early spring bloom. Most of the difference in annual DO range between the western and eastern Sound however, is a result of the extreme difference between the summer lows. Stronger thermal stratification and larger organic loads delivered to the bottom waters in the west result in significant declines in DO concentration in the bottom waters there.

In general, DO concentrations were lowest in the bottom waters of the Narrows and Western Basin and improved eastward. Although this pattern holds true for the axial (deep-water) portion of LIS, the shallower areas frequently had lower DO concentrations during the summer period, especially in the Central Basin. Figure 8 shows the tendency for lower DO to develop in the shallower waters along the northern and southern boundaries of the Sound. Depth, however, was not the singular factor in the development of low dissolved oxygen conditions. Hypoxia was observed at stations that ranged in depth from shallow (less than 10 meters) to deep (greater than 40 meters). Location within LIS was more consistently related to the occurrence of low DO than depth. In general, the farther west the station, the greater likelihood for lower DO.

Stations in the Narrows and Western Basin of LIS generally had lower mean DO concentrations in the bottom waters throughout the summer than the Central and Eastern Basin stations (Figure 9). A mean was calculated for each basin using the minimum DO observed at each station

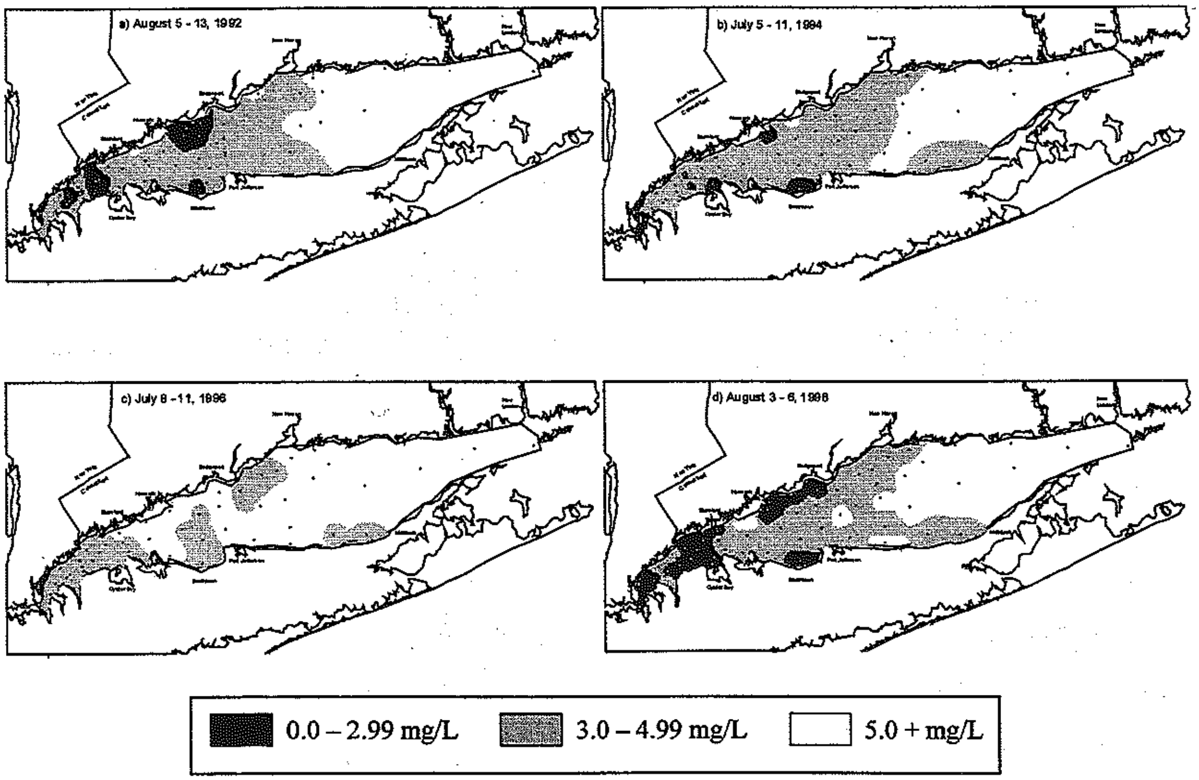


Figure 8. Areas of Long Island Sound affected by low dissolved oxygen concentrations during four individual cruises from four different years showing typical patterns.

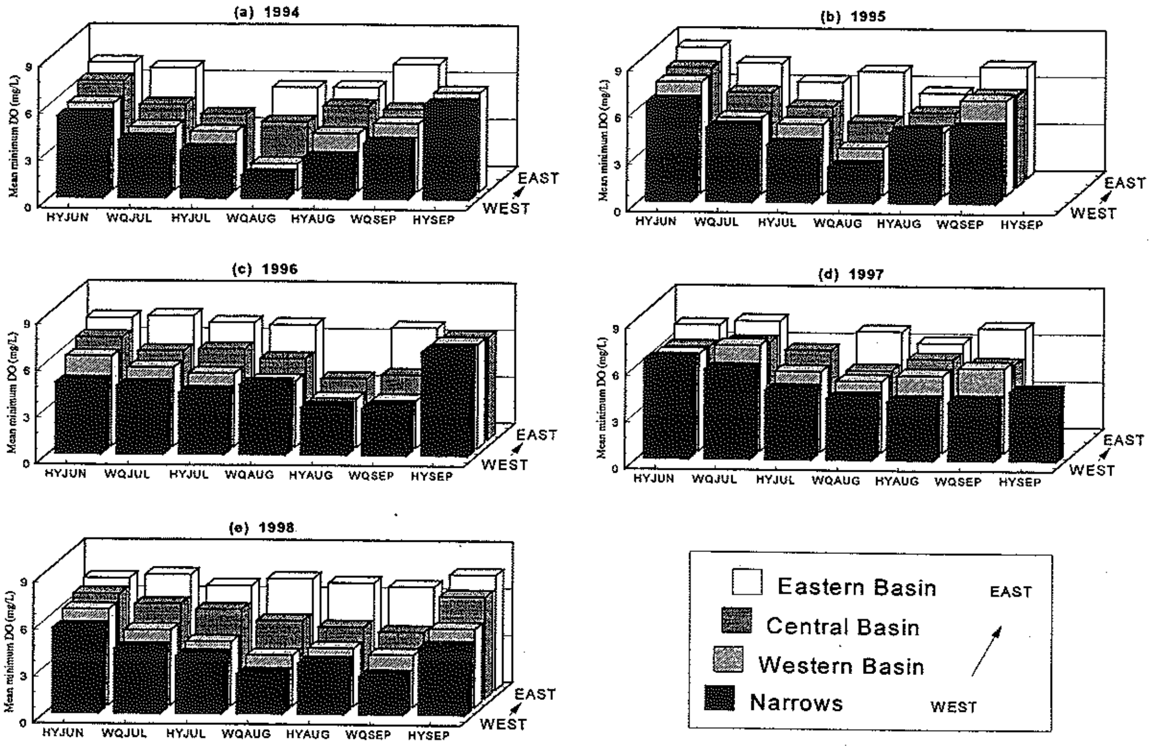


Figure 9. Mean minimum dissolved oxygen concentration in bottom waters by basin and cruise for the summers of (a) 1994, (b) 1995, (c) 1996, (d) 1997 and (e) 1998. The absence of a bar indicates insufficient or no data.

sampled. Lower DO concentrations were observed in the west and DO increased eastward during most cruise periods (Figure 9). The Eastern Basin consistently had the highest mean bottom DO concentrations. In fact, with a single exception, all the stations sampled in the Eastern Basin were at or above 5.2 mg/L. Station 33, at the southwestern edge of the Basin, regularly dropped below 5.0 mg/L, and even fell below 3.0 mg/L during the summer of 1994 (App. A: pp. 11-12).

Some portion of the Narrows experienced hypoxia every year (App. A: pp. 1-4). Some portion of the Western Basin experienced hypoxia in all years except 1997 when the smallest area affected was observed (App. A: pp. 5-6). Each station sampled in these regions exhibited hypoxic conditions at least once during the eight years of sampling. In comparison, the bottom waters of the Central Basin did not become hypoxic every year, and some stations in the Central Basin were never observed with DO concentrations below 3.0 mg/L (App. A: pp. 7-10).

Typically, the lowest bottom water DO concentrations were observed during the month of August. For the years 1994-1998 the minimum DO observed at each of the 48 stations during the biweekly summer sampling occurred 58% of the time during the first week of August, 17% the third week of August and 25% the first week of September. Additionally, the maximum bottom area impacted by low DO conditions was observed each year during the month of August, with the exception of 1998 when it occurred in early September. Of the 48 fixed

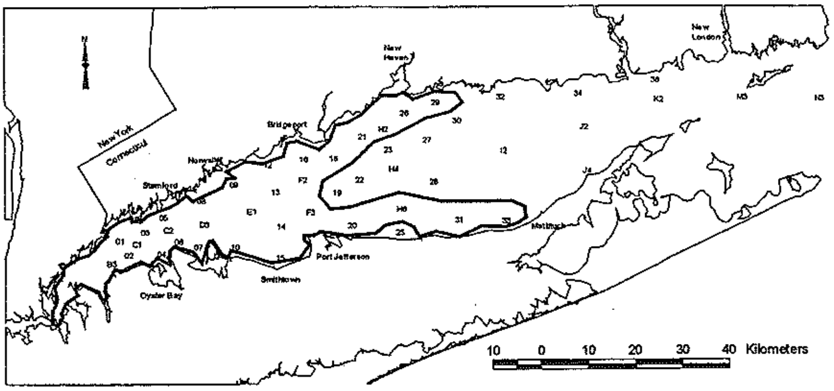


Figure 10. Long Island Sound station map showing stations (within the black-outlined area) that were observed with a DO concentration less than 3.0 mg/L at least once during the 1994-1998 period.

sampling stations (1994-1998), thirty-two became hypoxic at least once during the five-year period (Figure 10). Of these 32 stations, five had minimum observed DO concentrations of less than 1.0 mg/L; eleven had minimum observed DO between 1.0 and 1.99 mg/L; the remaining sixteen stations had minimum observed DO between 2.0 and 2.99 mg/L. Many of the minimum DO concentrations observed occurred during the summer of 1994 (cruise WQAUG94 in particular) when hypoxia was especially severe.

Summary of Summer Conditions by Year

1991

In the summer of 1991, four cruises were conducted between July 8 and September 12. The first sampling period was July 8 to July 18 (WQJUL91). In this period the minimum bottom water dissolved oxygen concentration observed was 3.1 mg/L in the Narrows. Although no hypoxia was observed at this time, the area with DO concentrations less than 5.0 mg/L was widespread, covering an area of approximately 960 square kilometers (km^2) encompassing most of the Narrows and Western Basin and a portion of the Central Basin (Table 5 and pp. C-1).

Hypoxia was observed at stations in western LIS during the second sampling period (WQAUG91, July 29 to August 13). Using the time series of DO concentrations at station A2 and weather conditions during this period, the onset of hypoxia was estimated to have begun on July 19. A continuous band of hypoxic bottom waters was observed through a large portion of the Narrows. An additional area in the Western Basin was also hypoxic (pp. C-1). The lowest DO concentrations observed all summer (1.4 - 1.6 mg/L) were observed on July 31 at 3 stations located in the Narrows and Western Basin. The total area affected by hypoxia during this period was 330 km^2, the maximum area of hypoxia observed during the summer of 1991, and 12% of the study area (Table 5 and Figure 11a). The total area with DO concentrations below 5.0 mg/L was 1541 km^2, over 56% of the study area (Table 5 and Figure 10a).

By the August 21-28 cruise (HYAUG91), hypoxia was limited to two deep water stations (22.7 and 37.6 meter depths) in the Western Basin, both with dissolved oxygen concentrations of 2.9

Table 5. Estimated area (square kilometers) of Long Island Sound affected by low dissolved oxygen in each of five 1.0 mg/L intervals during each cruise, 1991-1998*

YEAR	Dissolved Oxygen Interval mg/L	Sampling Cruise						
		HYJUN	WQJUL	HYJUL	WQAUG	HYAUG	WQSEP	HYSEP
1991	0.0-0.99	No cruise	-	No cruise	-	-	-	No cruise
	1.0-1.99		-		93	-	-	
	2.0-2.99		-		237	16	-	
	3.0-3.99		353		630	259	NO AREA ESTIMATE	
	4.0-4.99		607		581	409		
1992	0.0-0.99	-	-	-	-	-	-	No cruise
	1.0-1.99	-	3	2	19	-	-	
	2.0-2.99	-	14	69	205	20	-	
	3.0-3.99	NO AREA ESTIMATE	156	447	613	495	NO AREA ESTIMATE	
	4.0-4.99		620	982	506	547		
1993	0.0-0.99	-	3	-	-	-	▨	No cruise
	1.0-1.99	-	7	-	23	-	▨	
	2.0-2.99	-	25	14	495	126	▨	
	3.0-3.99	-	265	193	711	365	NO AREA ESTIMATE	
	4.0-4.99	54	959	854	344	752		
1994	0.0-0.99	-	-	-	73	-	-	-
	1.0-1.99	-	-	8	477	94	4	-
	2.0-2.99	-	100	248	472	260	85	-
	3.0-3.99	NO AREA ESTIMATE	397	1054	530	596	530	NO AREA ESTIMATE
	4.0-4.99		952	545	295	489	840	
1995	0.0-0.99	-	-	-	48	-	-	No cruise
	1.0-1.99	-	-	-	135	-	-	
	2.0-2.99	-	-	111	607	2	-	
	3.0-3.99	-	24	241	554	821	9	
	4.0-4.99	19	624	1027	245	704	424	
1996	0.0-0.99	-	-	-	-	-	13	-
	1.0-1.99	-	-	-	-	70	79	-
	2.0-2.99	-	-	-	-	499	462	-
	3.0-3.99	NO AREA ESTIMATE	96	207	153	730	704	NO AREA ESTIMATE
	4.0-4.99		570	540	1180	528	456	
1997	0.0-0.99	-	-	-	-	-	-	-
	1.0-1.99	-	-	-	-	6	-	-
	2.0-2.99	-	-	-	9	71	▨	-
	3.0-3.99	-	12	63	223	210	NO AREA ESTIMATE	NO AREA ESTIMATE
	4.0-4.99	34	53	513	1330	630		
1998	0.0-0.99	-	-	-	18	-	-	-
	1.0-1.99	-	-	-	92	21	90	-
	2.0-2.99	-	33	86	203	212	346	-
	3.0-3.99	NO AREA ESTIMATE	82	307	376	884	634	53
	4.0-4.99		647	617	696	399	578	587

* " -" indicates no observations within the associated DO interval (area = zero); shaded areas indicate the presence of hypoxia.

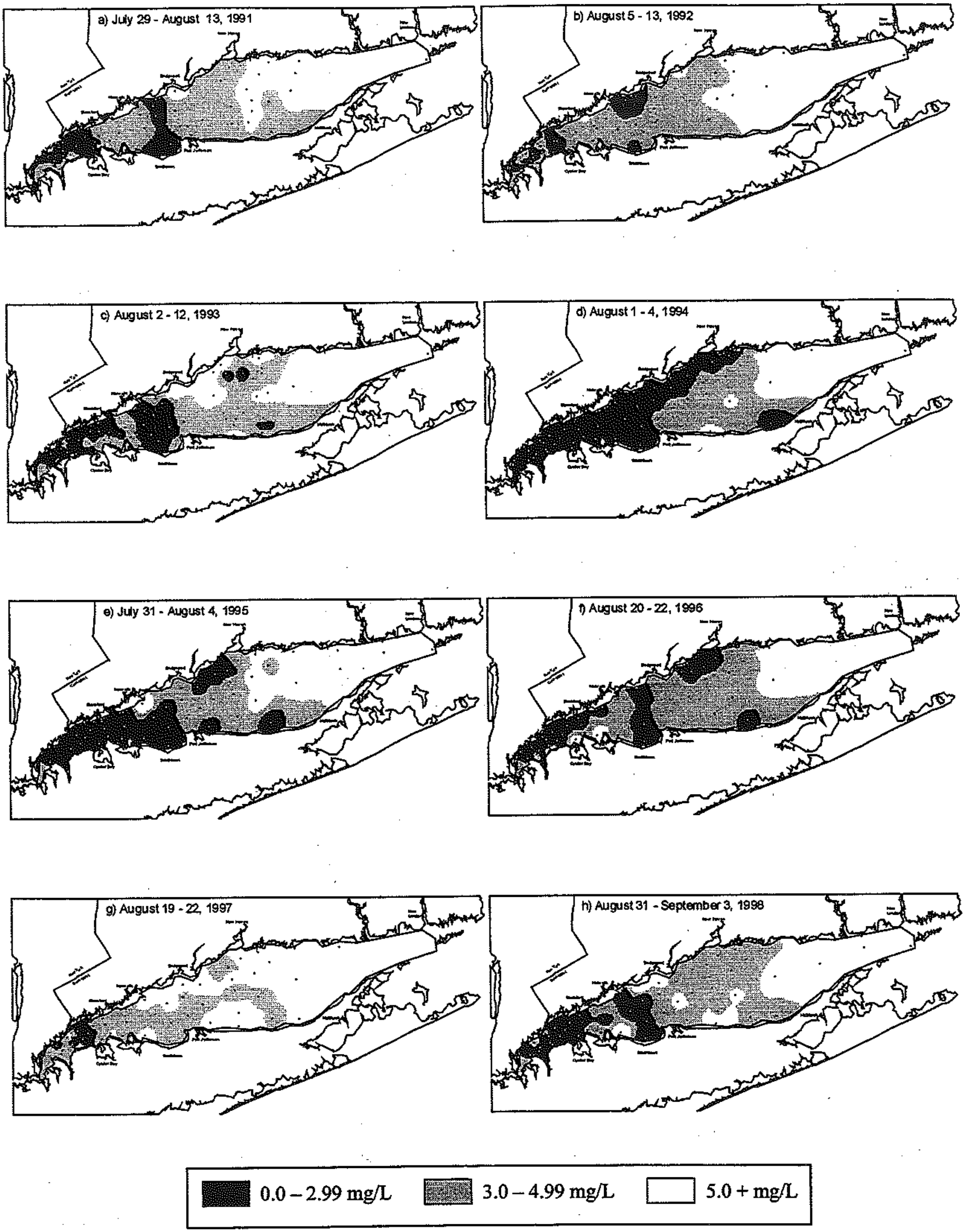


Figure 11. Maps of Long Island Sound showing areas affected by low dissolved oxygen concentrations during the peak hypoxic event (largest area with DO less than 3.0 mg/L) in each of the eight years 1991 through 1998.

mg/L (pp. C-1). No hypoxia was observed during the September 4-12 (WQSEP91) sampling period. Using the time series of DO concentrations at the two stations that were hypoxic on the prior cruise, data from other researchers, and weather conditions during this period it was estimated that low dissolved oxygen conditions persisted through August 28, for a duration of 41 days in the summer of 1991.

1992

In 1992 six cruises were conducted between June 29 and September 9. The first cruise was conducted from June 29 to July 2 (HYJUN92) and the lowest DO concentration observed was 3.9 mg/L at one station in the Narrows. During this cruise the only locations that had DO concentrations below 5.0 mg/L were an area in the Narrows and two additional isolated sites in the Western Basin (pp. C-2). By the July 7-20 sampling period (WQJUL92), the area with DO concentrations of less than 5.0 mg/L had increased, encompassing most of the Narrows and Western Basin and extending slightly into the Central Basin (pp. C-2). Hypoxia was observed at two stations in the Narrows during this sampling period, and the lowest DO concentration observed was 1.7 mg/L. Using the time series of DO concentrations at the two stations that were hypoxic on the cruise, the onset of hypoxia was estimated to have begun on July 7.

During the last week of July (HYJUL92), hypoxia was observed in the Narrows and in an isolated area in the Western Basin. The total area with DO concentrations less than 3.0 mg/L was 71 km^2 (Table 5). The area with DO concentrations below 5.0 mg/L continued to increase, expanding into shallower waters of the Western Basin and extending well into the Central Basin, for a total area of 1500 km^2, or 55% of the study area (Table 5 and pp. C-2). During the sampling period of August 5-13 (WQAUG92), the lowest DO concentrations of the year were observed, with observations at two stations below 2.0 mg/L. A minimum DO concentration of 1.2 mg/L was observed in the Narrows. The hypoxic area was the largest of the year during this sampling period, but was still made up of relatively small, isolated areas in the Narrows and Western Basin encompassing 224 km^2, 8% of the study area (Table 5, Figure 11b and C-2).

By the August 24-28 cruise (HYAUG92), DO concentrations had increased throughout the Sound. However, a few isolated areas with DO concentrations between 2.3 and 2.9 mg/L in the bottom waters remained, as did an extensive area with concentrations between 3.0 and 5.0 mg/L (pp. C-3). During a monthly water quality cruise conducted September 1-2, no DO concentrations less than 3.0 mg/L were observed, but the areas that remained hypoxic the previous week were not sampled during this cruise. Using the time series of DO concentrations at the stations that were hypoxic during the previous sampling period, weather patterns and data from other researchers, it was estimated that low dissolved oxygen conditions persisted through August 30, for a duration of 55 days in the summer of 1992. Although low DO conditions were not observed during the first week of September, supplemental data from the CTDEP Fisheries Division (Simpson et al., 1994) show an isolated shallow area in the Narrows (Hempstead Harbor) to be hypoxic. That area was above 3.0 mg/L on August 25 and may have become hypoxic for a short period of time in September because of weather patterns that influenced this shallow water station. In general, low dissolved oxygen conditions persisted in the Sound for a long period during the summer of 1992, but the area affected was not extensive.

1993

In 1993 six cruises were conducted between June 28 and September 9. The first cruise was conducted from June 28 to July 2 (HYJUN93) and DO concentrations below 5.0 mg/L were limited to two small isolated areas, one in the Narrows and one in the Western Basin. During the next cruise (WQJUL93, July 7 -15) hypoxia was observed at three isolated, shallow (less than 20 meters) stations in the Narrows. The lowest DO concentration observed was 0.9 mg/L in the western Narrows. This was the earliest date that such a low DO concentration (less than 1.0 mg/L) was observed during this study. Using the time series of DO concentrations at the stations that were hypoxic on the cruise, data from other researchers, and weather conditions during this period, the onset of hypoxia was estimated to have begun on July 4. Besides the hypoxic conditions, the area having bottom DO concentrations between 3.0 and 5.0 mg/L was very widespread, extending through the Narrows and Western Basin and into the Central Basin (pp. C-4).

Although in the July 26-29 cruise (HYJUL93) the area of LIS below 5.0 mg/L increased eastward to include more of the Central Basin, all of the three locations in the Narrows that were hypoxic on the previous cruise showed increased bottom water DO concentrations. Three other locations in the Narrows had DO concentrations fall below 3.0 mg/L, so that hypoxia continued to affect small isolated areas. During the August 2-12 sampling period (WQAUG93), hypoxic conditions became widespread, extending through the Narrows, a significant portion of the Western Basin, and including some isolated areas in the Central Basin. The total area affected by hypoxia at this time was 518 km^2, or 19% of the study area (Table 5, Figure 11c and pp. C-4). The minimum DO concentration observed was 1.8 mg/L in the Narrows. The area of dissolved oxygen concentrations below 5.0 mg/L increased to 1573 km^2, 58% of the study area, having spread north and east in the Central Basin and into the southwest edge of the Eastern Basin.

By the August 17-26 cruise (HYAUG93), there had been an increase in DO concentrations throughout the Sound. Hypoxia was limited to a 126-km2 area in the deep waters of the Western Basin, with DO concentrations ranging from 2.6-3.0 mg/L. A significant area, 1243 km^2, extending through the Narrows and the Western and Central Basins, continued to exhibit DO concentrations below 5.0 mg/L. During the September 7-8 water quality cruise, hypoxia was recorded at stations B3 and D3 (both in the Narrows) with DO concentrations of 0.7 and 2.1 mg/L, respectively (pp. C-5). The DO concentration at station B3, 0.7 mg/L, was the lowest value recorded during 1993. No hypoxia was observed during the next monthly water quality cruise, conducted October 5-6. Using the time series of DO concentrations at the stations that were hypoxic on the previous cruise, data from other researchers and weather conditions during this period it was estimated that low DO conditions persisted through September 19, for a duration of 78 days in the summer of 1993. This was the latest end date and the longest duration of hypoxia during the eight years of this study.

1994

In 1994 seven cruises were conducted from June 21 - September 8. During the first cruise, conducted June 21-23 (HYJUN94), dissolved oxygen concentrations below 5.0 mg/L were observed in the Narrows and Western Basin (pp. C-6). The lowest value observed was 4.1 mg/L at Station 15 in the Western Basin. By the July 5-11 cruise (WQJUL94), DO concentrations had decreased throughout the Sound, and hypoxia was observed in isolated areas of the Narrows and the Western Basin. The area affected by hypoxia (approximately 100 km^2) was split into widely scattered and relatively shallow (10.4-18.1 meters depth) areas. Using the time series of DO concentrations at the stations that were hypoxic on this cruise, data from other researchers and weather conditions during this period, it was estimated that the onset of hypoxia was July 1, which was the earliest of the eight years included in this survey. A large area with DO levels less than 5.0 mg/L (1448 km^2) extended through the Narrows, the Western Basin, a significant portion of the Central Basin and into the southwest edge of the Eastern Basin (Table 5 and pp. C-6).

As July progressed, the hypoxic areas increased with the area affected by hypoxia during the July 20-22 cruise (HYJUL94) including a large portion of the Narrows and a small area in the deep water of the Western Basin. The total area below 3.0 mg/L had increased to 256 km^2 and the area less than or equal to 5.0 mg/L had also increased to 1850 km^2. Station 02 in the Narrows had the lowest DO concentrations of the cruise at 1.9 mg/L.

During the August 1-4 cruise (WQAUG94), severe low DO conditions were observed in the Narrows and the Western Basin. Dissolved oxygen concentrations of between 0.6 and 0.9 mg/L were observed at five stations in the Narrows and Western Basin. Hypoxia was extensive and continuous throughout the Narrows, most of the Western Basin, well into the northern portion of the Central Basin, and even affected an area in the southwest portion of the Eastern Basin (Figure 11d and pp. C-6). This was the largest hypoxic area observed during this study, at 1022 km^2, 37.5% of the study area (Table 5). The lowest DO concentration observed was 0.6 mg/L at station 15 in the Western Basin. By the August 16-18 cruise (HYAUG94), the area affected by hypoxia had decreased significantly, to 354 km^2. Hypoxia was observed in the Narrows, and the Western and Central Basins, however these areas of hypoxia were now isolated. Dissolved oxygen concentrations had increased to above 3.0, and in some cases even above 5.0 mg/L in much of the area in the Western, Central, and Eastern Basins that had been hypoxic during the previous cruise (pp. C-7).

By the August 29 - September 1 cruise (WQSEP94) hypoxia was restricted to the Narrows. However, the area with DO concentrations between 3.0 and 5.0 mg/L had again increased in size to include again a large portion of the Central Basin. The lowest DO observed was 1.9 mg/L at station A2 in the Narrows. During the September 7-8 cruise (HYSEP94), no hypoxia was observed, and only one station sampled had a bottom DO concentration of 5.0 mg/L. Using the time series of DO concentrations at the stations that were hypoxic on the previous cruise, data from other researchers and weather conditions during this period, it was estimated that low dissolved oxygen conditions persisted through September 6, for a duration of 68 days for the summer of 1994.

1995

During the summer of 1995, six cruises were conducted between June 22 and September 12. The first cruise was from June 22 – 27 (HYJUN95) and only one station in the Narrows had a bottom DO concentration below 5.0 mg/L, at 4.6 mg/L. During the July 6 - 11 cruise (WQJUL95) DO values below 5.0 mg/L were observed in the Narrows, Western Basin, and into the Central Basin, for a total area of 648 km^2, but no hypoxia was observed. A week later, during the July 18 - 20 cruise (HYJUL95), the first DO concentrations below 3.0 mg/L were documented in the Narrows, with a total hypoxic area of 111 km^2 (Table 5 and pp. C-8). The area with bottom DO concentrations less than or equal to 5.0 mg/L had also increased, to 1379 km^2, expanding further into the Western and Central Basins, and extending into the southwestern edge of the Eastern Basin. Using the time series of DO concentrations at the hypoxic stations, data from Interstate Sanitation Commission (ISC 1996), and weather conditions during this period, the onset of hypoxia was estimated to have begun on July 12.

During the cruise conducted July 31 - August 4 (WQAUG95), hypoxia was widespread (Figure 10e and pp. C-8). Hypoxic conditions extended continuously through the Narrows and much of the Western Basin, and were additionally observed in three isolated areas in the Central Basin, for an estimated area of 790 km^2, or 29% of the study area (Table 5 and Figure 11e). Dissolved oxygen concentrations below 1.0 mg/L were observed at stations A4 and B3 in the Narrows, with concentrations of 0.8 and 0.9 mg/L, respectively. Severe low dissolved oxygen conditions (1.0-1.9 mg/L) were observed at four additional stations in the Narrows and the Western Basin.

By the August 14-16 cruise (HYAUG95), hypoxia was limited to a single station (A4) in the western Narrows, but the area with DO concentrations below 5.0 mg/L continued to be extensive, at 1545 km^2, almost 57% of the study area (Table 5 and pp. C-9). During the cruise conducted September 5-12 (WQSEP95), no hypoxia was observed in LIS. Using the time series of dissolved oxygen concentrations at station A4 (the only station hypoxic during the August 14-16 cruise) and the weather conditions favorable to the breakup of hypoxia created by Hurricane Bertha, it was estimated that low dissolved oxygen conditions persisted through August 15, for a duration of 35 days in the summer of 1995.

1996

In 1996, seven cruises were conducted from June 25 through September 20. During the first cruise conducted from June 25-27 (HYJUN96), the minimum dissolved oxygen concentration was 3.1 mg/L observed at Station 02 in the Narrows. During the July 8-11 cruise (WQJUL96), the DO concentrations in the Narrows were similar to those recorded during the prior cruise. In addition, isolated locations in the Western and Central Basins had decreased to 5.0 mg/L or less, increasing the total area less than 5.0 mg/L to approximately 666 km^2 (Table 5 and pp. C-10). By the July 22-25 cruise (HYJUL96), the area below 5.0 mg/L increased slightly (747 km^2), so that this area was continuous through the Narrows and Western Basin and into the Central Basin. No hypoxia was observed (pp. C-10).

By the August 5-8 cruise (WQAUG96), the area with dissolved oxygen concentrations of 5.0 mg/L or less had expanded into more of the Central Basin, and into the Eastern Basin. Although the size of the area affected by DO concentrations of 5.0 mg/L or less was extensive at 1333 km^2 (49% of the study area) no hypoxia was observed (Table 5 and pp. C-10). The lowest DO observed was 3.4 mg/L. This was the only summer during the eight-year period (1991-1998) that hypoxia was not observed by the first week of August. Typically, early August was the period when maximum areas were affected by hypoxia.

By the August 20-22 cruise (HYAUG96), hypoxic conditions had developed through the Narrows and part of the Western and Central Basins, with a total area with DO concentrations of 3.0 mg/L or less of 569 km^2, or 21% of the study area (Table 5, Figure 11f and pp. C-11). Dissolved oxygen concentrations in the Narrows and Western Basin dropped to levels below 2.0 mg/L at six stations (A4, A5-ISC, B3, E1, 12, and 14). Using the time series of DO concentrations at the stations that had DO concentrations below 3.0 mg/L, the hot and humid weather patterns during and prior to this period, and observations made by other researchers (Simpson et al 1997 and ISC 1997), the onset of hypoxia was estimated to have begun on August 10, which was the latest estimated onset date in the eight-year period.

By the September 3-6 cruise (WQSEP96), the area with dissolved oxygen concentrations of 3.0 mg/L or less (554 km^2), was similar to that observed during the previous cruise, although some very severe low DO concentrations, less than 1.0 mg/L, were observed where there had been none previously (Table 5). There were no longer any hypoxic areas observed in the Central Basin, but hypoxia persisted in the Narrows and Western Basin (pp. C-11). Dissolved oxygen concentrations had increased above 3.0 mg/L at some stations (12, E1, H2, and 31), but had decreased at other stations, dropping below 1.0 mg/L at stations A4, B3, and 02 in the Narrows. During the September 20 cruise (HYSEP96) all stations that were significantly below 3.0 mg/L during the prior cruise were sampled and all had DO values above 5.6 mg/L. Using the time series of DO concentrations at the stations sampled during the September 20 cruise, data from the Interstate Sanitation Commission's September 9 and 16 cruises (ISC 1997), and weather conditions during this period, it was estimated that hypoxic conditions persisted through September 12, for a duration of 34 days in the summer of 1996.

1997

During the summer of 1997, seven cruises were conducted between June 27 and September 17. The first cruise was conducted from June 27 – 30 (HYJUN97) and only three stations had DO levels below 5.0 mg/L (A4, B3, and 15, with 4.6, 4.8 and 4.8 mg/L respectively). The next sampling cruise was conducted July 8-9 (WQJUL97) and the conditions observed were similar to the previous cruise. The lowest observation was at station A4, which had a DO concentration of 3.7 mg/L. Only three additional stations (B3, 01, and 02) had concentrations below 5.0 mg/L.

By the July 22-24 cruise (HYJUL97) the area of LIS that had DO levels below 5.0 mg/L had increased to 576 km^2 in the Narrows, Western Basin and Station 22 in the Central Basin (Table 5 and pp. C-12). Although DO concentrations less than 5.0 mg/L became prevalent, no areas fell below 3.0 mg/L. The lowest DO concentration observed was 3.0 mg/L at Station A5 sampled by

ISC. Two CTDEP stations, A4 and B3, had similar concentrations, with 3.2 and 3.1 mg/L respectively.

Hypoxia was first observed during the August 4-7 cruise (WQAUG97) at station A4, with a DO concentration of 2.5 mg/L. It was estimated from the DO time series from station A4, supplementary data from Interstate Sanitation Commission (ISC 1998), and the hot/still weather patterns during and prior to this period, that the onset of hypoxia probably had occurred on July 26. In addition to the hypoxic area, the area that had DO concentrations less than 5.0 mg/L increased significantly in size to encompass more than 1562 km^2, or over 57% of the study area (Table 5 and pp. C-12). By the August 19-22 cruise (HYAUG97), the hypoxic area had increased to 77 km^2, or less than 3% of the study area (Table 5, Figure 11g and pp. C-13). The DO concentration at station A4, previously hypoxic, had increased to 4.3 mg/L, but six other stations (B3, 01, 02, C1, B2-ISC and H-B-ISC) had experienced a decline in DO and were hypoxic. Station 02 had the lowest oxygen concentration (1.9 mg/L) for the cruise and for the year. In contrast to the increase in hypoxic area, the area less than 5.0 mg/L decreased to 917 km^2.

During the September 2-5 cruise (WQSEP97), hypoxia was observed at only two stations in the Narrows, A4 and 02, with DO concentrations of 2.3 and 2.5 mg/L respectively. There was not sufficient coverage in the Narrows to permit an acceptable area estimate. By the September 17 cruise (HYSEP97), no hypoxia was observed in Long Island Sound and the area with DO concentrations below 5.0 mg/L was confined to the Narrows. Using DO time series from stations A4 and 02, supplementary data from Interstate Sanitation Commission (ISC 1998), and the weather patterns during and prior to this period, it was estimated that hypoxia ended on September 12, for a duration of 48 days during the summer of 1997.

1998

In 1998, seven cruises were conducted between June 24 and September 17. The first cruise was conducted from June 24 - 26 (HYJUN98) and only four stations in the Narrows had DO concentrations below 5.0 mg/L (A4, B3, 02, and C1). The next sampling cruise was conducted from July 6-9 (WQJUL98) and hypoxic conditions were present at four stations in the Narrows (A4, 02, 04 and B4-ISC). It was estimated that the onset of hypoxia in Long Island Sound occurred on July 5. The hypoxic area was estimated at 33 km^2 and the area of DO concentration less than 5.0 mg/L was 762 km^2 (Table 5 and pp. C-14).

Observations made during the July 21-23 cruise (HYJUL98) showed the area of bottom waters with DO concentrations under 5.0 mg/L had increased to 1010 km^2, while the hypoxic area had increased to 86 km^2 (Table 5 and pp. C-14). The hypoxic area in the Narrows had persisted and an additional isolated location in the Western Basin (station 15) was also hypoxic. By the August 3-6 cruise (WQAUG98), DO conditions had worsened in the Sound. Two stations, A4 in the Narrows and 09 in the Western Basin had very severe low DO concentrations. The bottom water DO concentration at station A4 was 0.3 mg/L, which was the lowest concentration observed during this eight-year survey. Station 09 had a DO level of 1.0 mg/L in the bottom waters. Additional areas in the Western Basin were also hypoxic during this cruise. The total hypoxic area encompassed 313 km^2 (11.5% of the study area) and the area of DO concentrations below 5.0 mg/L increased to 1385 km^2 (51%) (Table 5 and pp. C-14). Although the maximum hypoxic area for the year occurred later (see below), the maximum area observed with DO less than 1.0 mg/L and the maximum area with DO less than 2.0 mg/L both occurred during this cruise (Table 5).

By the August 17-21 cruise (HYAUG98) the overall DO conditions in the Sound had improved. No stations were observed with severe conditions and the hypoxic area decreased slightly to 233 km^2 (Table 5 and pp. C-15). The area of the Sound with DO concentrations below 5.0 mg/L had increased somewhat to 1516 km^2. Although DO concentrations had increased at most stations in the Narrows and Western Basin, DO concentrations had decreased at most stations in the Central and Eastern Basins.

By the next cruise, August 31 - September 3 (WQSEP98), DO conditions had worsened again. The hypoxic area increased to the maximum for the year at 436 km^2 (16% of the study area), as did the area below 5.0 mg/L, which increased to 1648 km^2 (60.5%) (Table 5 and Figure 11h). 1998 had the latest maximum hypoxic area (during the WQSEP98 cruise) of all eight years (Table 5). Conditions improved greatly by the next sampling cruise (HYSEP98, September 15-17). No stations were hypoxic and the lowest DO concentration observed was 3.1 mg/L at station A4 in the Narrows. Although there were no hypoxic areas, the area with DO concentrations under 5.0 mg/L still encompassed 640 km^2. Using the time series of the stations that were hypoxic on the previous cruise, it was estimated that hypoxic conditions in LIS persisted until September 15. Therefore, the duration of hypoxia in the Sound was estimated at 73 days for the summer of 1998.

Trends in Timing and Duration of Hypoxia

The estimated start date of hypoxia in LIS over the eight years, 1991-1998, ranged from July 1 (Julian date 182) in 1994, to August 10 (Julian date 223) in 1996, a difference of 41 days (Table 6 and Figure 12). The mean start date was July 15(±14 days). The end date of hypoxia also varied annually, ranging from August 15 in 1995, to September 19 in 1993 (a difference of 36 days). The mean end date was September 6(±12 days).

The duration of hypoxia also varied annually, from the shortest duration in 1996 of 34 days, to the longest duration in 1993 of 78 days (Table 6 and Figure 12). The average duration over the eight years was 54 days (±17 days).

These results were compared with previous studies of hypoxia in Long Island Sound from 1987 - 1990 (Welsh and Welsh, 1992) (Table 7). The earlier studies generally show estimated start and end dates of hypoxia within the range seen in the current study. The exceptions are that two years (1988 and 1989) had later end dates, extending the latest observed end date to September 30 in 1988. The 82-day duration of hypoxia observed in 1989 was longer than any observed through 1998.

Table 6. Estimates of area and duration of hypoxia (dissolved oxygen concentrations less than 3.0 mg/L) in Long Island Sound 1991-1998.

Year		Estimated Start Date	Estimated End Date	Maximum Area (km^2)	Percent of Study Area	Duration (days)
1991	Calendar date	July 19	August 28	330	12.1	41
	Julian date	200	240			
1992	Calendar date	July 7	August 30	224	8.2	55
	Julian date	189	243			
1993	Calendar date	July 4	September 19	518	19.0	78
	Julian date	185	262			
1994	Calendar date	July 1	September 6	1022	37.5	68
	Julian date	182	249			
1995	Calendar date	July 12	August 15	790	29.0	35
	Julian date	193	227			
1996	Calendar date	August 10	September 12	569	20.9	34
	Julian date	223	256			
1997	Calendar date	July 27	September 12	77	2.8	48
	Julian date	208	255			
1998	Calendar date	July 5	September 15	436	16.0	73
	Julian date	186	258			
1991-1998 Mean ±SD	Calendar date	**July 15**	**September 6**	**496 ±305**	**18.2 ±11**	**54 ±17**
	Julian date	**196 ±14 days**	**249 ±12 days**			

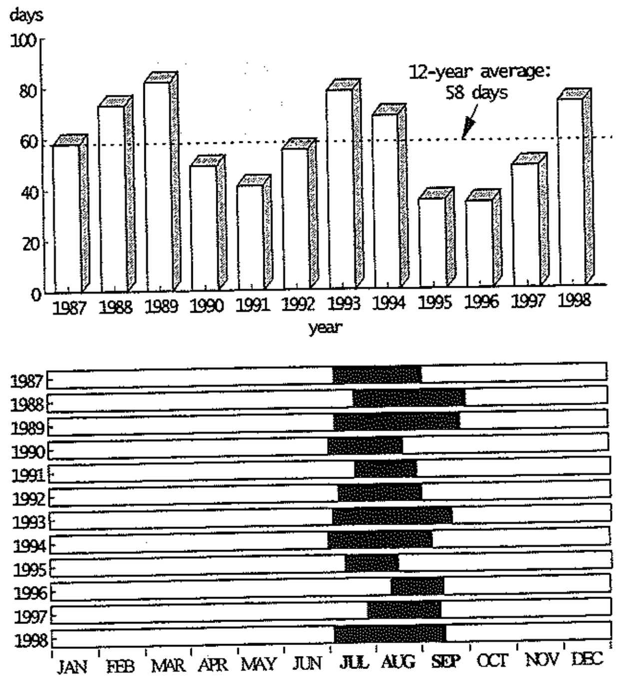


Figure 12. Duration in days (top) and timing (bottom) of hypoxia in Long Island Sound, 1987 through 1998. 1987 through 1990 data from Welsh and Welsh, 1992.

If all twelve years of data are considered (1987-1998), hypoxia has been observed from as early as July 1 in 1994 (the earliest estimated onset) to as late as September 30 in 1988 (the latest estimated end date). The average duration over all twelve years was 58 days with a standard deviation of 17 days.

There appeared to be a cyclic pattern to the duration data, with peaks occurring in 1988-1989, 1993-1994, and again in 1998 (Figure 12). Also apparent from the data was a relationship between the date of onset of hypoxia and the duration. Clearly, the potential for a longer duration existed when the date of onset was early. In fact, the data show that the earlier hypoxia developed in the Sound, the more likely it was that the duration would be long (Figure 13). The three years with the earliest onset dates (1993, 1994 and 1998) were also the years with the longest duration of hypoxia (Table 6). 1996 had the latest onset date (August 10) and the shortest duration (34 days) (Table 6).

Table 7. Estimates of duration of hypoxia (dissolved oxygen concentrations less than or equal to 3.0 mg/L) in Long Island Sound 1987-1990. Data from Welsh and Welsh, 1992.

Year		Estimated Start	Estimated End	Duration (days)
1987	Calendar date	July 6	September 1	58
	Julian date	187	244	
1988	Calendar date	July 18	September 30	73
	Julian date	200	273	
1989	Calendar date	July 6	September 25	82
	Julian date	187	268	
1990	Calendar date	July 2	August 20	49
	Julian date	183	232	
1987-1990 Mean ±SD	Calendar date	**July 8**	**September 11**	**65 ±15**
	Julian date	**189 ± 7 days**	**254 ±19 days**	

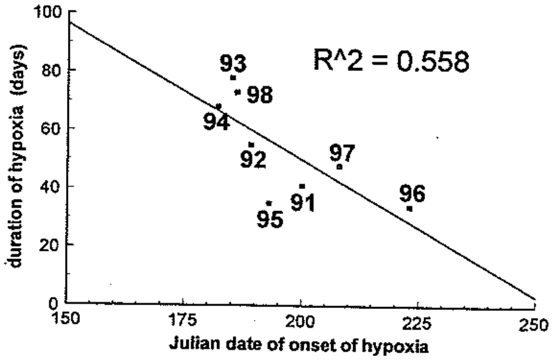


Figure 13. Relationship between the date of onset and the duration of hypoxia, 1991-1998.

Patterns in Hypoxic Area

The maximum area affected annually by hypoxia (dissolved oxygen concentration of 3.0 mg/L or less) for the years 1991-1998 ranged from a low of 77 km^2 during the height of the 1997 event, to a high of 1022 km^2 in 1994, with a mean of 496 km^2 (±305 km^2) (Table 6 and Figure 14c). The percent of the study area of LIS impacted ranged from 3 - 38% with a mean of 18% (Table 6).

From 1991 through 1995, the maximum area of hypoxia was observed between July 29 and August 13 (Table 5). In 1996, an unusually late onset of hypoxia was observed (22 days later than any other year) and the maximum area affected by hypoxia was observed during August 20-22. The timing of the peak area affected by hypoxia was also later in 1997 (August 19-22) and 1998 (August 31-September 3) (Table 5).

To compare hypoxia severity over the eight years, the maximum area affected in each cumulative dissolved oxygen interval (0.0 – 0.99, 0.0 – 1.99, 0.0 – 2.99, 0.0 – 3.99, and 0.0 – 4.99 mg/L) was calculated (Table 5 and Figure 14). For dissolved oxygen concentrations below 1.0 mg/L, the years 1994 and 1995 had the greatest areas (Figure 14a). In 1991, 1992 and 1997,

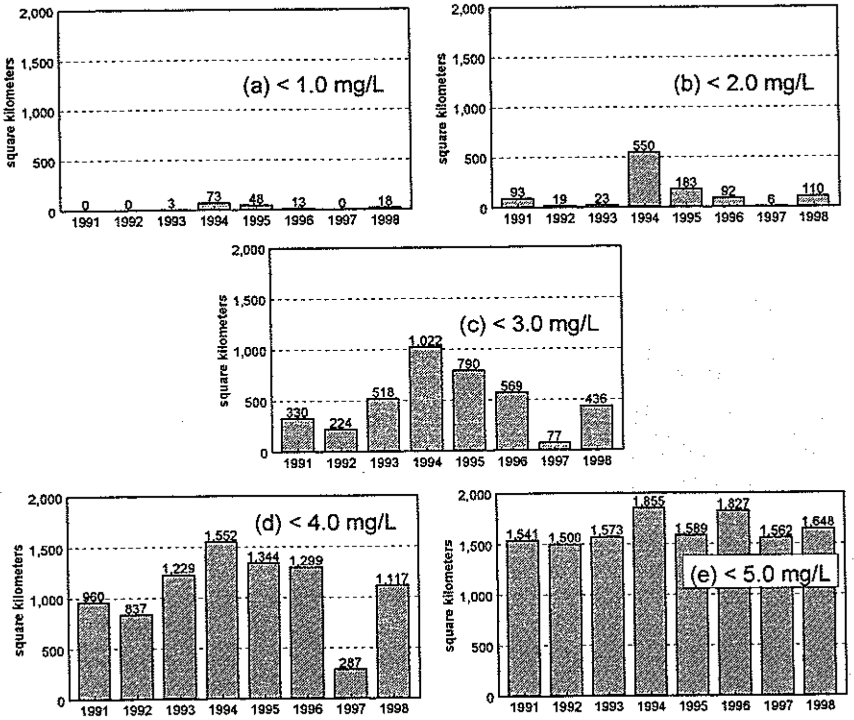


Figure 14. Maximum estimated area of Long Island Sound (in square kilometers) with dissolved oxygen concentration below (a) 1.0, (b) 2.0, (c) 3.0, (d) 4.0 and (e) 5.0 mg/L for each year, 1991 through 1998.

no dissolved oxygen concentrations less than 1.0 mg/L were observed. In 1993, observations from two different cruises each produced a single station with a dissolved oxygen value less than 1.0 mg/L. For the WQJUL93 cruise, this resulted in an area estimate of three square kilometers; no area estimate was calculated for the HYSEP93 cruise due to insufficient coverage.

Dissolved oxygen concentrations less than 2.0 mg/L were observed each year of this study. The area impacted in 1994 (550 km^2) in the 0-2.0 mg/L oxygen interval was significantly larger than any other year. The maximum area impacted by DO concentrations less than 2.0 mg/L during the other seven years ranged from 6 - 183 km^2 (Table 5 and Figure 14b).

Some of the differences observed in the area estimates may be attributed to the changes in sampling design (*i.e.,* mostly random site sampling with some fixed stations from 1991-1993 and all fixed station sampling from 1994-1998) and sampling schedule (Table 4), although station coverage by basin and depth strata were similar between the two designs. Additionally, conditions changed rapidly during the summer months, so that results from two consecutive cruises (generally with two weeks between them) could be quite different. It is possible that a peak hypoxic event was not observed as a result of the semi-weekly sampling schedule.

Hypoxic area maxima and duration were not correlated (R^2=0.012) and seemed independent of each other. While it might seem logical to assume that the longer hypoxia persists in the Sound the greater an area that is likely to be affected, or conversely, that the larger an area that is affected, the longer it would take for the hypoxic conditions to disappear completely, the data do not show this to be true. For example, 1995 and 1996 had the second and third largest areas affected by hypoxia over the eight years and the two shortest durations. In 1994 a long duration combined with a large area affected, while in 1991 both a small area and short duration were observed. The data revealed no obvious relationship between the area and duration of hypoxia.

Vertical Dissolved Oxygen Distribution

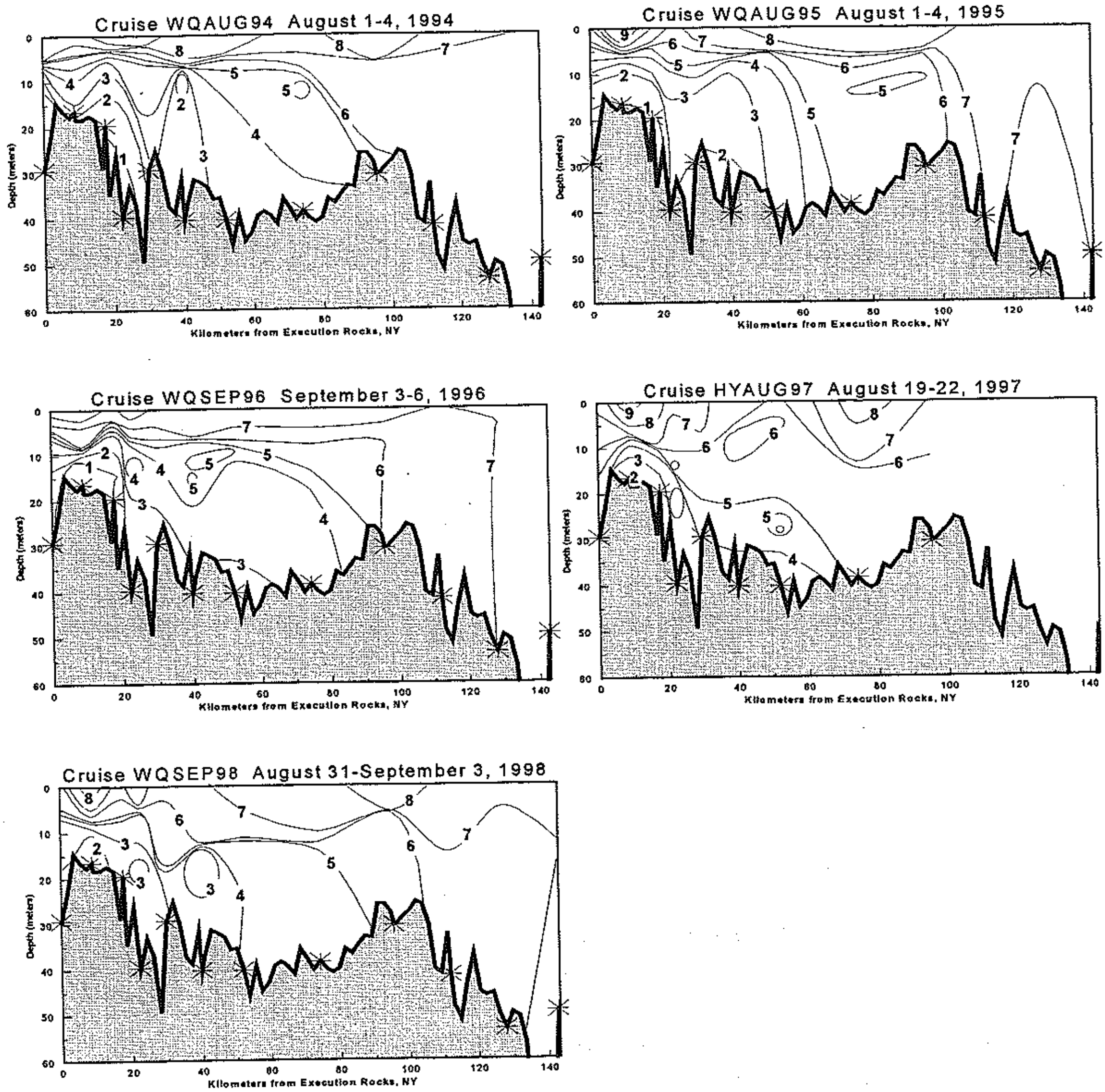
Generally, the first five meters (surface) of the water column were well oxygenated (above 5.0 mg/L) throughout the year in Long Island Sound (Figure 15). Figure 15 shows the worst case condition (peak hypoxic event) from each of the years 1994-1998. As the summer season approached, the pycnocline (location of the most rapid change in density along the density gradient), generally located between the five and ten meter depth interval, strengthened and lower dissolved oxygen concentrations became established in the bottom waters of western and central LIS. The area of low dissolved oxygen increased and extended eastward toward the Central Basin of LIS. This water mass of low dissolved oxygen concentrations encompassed a significant portion of the axial volume of LIS. In the western and central Sound, the dissolved oxygen concentrations progressively fell below the state water quality standard (6.0 mg/L). There was an eastward push of lower dissolved oxygen concentrations below the surface waters. As late summer approached a retreat of low dissolved oxygen concentrations generally occurred as stratification weakened.

Stratification

Stratification, the density difference between the surface and bottom waters, influenced dissolved oxygen concentrations in the bottom waters of Long Island Sound. The density stratification of the water column creates a barrier between the surface and bottom waters, and it is this barrier, the pycnocline (where the change in density with depth is at its greatest), that prevents mixing between the layers. Both temperature and salinity differences between the surface and bottom waters can contribute to the density gradient. The temperature gradient (thermocline) develops with warmer, lighter water on top and cooler heavier water on the bottom. The salinity gradient (halocline) develops with less saline, lighter water on top and more saline, heavier water on the bottom. In Long Island Sound it is the difference in temperature (the thermal gradient or thermocline) that accounts for most of the difference in density from the surface to the bottom. Long Island Sound is a thermally stratified estuary. The more rapid the change in temperature with depth, the stronger a barrier the thermocline presents to mixing of the water column.

Surface and bottom water temperatures were influenced by many natural factors including:

- timing and the amount of precipitation
- air temperatures
- weather patterns (both short and long term)


Cruise WQAUG94 August 1-4, 1994

Cruise WQAUG95 August 1-4, 1995

Cruise WQSEP96 September 3-6, 1996

Cruise HYAUG97 August 19-22, 1997

Cruise WQSEP98 August 31-September 3, 1998

Figure 15. Dissolved oxygen distribution from west to east (Execution Rocks, Station A4 to Fisher's Island/The Race, Station M3) along the deep water axial transect through Long Island Sound during the peak hypoxic event of each of the years 1994 through 1998. "✻" indicates location of stations for which data are plotted.

Some physical factors that influence thermocline strength at particular stations include:

- station depth
- location in LIS
- surrounding bathymetry
- circulation patterns of LIS

Stratification is generally at its strongest during June or the early part of July (Figure 16). As the summer progresses, stratification weakens so that it becomes easier for mixing to occur between surface and bottom waters. The arrival of cooler, autumn weather brings about surface water

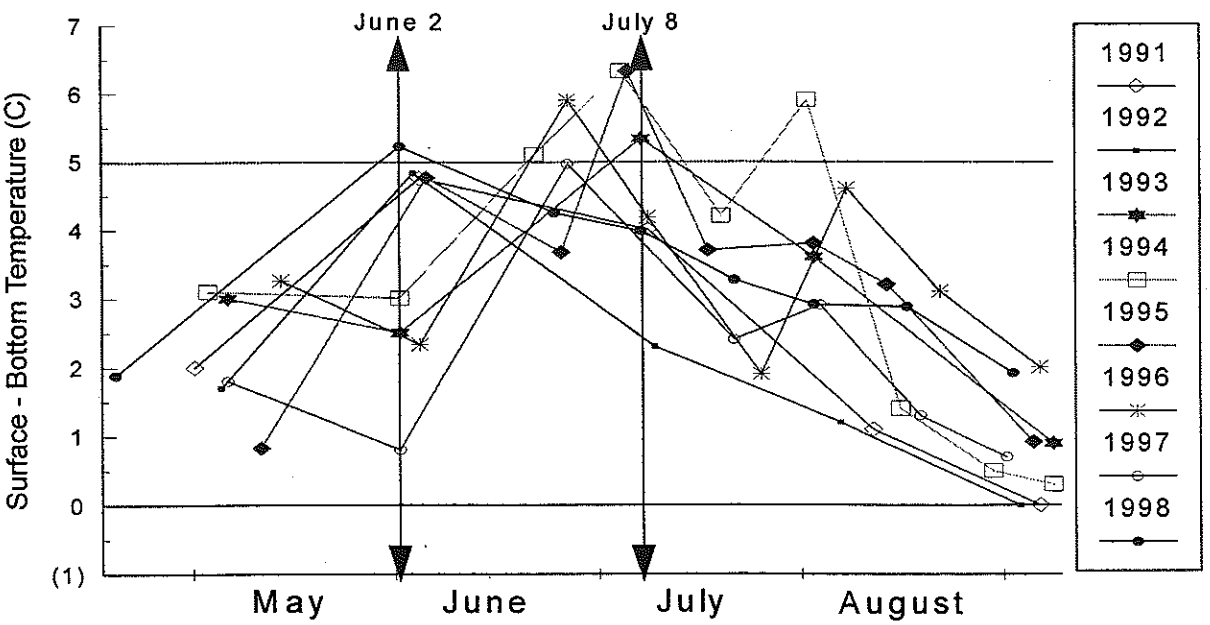


Figure 16. Time series (April 18 through September 9) of ▵T (surface water temperature – bottom water temperature) at station D3, 1991 through 1998. Arrows show the range of dates for ▵Tmax, the earliest, June 2, in 1998, and the latest, July 8, in 1993.

cooling, further weakening the thermal stratification of the water column and allowing reoxygenation of the bottom waters. Consequently, the later hypoxia develops in the Sound, the more likely it is that conditions exist to allow for mixing between surface and bottom waters, and the more likely it is that the hypoxic event will be shorter in duration.

The annual variations in the duration of hypoxia likely resulted from a combination of annual variations in:

- Short and long term weather patterns, which include:
    - precipitation patterns
    - wind events
- Phytoplankton blooms
- Nutrient loading
- Nutrient cycling and recycling
- Other natural and anthropogenic influences

Station D3

Station D3 is located in the eastern-most and the deepest portion of the Narrows. Station D3 does not experience hypoxia every year. The station is used as an example to show how stratification and the development of hypoxia in the Sound relate. Figure 17 shows a time series of the surface minus bottom water temperature (▵T) at station D3 for the years 1991 - 1998. The seasonal pattern of ▵T is clear. The largest ▵T (▵Tmax) occurred in the early summer when rapid

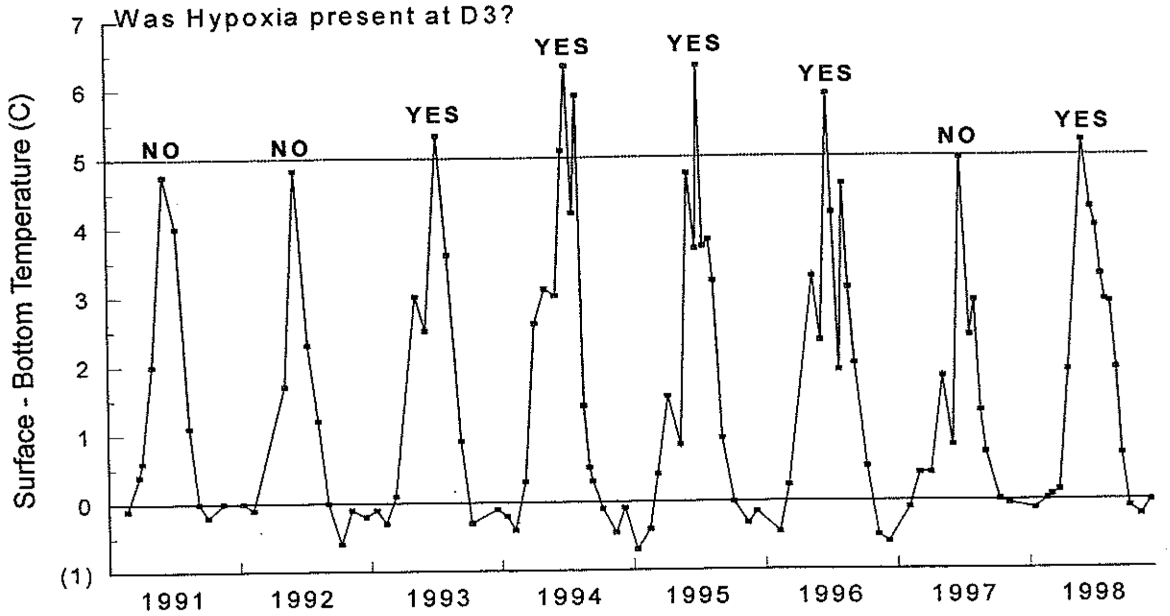


Figure 17. Time series of ΔT (surface water temperature – bottom water temperature) at station D3, 1991 through 1998.

surface water warming exceeded the rate of warming in the bottom waters. The smallest ΔT occurred during the winter when bottom waters were actually warmer than the surface (negative ΔT) (Figure 17).

The years when station D3 became hypoxic (1993-1996 and 1998) coincided with the largest observed values of ΔT (Figure 17). In each case, the observed maximum ΔT was greater than 5.0 degrees C. The timing of the maximum ΔT varied annually, occurring from early June to early July (Figure 16).

The maximum area of hypoxia was related to the strength of the thermocline. There was a positive correlation (R^2=0.8275) between the maximum ΔT observed at station D3 and the maximum area of hypoxia in the same year (Figure 18). Maximum ΔT and the maximum area of hypoxia never occurred at the same time during the 1991-1998 period.

A positive relationship also existed between ΔTmax and the maximum area of hypoxia when the maximum ΔT from other stations were used (e.g. Station B3, R^2=0.36; Station F3, R^2=0.41), but none exhibited as strong a correlation as that when the data from Station D3 were used. Just why conditions at D3 should be so suggestive of the eventual hypoxic event throughout the Sound is not known, although it is likely a function of the station's location and its physical characteristics.

Conditions at Station D3 appeared helpful in characterizing the magnitude of hypoxia for each year. In general, when D3 was not affected by hypoxia the area of hypoxia in that year was smaller (less than 350 km^2), and if D3 was hypoxic ('93, '94, '95, '96 and '98) the extent of

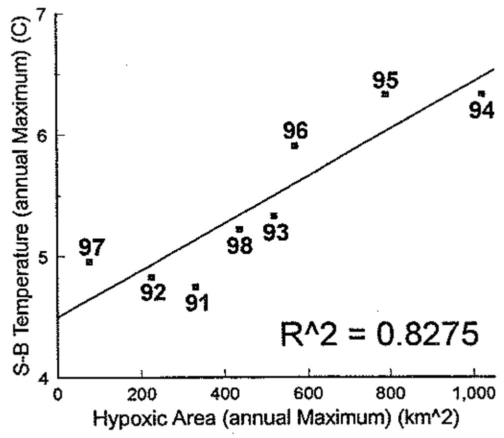


Figure 18. Relationship between the maximum area of hypoxia and the maximum ΔT (surface temperature – bottom temperature) at station D3, 1991 through 1998.

hypoxia was substantial (greater than 400 km^2). When stratification is strong, the potential for a large hypoxic area exists. Whereas ΔT was positively correlated to the area of hypoxic conditions, it was not correlated to the duration of hypoxia in LIS (R^2=0.009). This was attributed to the general weakening of the thermocline as the summer progressed, and short-term weather patterns having more influence over conditions. Once ΔT is diminished from its high, which occurred in June or early July, the potential for the reoxygenation of the water column became greater and dependent on short term weather patterns. A strong wind event could more easily transport oxygen from the surface waters into the water column because the thermal barrier that would prevent mixing was weakening.

Trend Analyses

The results of trend analyses indicated that five stations had a significant increasing trend ($p<0.05$) over the five-year period of 1994-1998 (Figure 19 and Table 8). Thirty-three additional

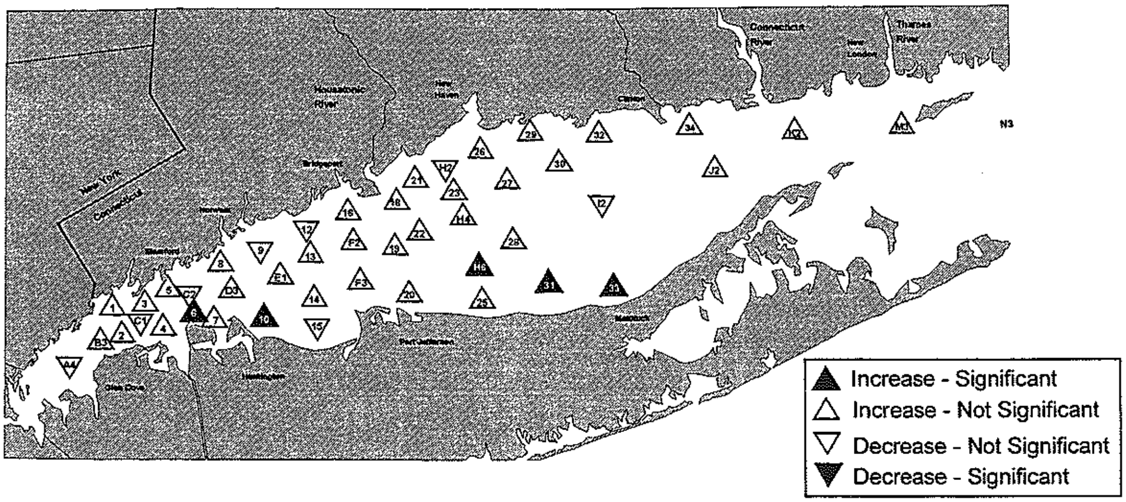


Figure 19. Trends in summertime bottom dissolved oxygen concentration at stations sampled over the five-year period of 1994 through 1998. No significant decreases in bottom water DO were observed.

Table 8. Results of trend analyses of summer bottom dissolved oxygen concentrations at fixed stations sampled from 1994-1998. Significant trends ($p<0.05$) are highlighted in grey.

				Linear Regression: Deseasonalized data is normally distributed			Seasonal Kendall's Test: Data not normally dist.
Station	Trend	Significant? ($p<0.05$)	p-value	R^2	Slope	Rate of Trend	Rate of Trend
A4	dec	No	0.7718	-	-	-	ns
B3	inc	No	0.8021	0.0021	8.14E-05	ns	-
C1	dec	No	0.3448	0.0407	-3.98E-04	ns	-
C2	dec	No	0.8705	0.0012	-7.03E-05	ns	-
D3	inc	No	0.2996	0.0370	1.77E-04	ns	-
09	dec	No	0.8414	-	-	-	ns
E1	inc	No	0.1717	0.0680	3.68E-04	ns	-
15	dec	No	0.6561	0.0072	-2.22E-04	ns	-
F2	inc	No	0.1281	0.0868	3.80E-04	ns	-
F3	inc	No	0.2629	0.0480	2.28E-04	ns	-
H2	dec	No	0.8728	-	-	-	ns
H4	inc	No	0.3672	0.0302	2.00E-04	ns	-
H6	**INC**	**Yes**	**0.0106**	**0.2341**	**5.92E-04**	**0.22 mg/L/yr**	-
I2	dec	No	0.7872	-	-	-	ns
J2	inc	No	0.0836	-	-	-	ns
K2	inc	No	0.5962	-	-	-	ns
M3	inc	No	0.0536	-	-	-	ns
N3	---	No	1.0000	-	-	-	ns
01	inc	No	0.0650	0.1092	4.96E-04	ns	-
02	inc	No	0.8624	0.0011	5.01E-05	ns	-
03	inc	No	0.2970	0.0362	2.48E-04	ns	-
04	inc	No	0.2340	-	-	-	ns
05	inc	No	0.5170	0.0151	2.07E-04	ns	-
06	**INC**	**Yes**	**0.0090**	**0.2428**	**8.65E-04**	**0.32 mg/L/yr**	-
07	inc	No	0.2224	-	-	-	ns
08	inc	No	0.3192	0.0431	3.59E-04	ns	-
10	**INC**	**Yes**	**0.0012**	**0.3578**	**8.55E-04**	**0.31 mg/L/yr**	-
12	dec	No	0.9684	0.0001	-1.40E-05	ns	-
13	inc	No	0.1750	0.0820	3.89E-04	ns	-
14	inc	No	0.0702	-	-	-	ns
16	inc	No	0.0918	0.1017	6.32E-04	ns	-
18	inc	No	0.1114	0.1022	5.54E-04	ns	-
19	inc	No	0.0536	-	-	-	ns
20	inc	No	0.1082	0.1238	4.69E-04	ns	-
21	inc	No	0.1587	0.0923	4.46E-04	ns	-
22	inc	No	0.0892	-	-	-	ns
23	inc	No	0.2011	0.0891	2.86E-04	ns	-
25	inc	No	0.5112	0.0231	2.21E-04	ns	-
26	inc	No	0.1487	0.0885	5.77E-04	ns	-
27	inc	No	0.0930	-	-	-	ns
28	inc	No	0.2997	0.0511	2.25E-04	ns	-
29	inc	No	0.2656	0.0646	3.63E-04	ns	-
30	inc	No	0.1738	-	-	-	ns
31	**INC**	**Yes**	**0.0423**	**0.1608**	**5.42E-04**	**0.20 mg/L/yr**	-
32	inc	No	0.0802	-	-	-	ns
33	**INC**	**Yes**	**0.0025**	**0.3343**	**6.92E-04**	**0.25 mg/L/yr**	-
34	inc	No	0.1010	-	-	-	ns
36	---	No	Insufficient data				

stations had increasing DO trends that were not significant ($p>0.05$). Only eight stations showed a decreasing DO trend, and none was significant ($p>0.05$). The eight stations that showed a declining trend in DO concentration, albeit insignificant, were spread throughout the Narrows and Western and Central Basins (stations A4, C1, C2, 09,12, 15, H2 and I2). The five stations that showed a significant increase in DO concentrations over the five year period were spread throughout the Sound: one in the Narrows, one in the Western Basin, two in the Central Basin, and one in the Eastern Basin (Table 8 and Figure 19). The summer of 1994 had the most severe hypoxic event of the five years included in the trend analysis. Since 1994 is at the beginning of the time period analyzed it would clearly affect the trend observed, especially at those stations that typically do not experience very low DO concentrations so that the widespread event of 1994 brought about unusually low DO concentrations. Station 33 in the Eastern Basin provides a good example; 1994 was the only year that the DO at this station was observed to fall below 3.0 mg/L.

There are additional data available from stations sampled since 1991. Year round bottom water dissolved oxygen data, from stations B3, D3 and F3, 1991-1997, have been evaluated using the same trend analysis technique as described above. The results of these analyses (reported separately in Program's Monthly Water Quality Monitoring data report, in draft) reveal increasing trends in bottom water DO at stations D3 (significant, $p=0.024$), F3 (significant, $p=0.005$), and B3 (not significant, $p=0.053$). From the review of these additional results, it is concluded that the trends seen in the 1994-1998 data need not be wholly attributed to the fact that 1994 was a particularly severe year for hypoxia. The longer-term data set supports the increasing trend seen at these three stations over the 1994-1998 period.

Weather Patterns and Hypoxia

Table 9. Water temperature and hypoxic area summary data from Station D3. 1994 (bold) had the lowest and highest water temperatures recorded, tied for the highest ΔTmax, and had the largest area of hypoxia. See Figures 11 and 15.

Year	Minimum Winter Temp (C)	Maximum Summer Temp (C)	Maximum ΔT (C)	Maximum Area of Hypoxia (km^2)
1991	2.69	22.23	4.75	330
1992	1.86	20.89	4.83	224
1993	1.06	22.68	5.33	518
1994	**-0.68**	**24.08**	**6.33**	**1022**
1995	0.95	23.78	6.33	790
1996	-0.19	23.78	5.91	569
1997	1.87	21.81	4.96	77
1998	3.40	23.20	5.22	436

We have already discussed the relationship between thermal stratification, specifically ΔTmax, and the area of hypoxia (see *Stratification* section). It is both long and short-term weather patterns that affect water temperatures and determine ΔT at any given time. In 1994, for example, a very cold winter resulted in the lowest winter water temperatures of the eight-year study (Table 9). With very cold bottom water temperatures, slow to warm, and surface water temperatures pushed higher by a record early June heat wave, the largest ∆T (tied with 1995) of the eight years resulted (Station D3, see Figure 17; Table 9). The highest surface water temperature was also recorded that summer, so it is not surprising that 1994 had the most severe hypoxic event of the eight years (Table 6 and Figure 11d).

The three years with the lowest winter water temperatures, the highest summer water temperatures, and the largest ∆Tmax (1994, 1995 and 1996) are also the three years with the largest areas of hypoxia (Table 9). We have already seen a strong relationship between ∆Tmax and the maximum area of hypoxia (R^2=0.83; Figure 18). The data also revealed relationships between the area of hypoxia and the annual extreme water temperatures (Figure 20). Higher summer water temperatures (maximum summer water temperatures occur in surface waters) and lower winter water temperatures were both related to larger areas of hypoxia. These relationships were likely due to affects on ∆T and ∆Tmax and the strength of stratification that resulted. Clearly the weather patterns that determined water temperatures in the Sound had an important influence on the extent of hypoxia.

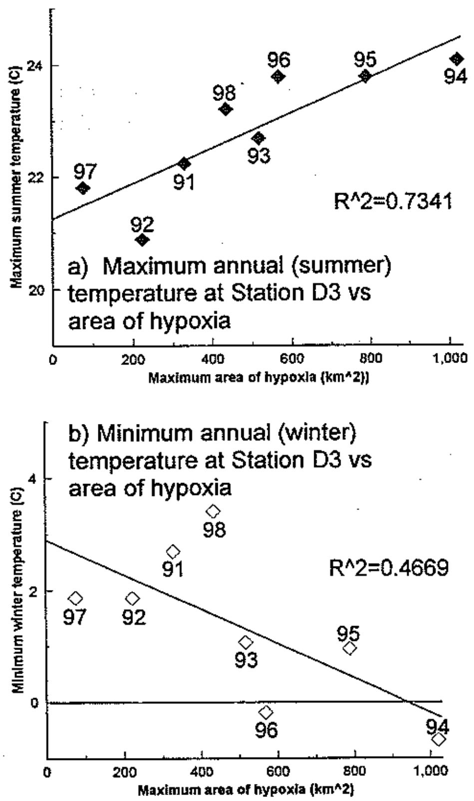


Figure 20. Relationship between a) maximum and b) minimum annual temperatures at Station D3 and the maximum area of hypoxia, 1991-1998.

Analyses of additional weather data revealed possible relationships between the hypoxia event and precipitation patterns. Winter precipitation (Figure 21) was defined as the total January, February and March precipitation. Summer precipitation (Figure 23) was defined as the total June, July and August precipitation. Duration and area both appear to be related to weather patterns and events, however these relationships seem independent of each other. Monthly precipitation data collected by the National Weather Service at Sikorsky Airport in Bridgeport, Connecticut were compared with hypoxia patterns. The sum of January, February and March precipitation correlated somewhat with the duration and area (Figure 22).

The duration of hypoxia in LIS was correlated with winter precipitation (January to March) during the period of study (R^2=0.4291) (Figure 22a). The three years with the longest duration of hypoxia (1993, 1994 and 1998) also had the highest precipitation totals for these three months and these monthly precipitation totals were greater than the 1950-1981 median precipitation (Figure 21).

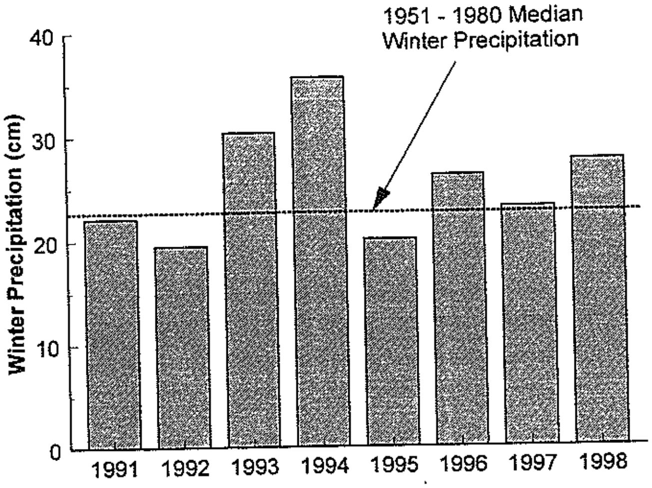


Figure 21. Winter precipitation (January through March) totals for the years 1991-1998. 30-year median precipitation data from Hunter and Meade, 1983.

The maximum area of hypoxia also showed a slight correlation with winter precipitation totals ($R^2=0.3479$) (Figure 22b). 1994, the year with the largest area of hypoxia was also the year with the highest January - March precipitation.

Increased winter precipitation appeared to contribute to lower summer dissolved oxygen concentrations in LIS. Increased winter/spring runoff likely resulted in higher nutrient loading and stronger stratification of the water column. Both factors raised the potential for hypoxic conditions in LIS by supporting winter/spring phytoplankton blooms and strengthening the barrier to the reoxygenation of the bottom waters during the summer. Freshwater runoff affects water temperature, salinity and contributes increased nutrient and particulate loads to the Sound. Larger runoff volume increases the potential for early water column stratification driven by temperature and salinity differences and also delivers excess nutrients to the surface waters that may stimulate phytoplankton growth.

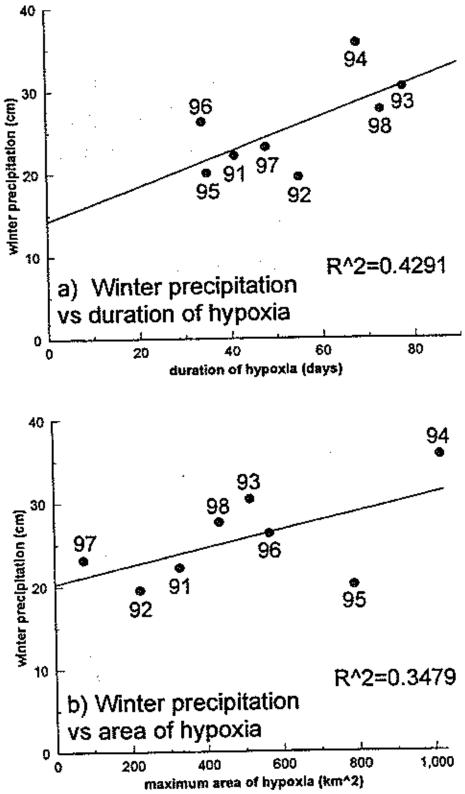


Figure 22. Relationship between winter precipitation (January through March total) and the a) duration and b) maximum area of hypoxia, 1991-1998.

Another precipitation pattern that was weakly correlated (negative) with the maximum area of hypoxia in LIS was the total summer (June, July and August) precipitation ($R^2=0.2603$) (Figure 24a). This relationship was likely a result of the combined effects of storm-related wind-induced mixing and mixing caused by storm-induced runoff that was colder than the surface waters. Summer rainfall and accompanying winds have the potential to weaken stratification allowing some mixing of the water column and oxygenation of the water column below the pycnocline.

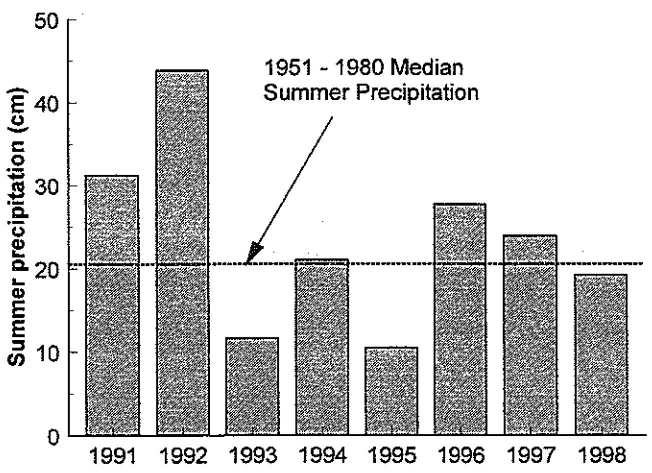


Figure 23. Summer precipitation (June through August) totals for the years 1991-1998. 30-year median precipitation data from Hunter and Meade, 1983.

Summer precipitation did not correlate with the duration (R^2=0.0591) or date of onset (R^2=0.0574) of hypoxia. Since hypoxia typically begins in July (only in 1996 was an August start observed), June and July precipitation was evaluated for any relationship to the date of onset of hypoxia. Total June and July precipitation correlated somewhat to the date of onset of hypoxia, with increased precipitation during these months contributing to a later onset date (R^2=0.3291) (Figure 24b). Mixing of the water column during these months had the potential to temporarily weaken or break up the stratification. Weakening of the water column stratification led to delayed onset, reduced area, or lessened severity of hypoxia.

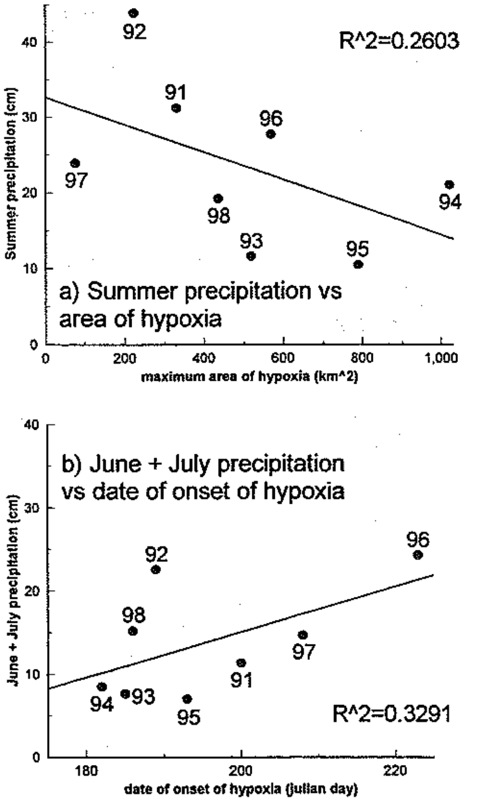


Figure 24. Relationship between a) summer precipitation and the maximum area of hypoxia; and b) June + July precipitation and the date of onset of hypoxia, 1991-1998.

Increased summer precipitation appeared to contribute to improved summer dissolved oxygen concentrations in LIS through its effects on water column mixing. Water column mixing was promoted by an increase in freshwater runoff and winds associated with storm events. Increased water column mixing interrupted the development of water column stratification, delaying the development and persistence of hypoxia.

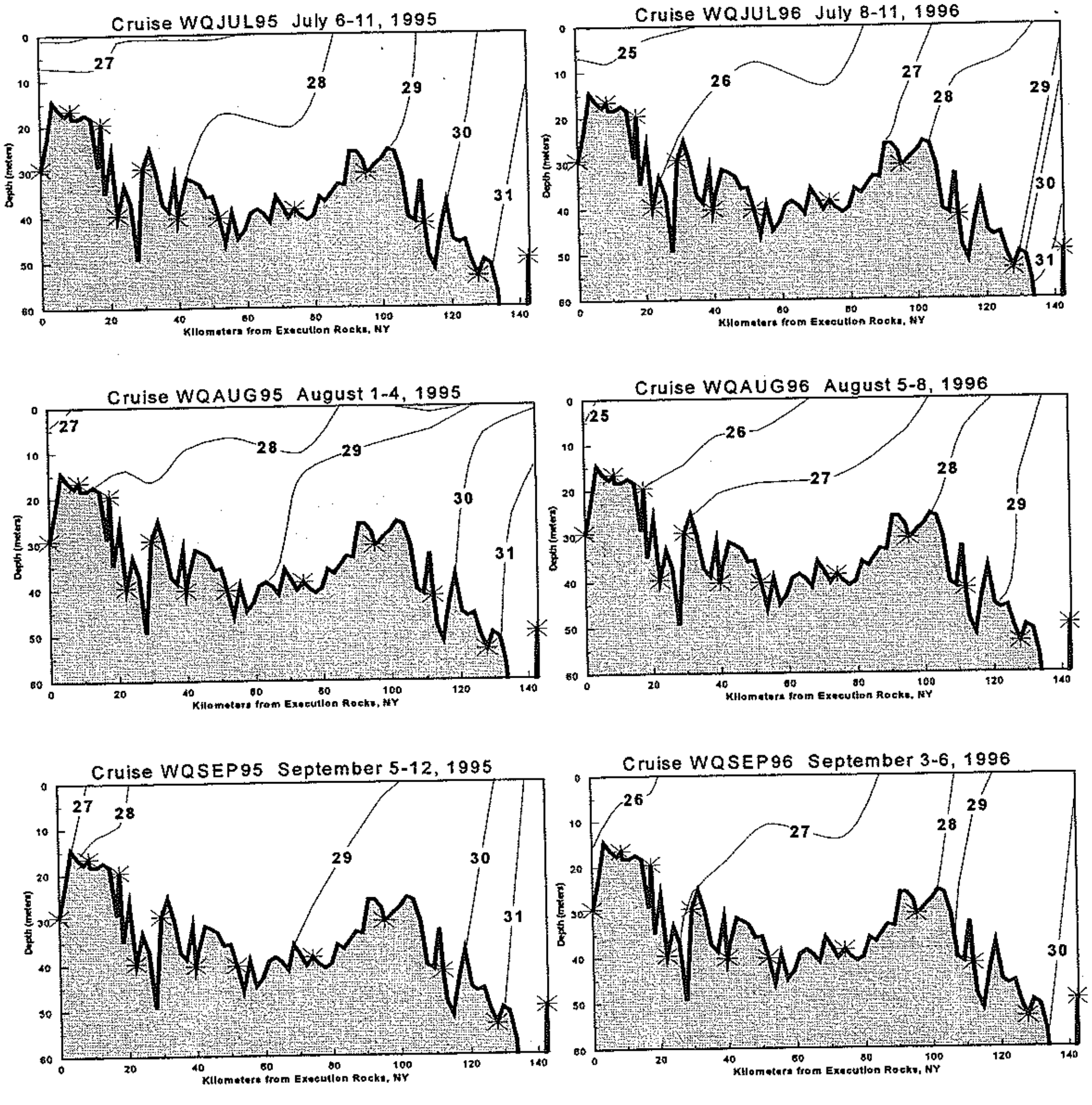
Axial Profiles

Temperature and salinity distributions from west to east along the deep water axial transect of LIS (Figure 5) provide a useful means of reviewing data for cruise-to-cruise or year-to-year comparisons. Variations in water column distributions of temperature and salinity attributed to varying weather patterns, for example, could be easily evaluated.

Following are some examples of distribution plots.

Salinity

Figure 25 shows salinity distributions for three summer cruises from 1995 and 1996. The winter precipitation in 1995 was below the 30-year median so the freshwater input into LIS in the spring was less than in other years. One main consequence of this was the increased salinity values in the Sound. With continued low rainfall during the spring and summer (the lowest summer precipitation of the eight years) the higher salinity waters persisted through the summer months (Figure 25). In contrast, 1996 winter precipitation was higher than the 30-year median (Figure


Cruise WQJUL95 July 6-11, 1995

Cruise WQJUL96 July 8-11, 1996

Cruise WQAUG95 August 1-4, 1995

Cruise WQAUG96 August 5-8, 1996

Cruise WQSEP95 September 5-12, 1995

Cruise WQSEP96 September 3-6, 1996

Figure 25. Salinity distribution from west to east (Execution Rocks, Station A4 to Fisher's Island/The Race, Station M3) along the deep water axial transect through Long Island Sound during WQJUL, WQAUG, and WQSEP cruises, 1995 and 1996. "✳" indicates location of stations for which data are plotted.

21), providing larger freshwater runoff volume and lower salinity throughout the Sound (Figure 25). In addition, 1996 summer precipitation was greater than the 30-year median (Figure 23) (in fact, 1996 had the highest June+July precipitation of the eight years), so that continued freshwater inputs kept salinity values low through the summer.

Temperature

Figure 26 shows temperature distributions for three summer cruises from 1995 and 1996. Unlike the salinity distributions, the temperature distributions for these two years are fairly similar. Using data from Station D3 as an example, we can see that these two years had very similar

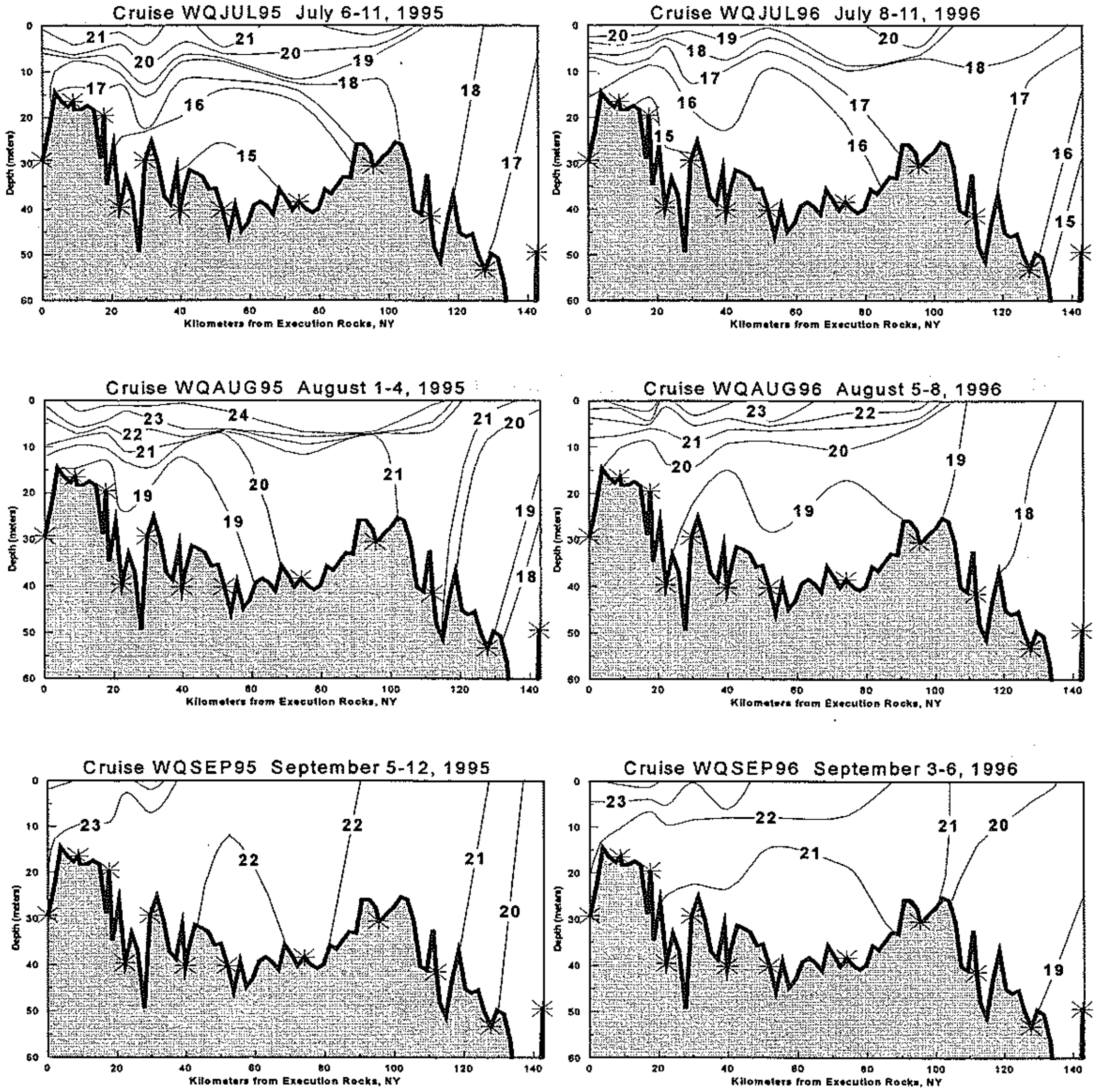


Figure 26. Temperature distribution from west to east (Execution Rocks, Station A4 to Fisher's Island/The Race, Station M3) along the deep water axial transect through Long Island Sound during WQJUL, WQAUG, and WQSEP cruises, 1995 and 1996. "✱" indicates location of stations for which data are plotted.

temperature patterns. Both started out with very similar low winter water temperatures (the second and third lowest after 1994) of 0.95 (1995) and –0.19 (1996) degrees C. Similarly, these two years had identical high summer water temperatures, at 23.8 degrees C. The higher summer precipitation in 1996 (Figure 23) is likely the cause of the slightly cooler surface water temperatures in that year.

As mentioned previously, the stratification in the Sound is primarily a function of temperature. In Figure 26, we can see that the difference between the surface and bottom water temperatures during the WQJUL and WQAUG cruises was generally larger in 1995 than in 1996 (as was seen for Station D3 in Figure 17). In addition, we can see in the WQAUG95 profile (Figure 26) isotherms that are very close together. Both of these pieces of information are consistent with a stronger thermocline (and, therefore, a stronger pycnocline) and a stronger barrier to the vertical mixing of dissolved oxygen. As discussed earlier, the strength of the stratification in the water column was related to a difference in the area of the Sound affected by hypoxia, and 1995 had a larger maximum area of hypoxia than did 1996

Summary

The Summer Hypoxia Monitoring Survey which is part of the broader Long Island Sound Ambient Water Quality Monitoring Program, has provided an eight year description of the extent, severity, and duration of low dissolved oxygen concentrations. The annual variations in the conditions of Long Island Sound during this study support the need for the continuation of the monitoring program in order to document changing trends in water quality. Hypoxia is one of the most pressing issues concerning the health of the Sound (LISS 1994). A continuous and up-to-date long term database will make it possible to evaluate the results and success of management strategies implemented in an effort to improve the water quality of Long Island Sound. The nutrients entering the Sound are expected to decrease in response to the phased nitrogen reduction strategies implemented by the states of New York and Connecticut. Some point source reductions have already been made. Although these nitrogen reductions may not yet be positively detectable beyond the year-to-year variability in the system, improved water quality, measured as a trend of increasing DO concentrations, is anticipated in response to these decreasing nutrient loads.

The current sampling design, which was initiated in 1994, provides excellent station-specific time series of DO concentrations and gives a good Sound-wide representation of conditions. In this report, the DO trend analyses are based on five years of data and the apparent trends may be short-term phenomena. Continued data collection and analysis efforts will enhance our understanding of the trends in DO conditions. The apparent increasing trend in bottom water DO concentrations, the cyclic pattern in the duration of hypoxia, and the annual fluctuations in the area affected will be interpreted more accurately as we are able to remove effects of natural variations and focus on the effects of management efforts to reduce nutrient loading to the Sound.

Review of Descriptive and Significant Findings

During the period 1991-1998:

- Many patterns observed concerning DO concentrations in LIS were consistent from year to year; typically, the Narrows showed the lowest mean bottom water DO concentration with DO increasing eastward
- Hypoxia (DO less than 3.0 mg/L) was observed every year during the month of August; five of the eight years during July; and five of the eight years during September
- The maximum area of hypoxia (DO of 3.0 mg/L or less) generally occurred during August
- The average hypoxic event (1991-1998) began on July 15th, ended on September 6th , lasted 54 days, and covered a maximum area of 494 km^2, 18% of the study area
- There appeared to be some relationship between the date of onset of hypoxia and its duration: a late onset seemed to affect a shorter duration
- DO concentrations less than 2.0 mg/L were observed every year; DO less than 1.0 mg/L were observed in five of the eight years
- Five stations showed a significant increase in bottom water DO based on trend analysis of 1994-1998 data; no stations showed significantly decreasing DO
- Stratification strength and timing was very important to the development and eventual extent of hypoxia: when thermal stratification was strong during the early summer, the area of hypoxia that developed later in the summer was large
- Weather patterns and events were also very important, such as annual high and low air temperatures, precipitation, runoff volume and timing, wind events and other physical factors as they influenced stratification and water column mixing in the Sound

This work was partially funded by the United States Environmental Protection Agency's Long Island Sound Study. Questions regarding this report and requests for additional data or information from the Long Island Sound Ambient Water Quality Monitoring Program should be brought to the attention of the Planning and Standards Division of the Bureau of Water Management.

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APPENDIX A

Time Series of Bottom Water Dissolved Oxygen (mg/L) by Basin and Station

1991 – 1998
(Some station records begin in 1994)

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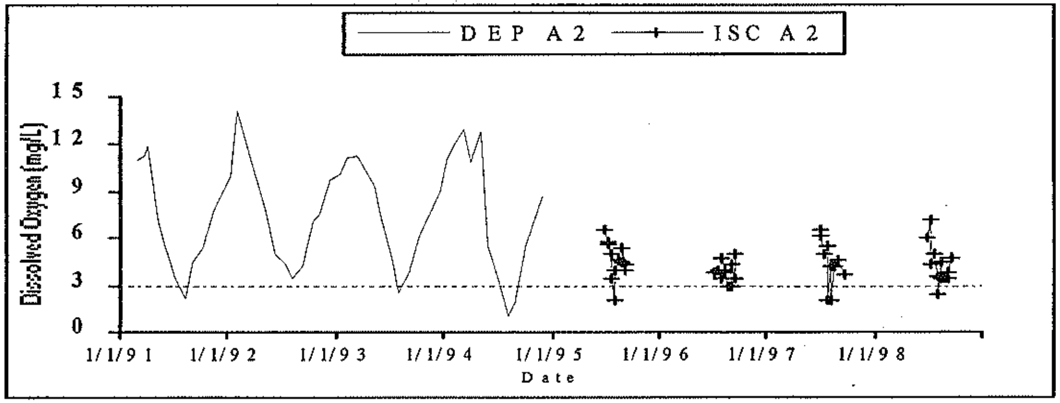
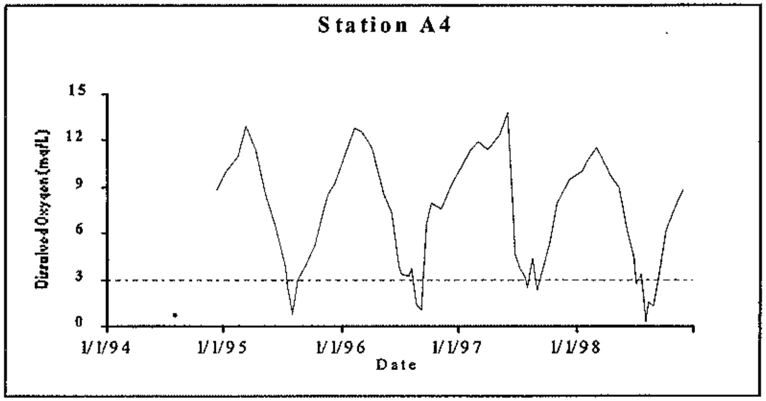
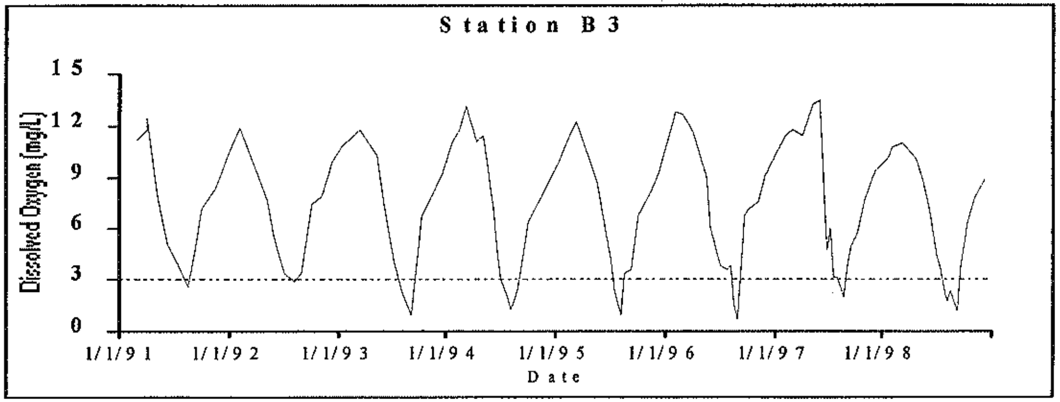
Narrows - Bottom water D.O.



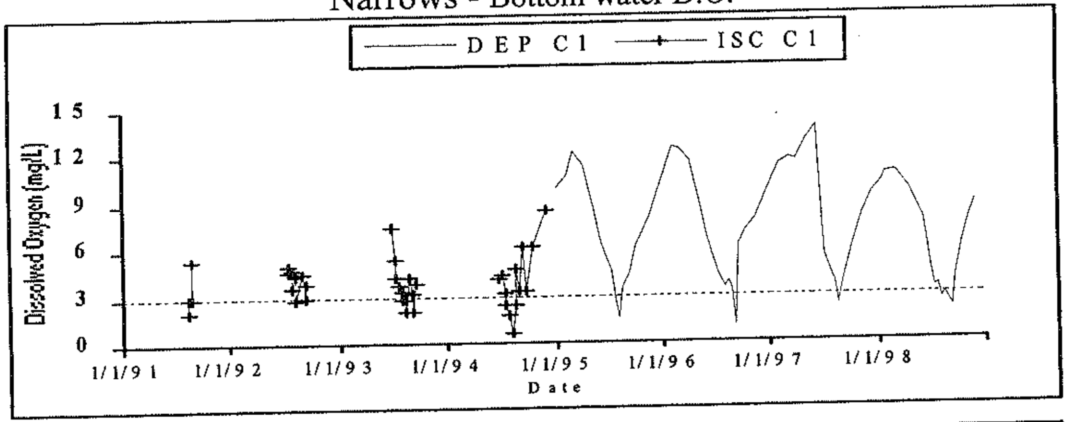
Station A4

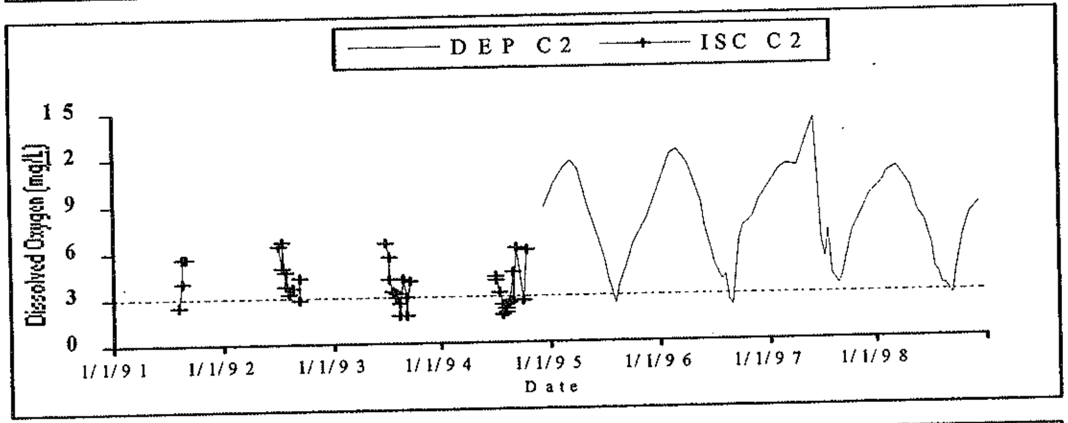


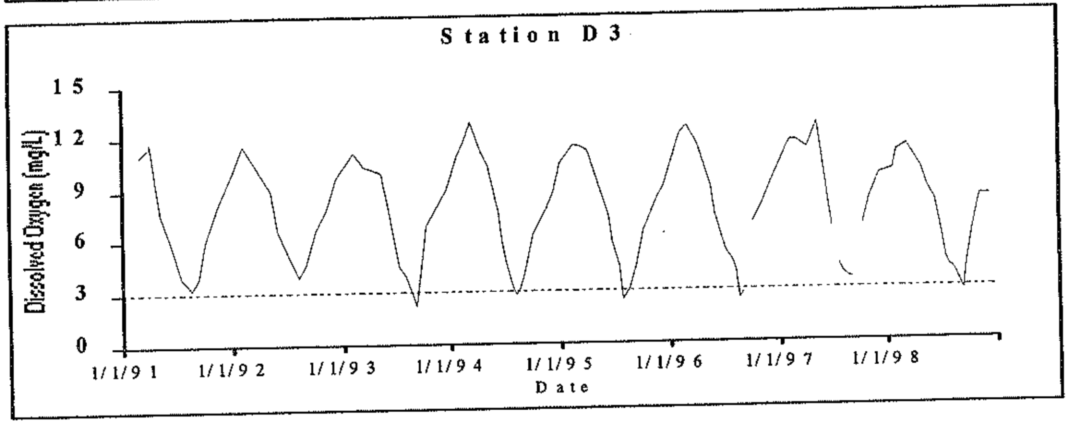
Station B3



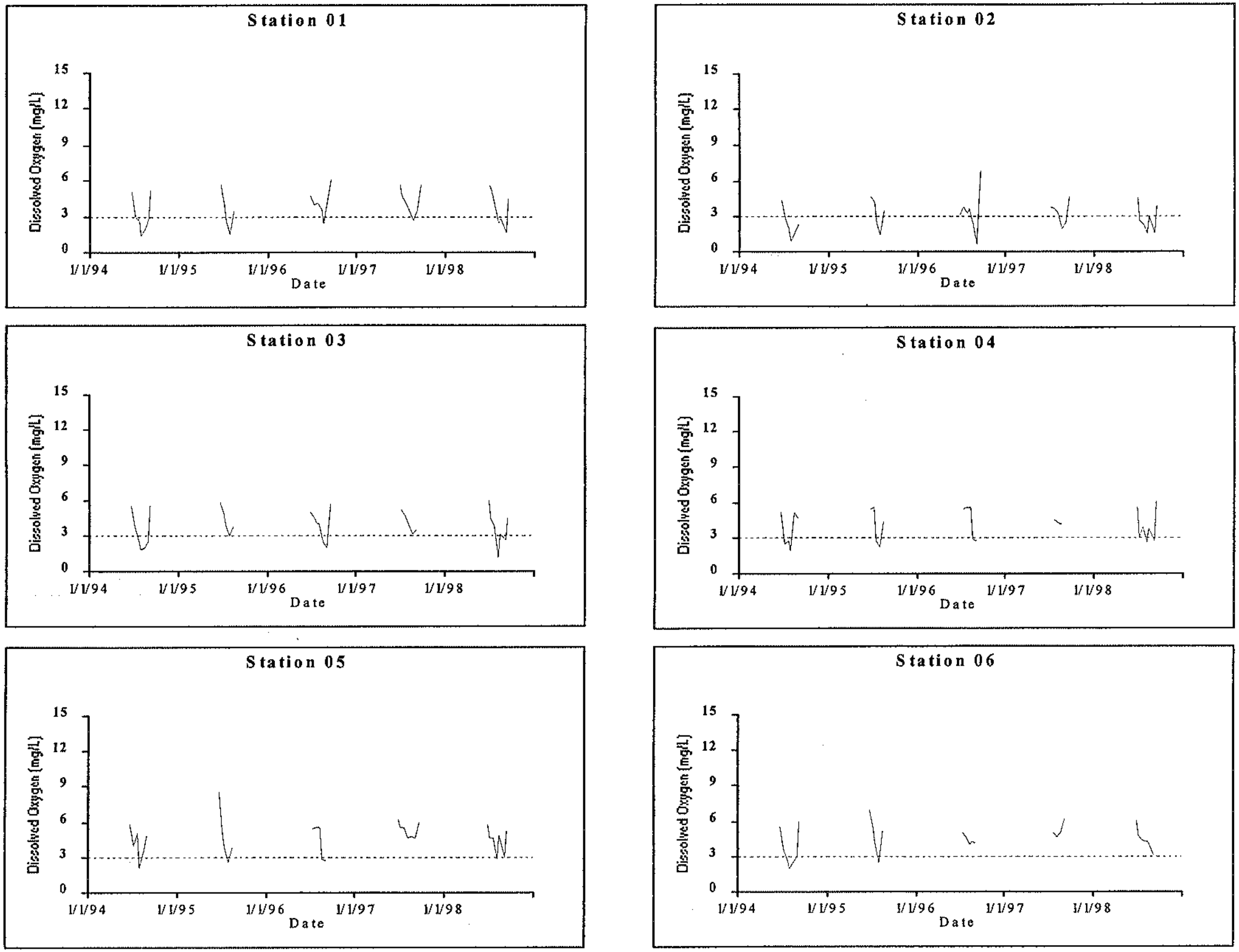
Narrows - Bottom water D.O.



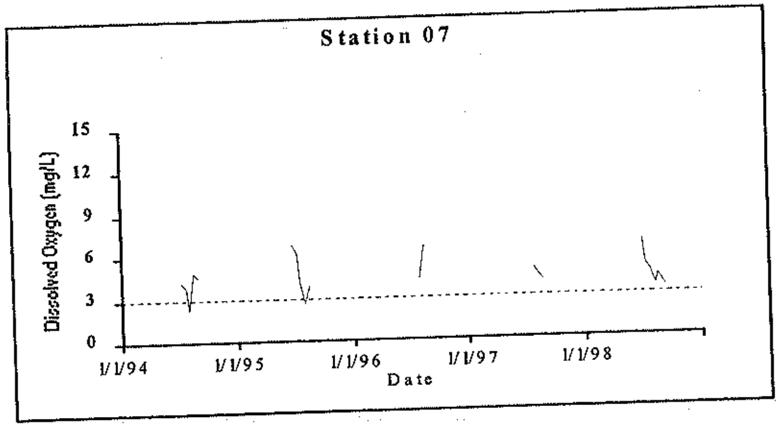


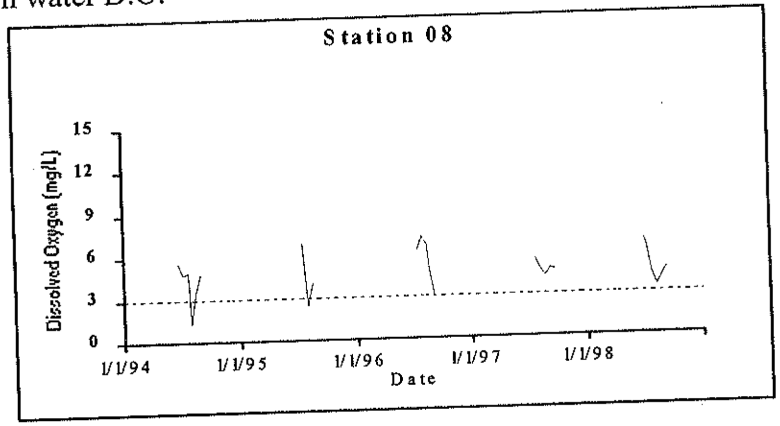


Narrows - Bottom water D.O.

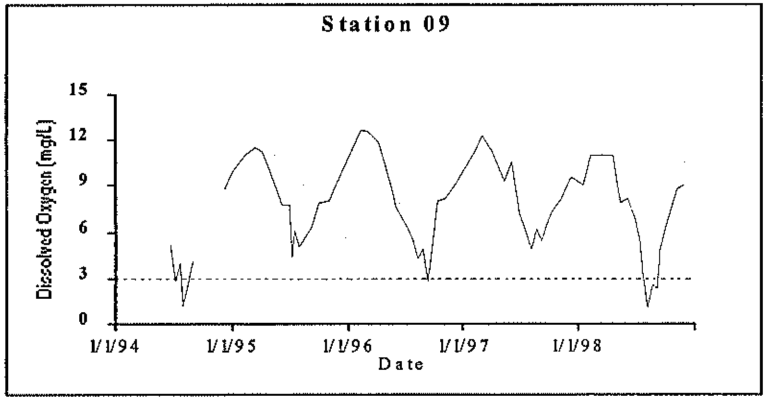


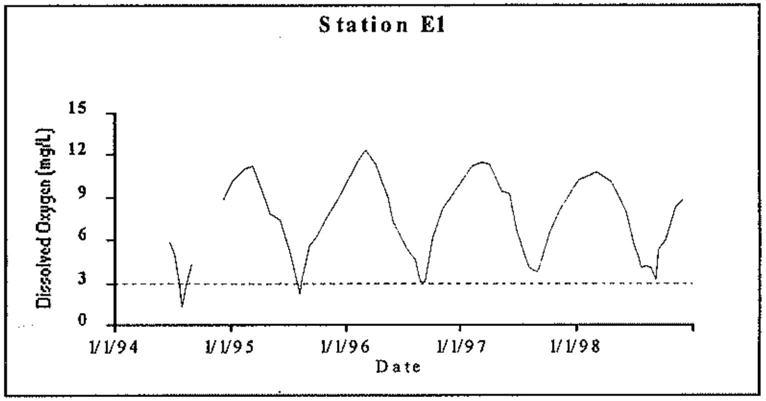
Narrows - Bottom water D.O.

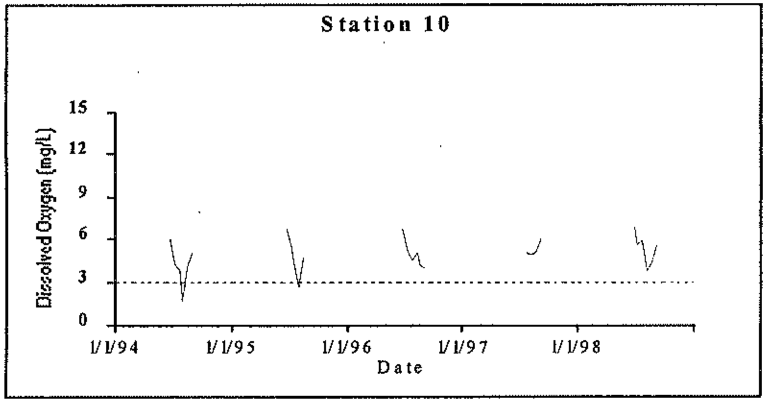




Western Basin - Bottom water D.O.


Station 09


Station E1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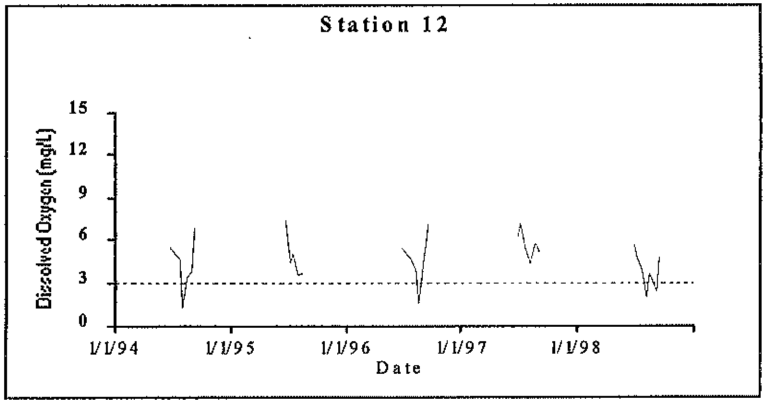
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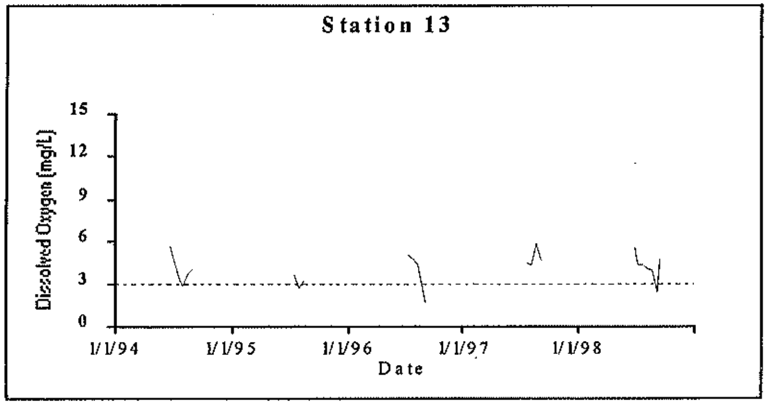
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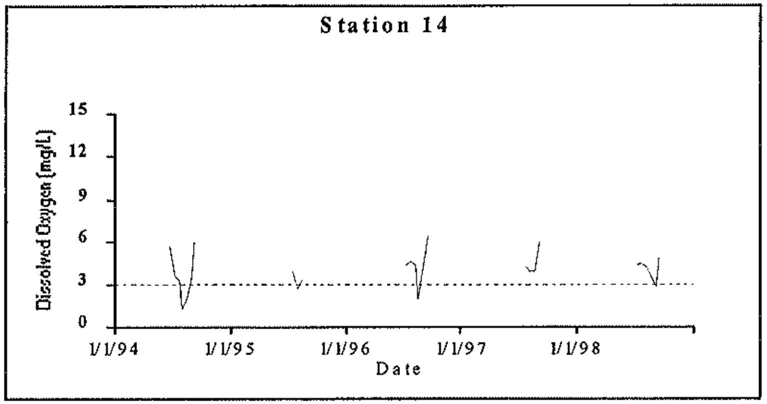
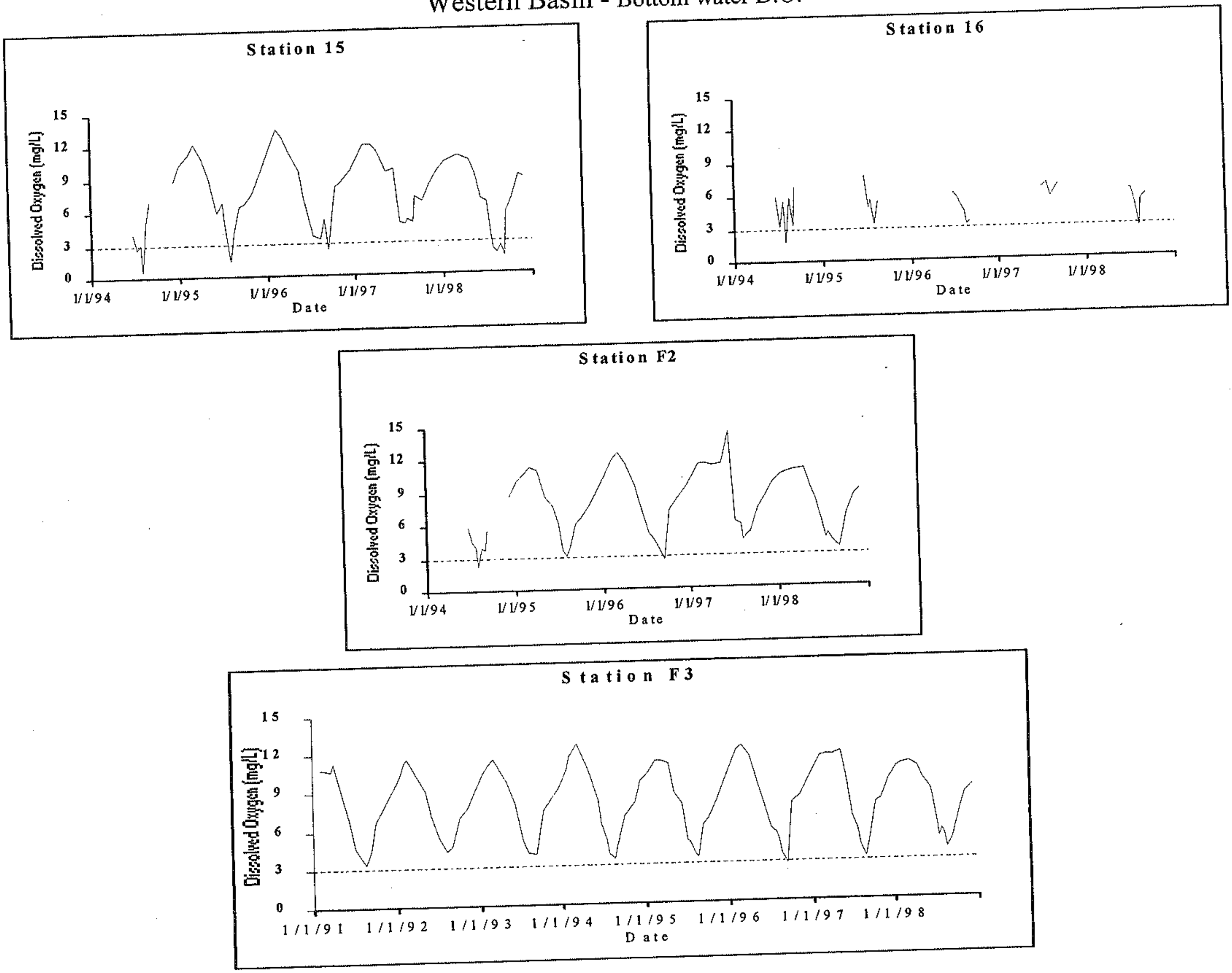

Station 14

Western Basin - Bottom water D.O.

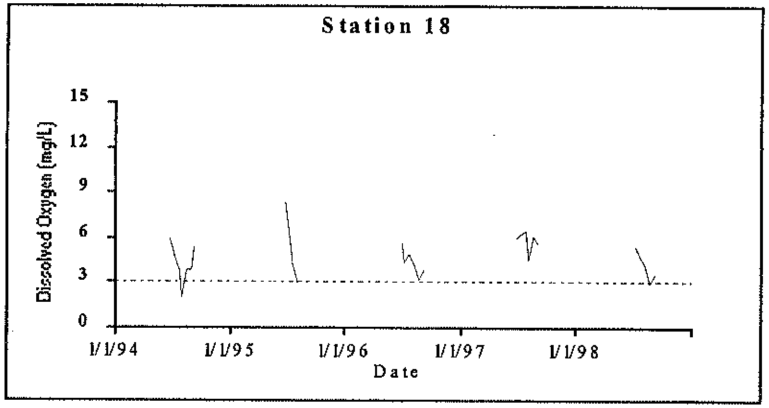

Station 15

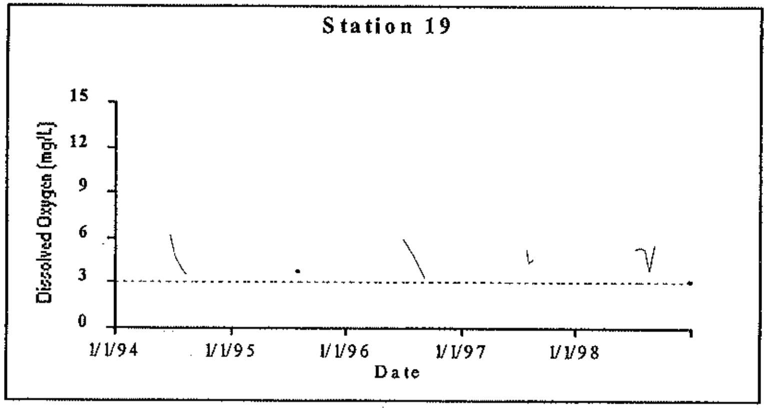
Station 16

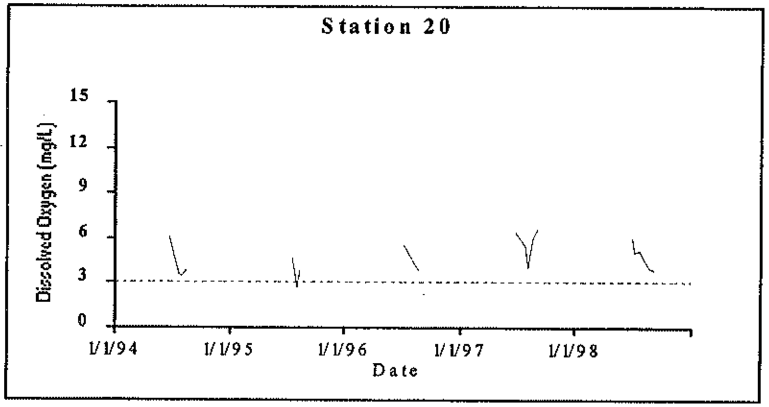
Station F2

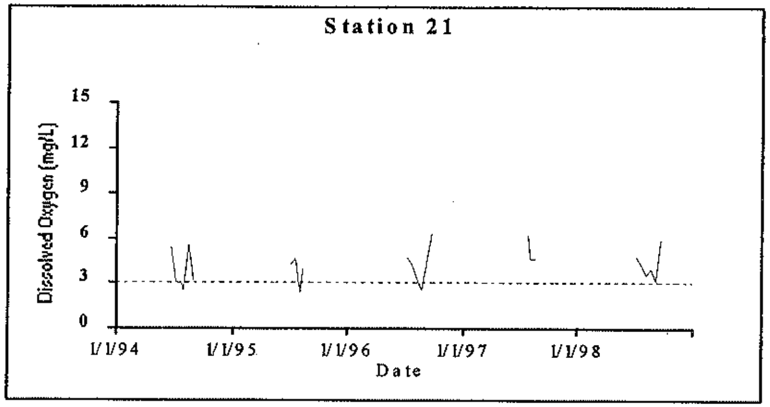
Station F3

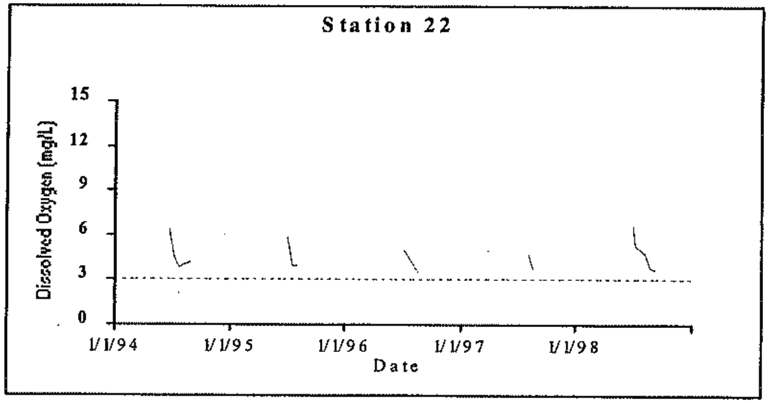
Central Basin - Bottom water D.O.

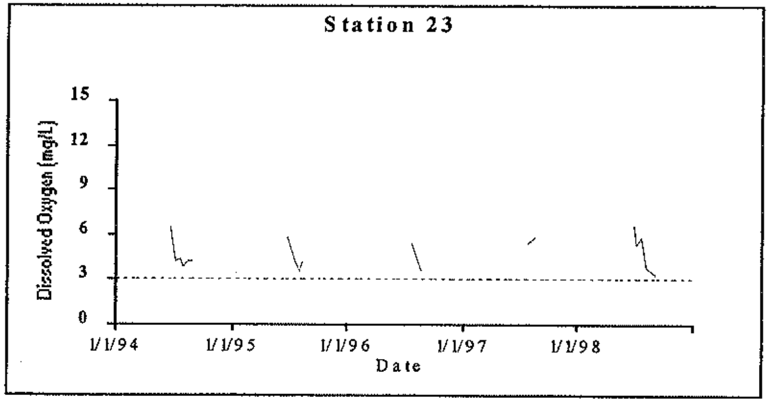




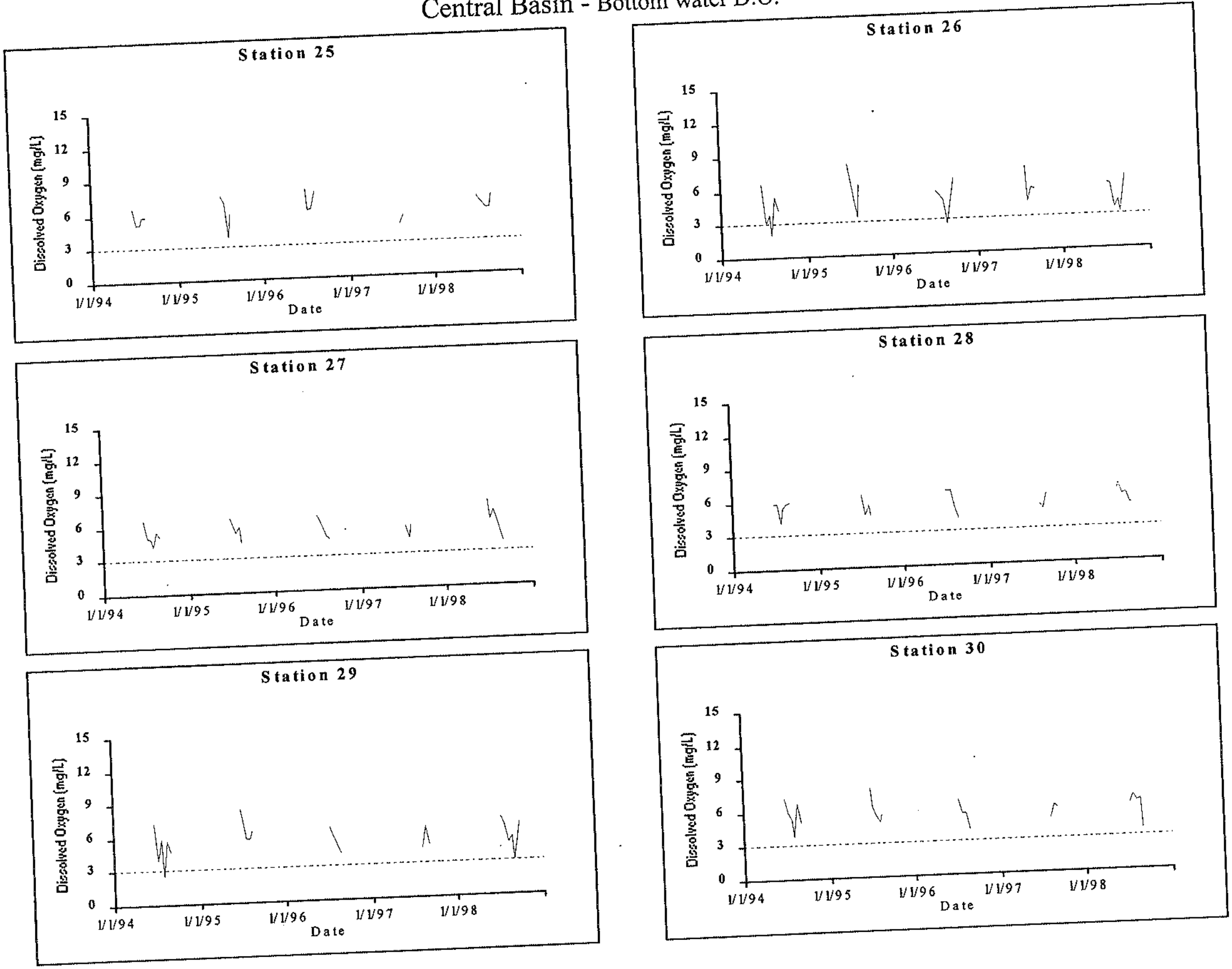




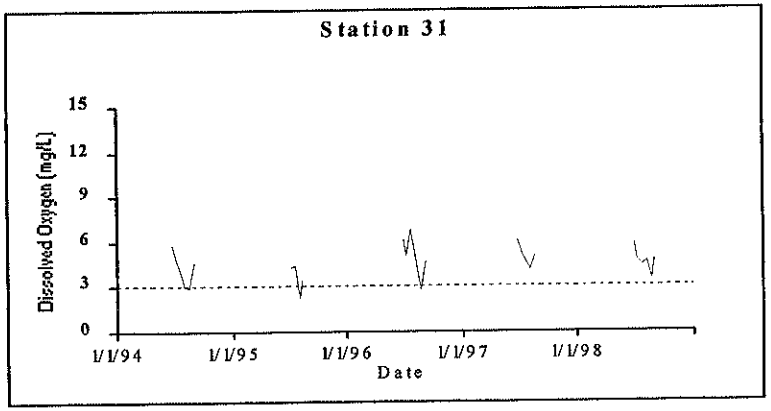




Central Basin - Bottom water D.O.



Central Basin - Bottom water D.O.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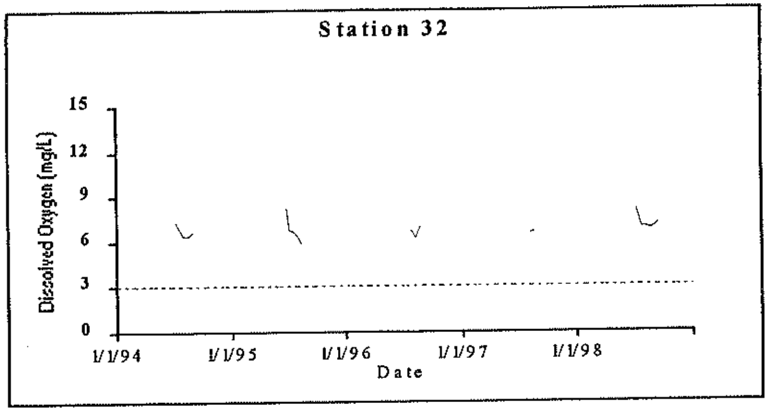
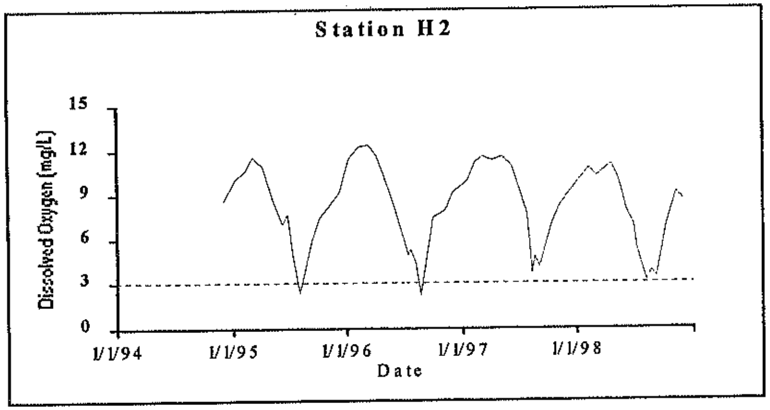
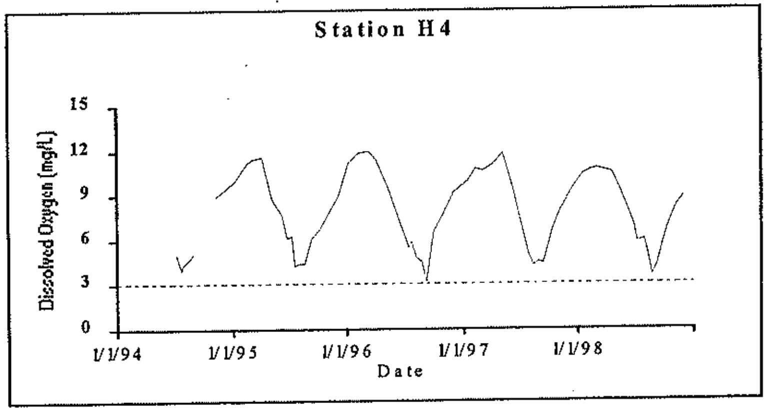
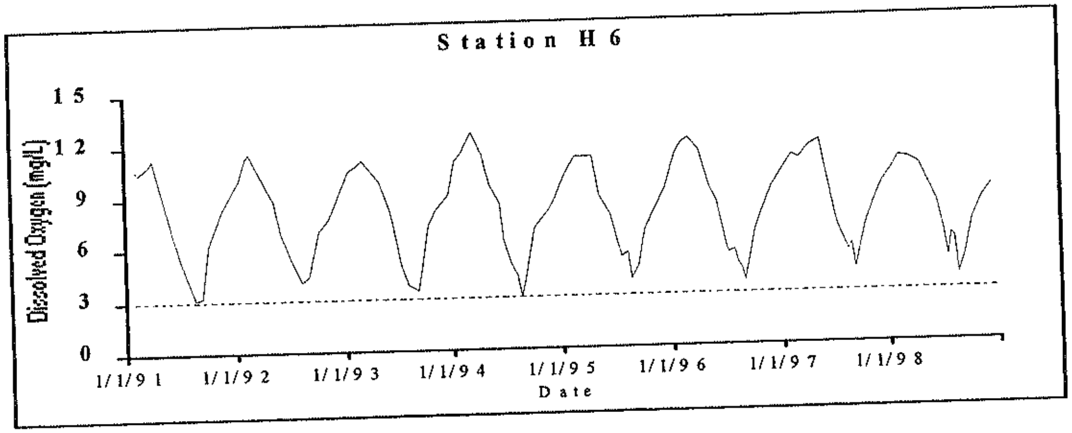
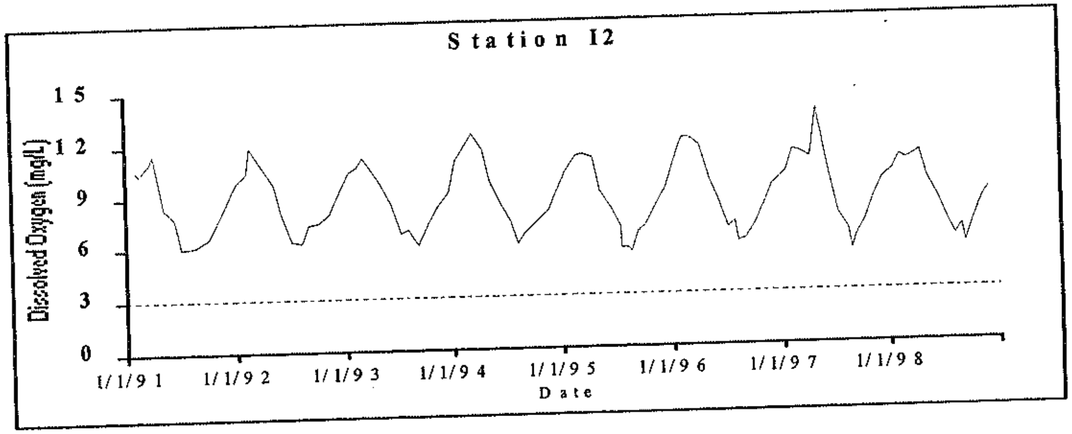

Station 32


Station H2

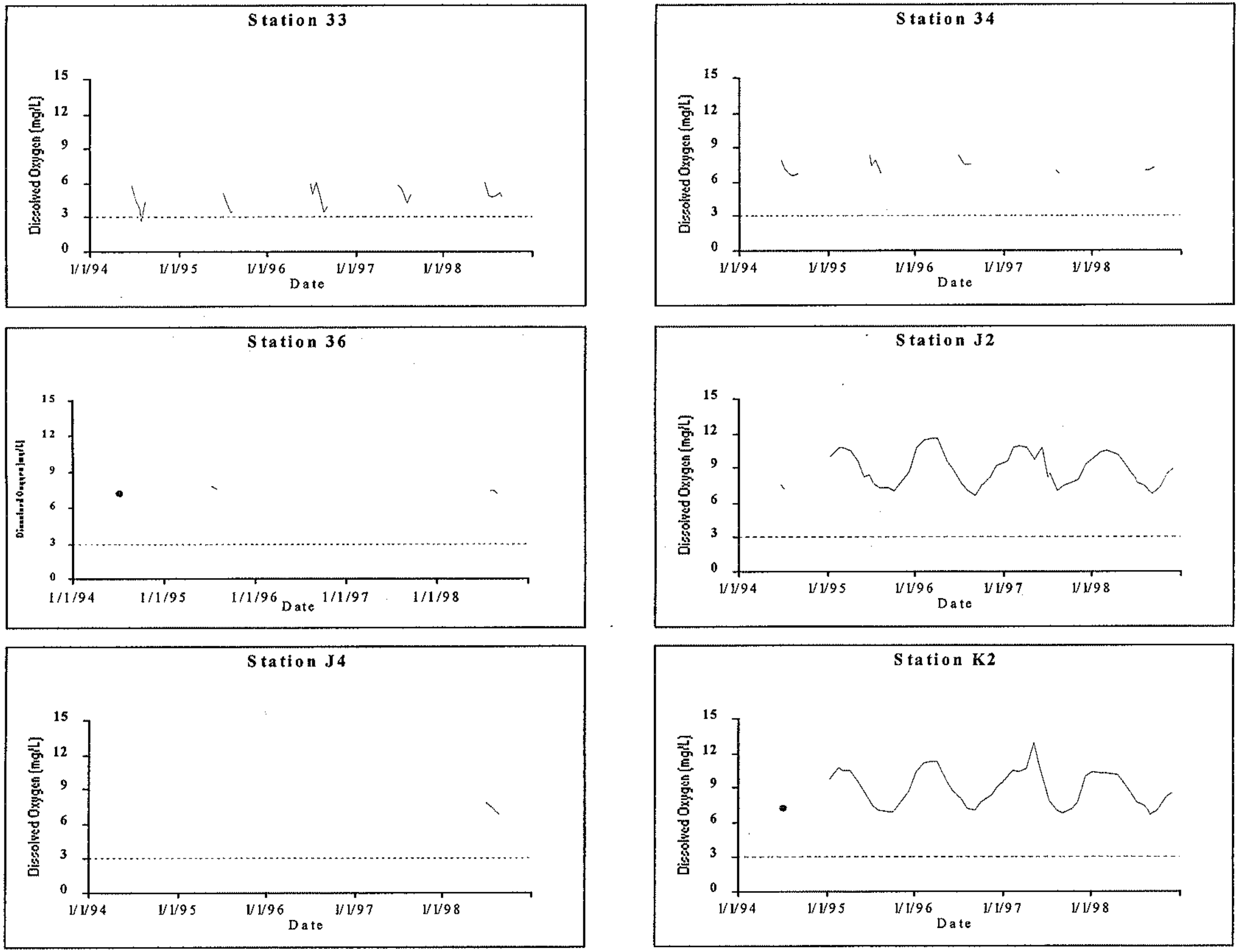

Station H4

Central Basin - Bottom water D.O.

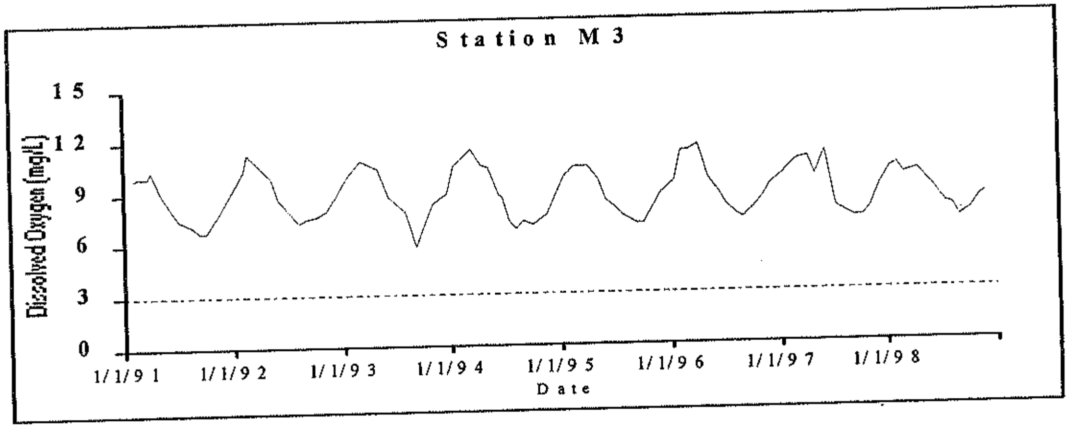

Station H6

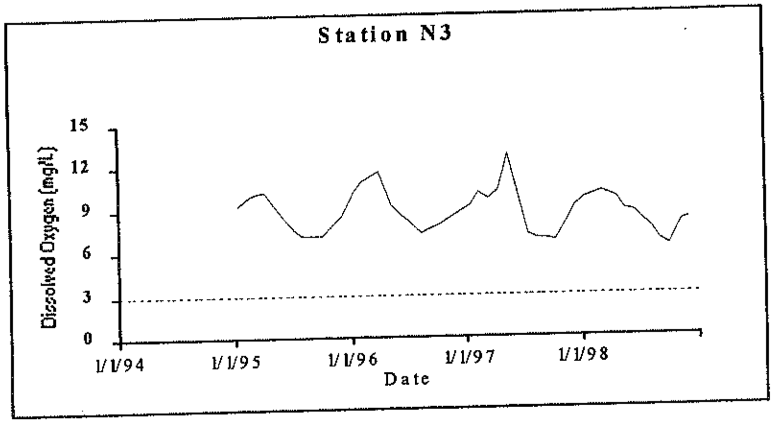

Station I2

Eastern Basin - Bottom water D.O.



Eastern Basin - Bottom water D.O.





APPENDIX B

Summary of Bottom Dissolved Oxygen Data for Each Station/Cruise

Stations Organized by Basin

1991 – 1998

(Some station records begin in 1994)

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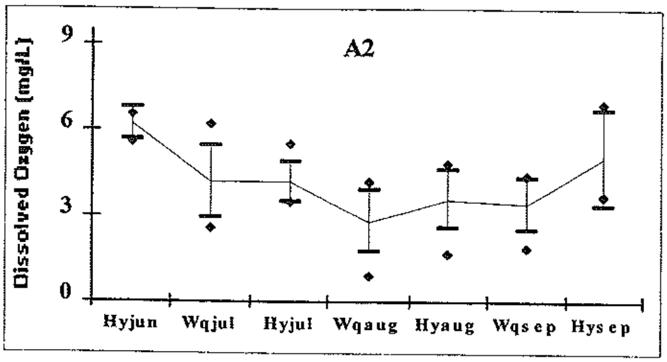
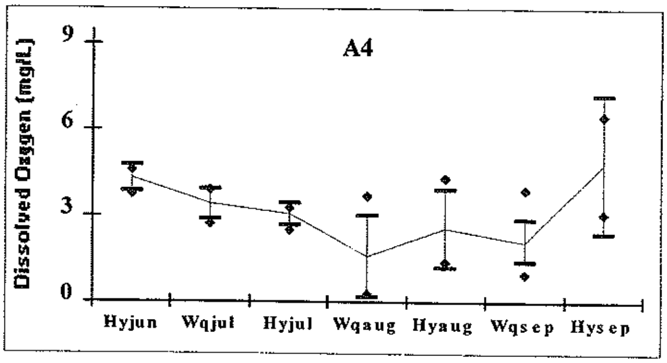
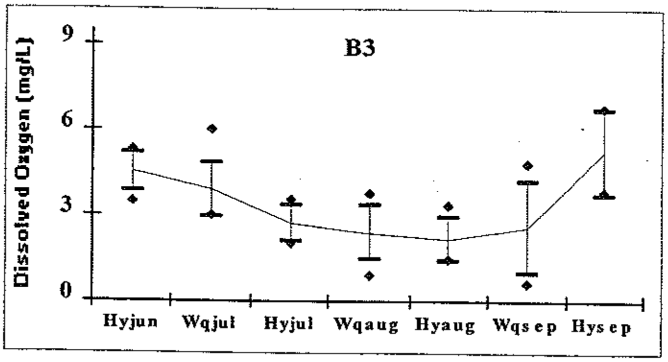
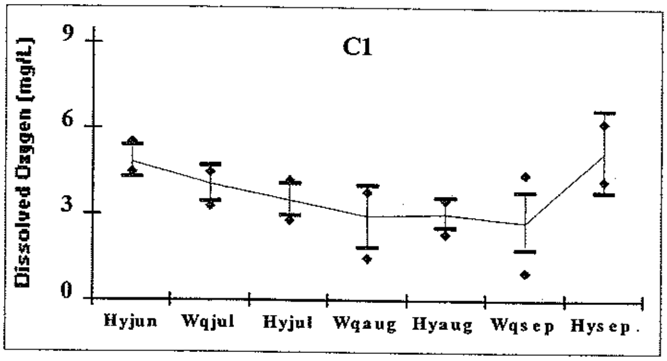
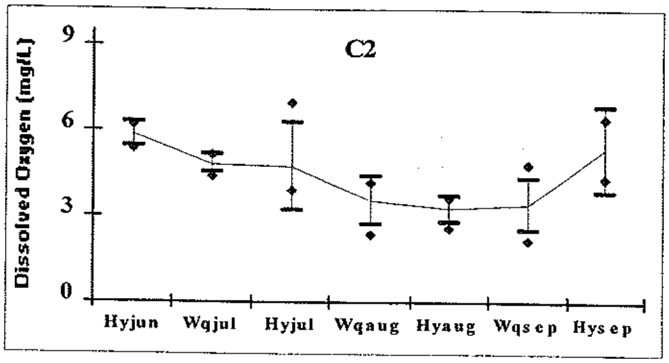
The Narrows

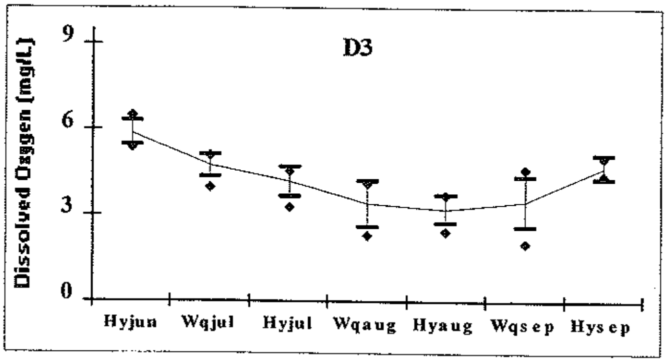


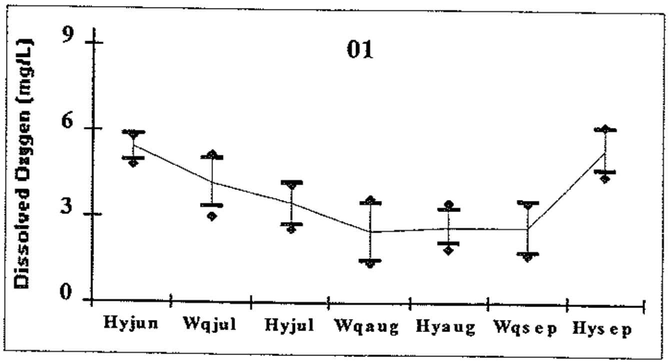










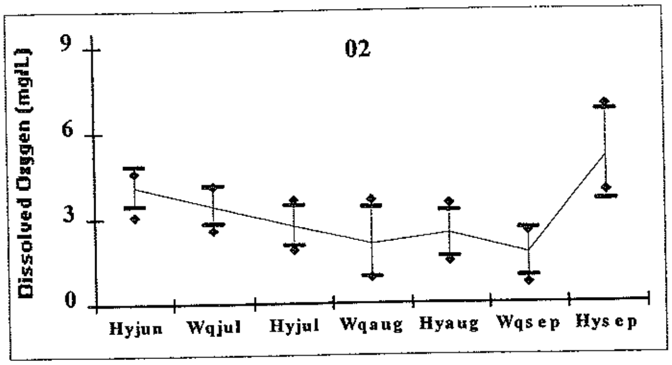


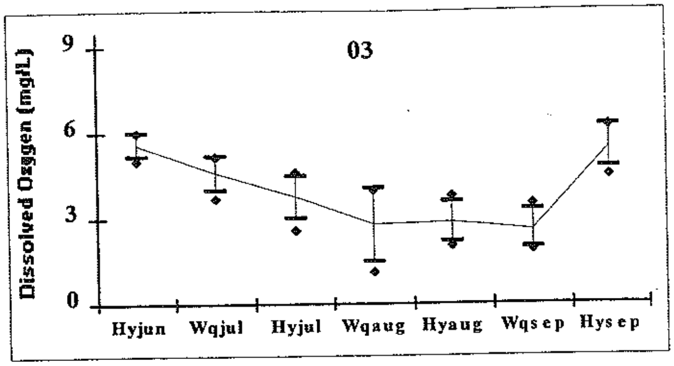
Number of observations for cruise (n)

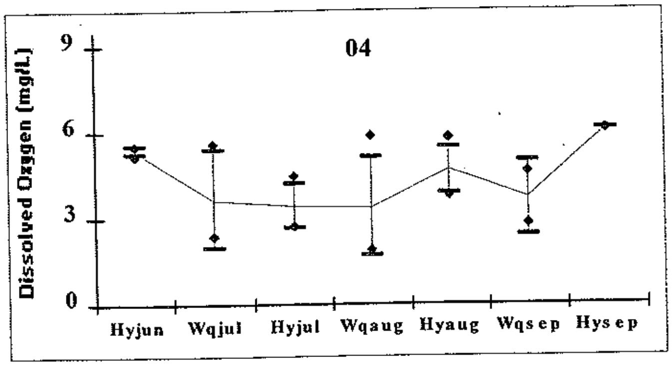
Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
A2	3	8	7	8	8	7	3
A4	3	4	4	5	4	4	2
B3	5	8	5	8	5	8	3
C1	3	3	4	4	4	4	2
C2	3	4	4	4	4	4	2
D3	5	7	5	8	5	8	2
01	5	5	5	5	5	3	4

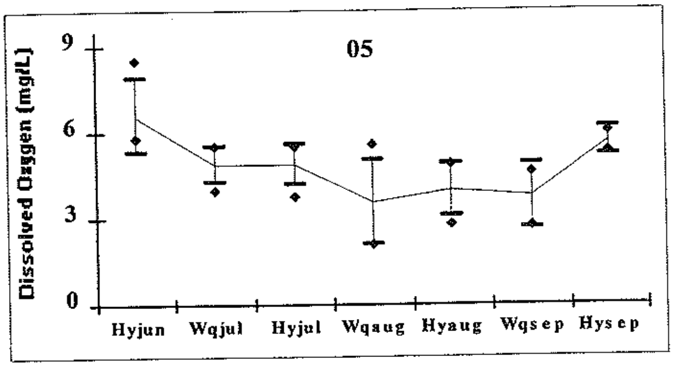
Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◇), by survey.

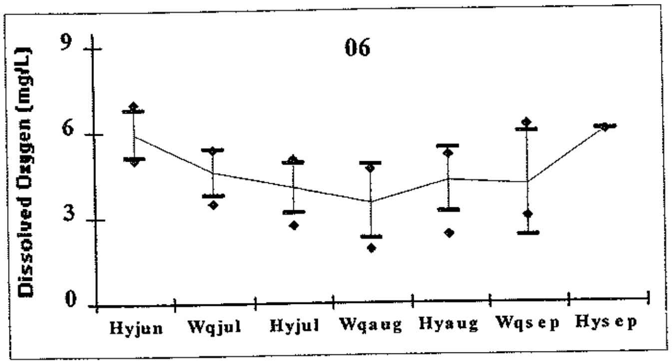
The Narrows

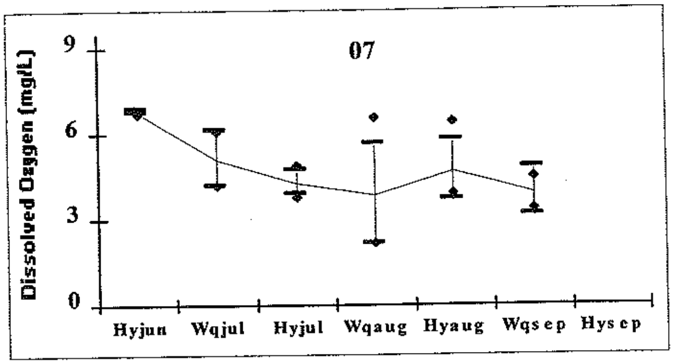


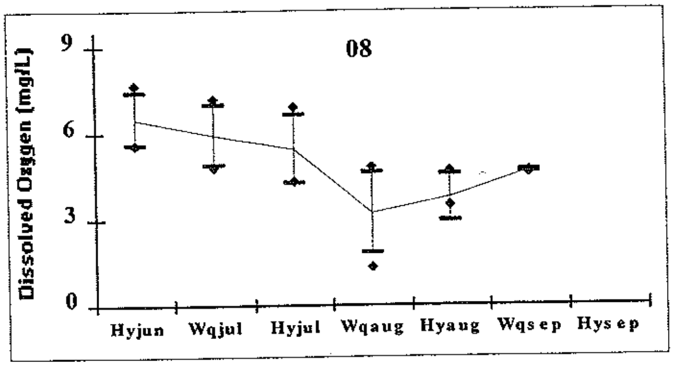








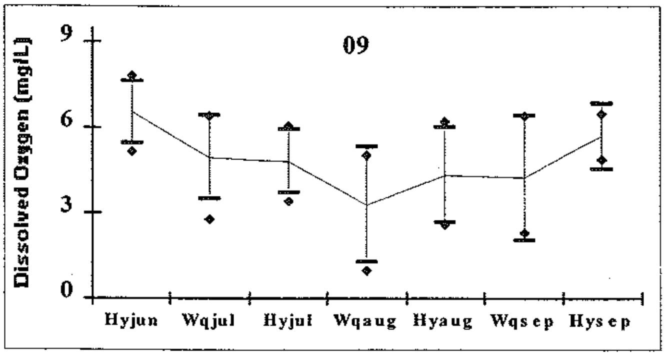


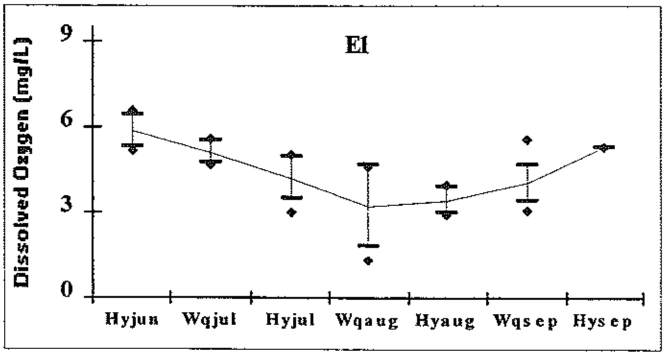


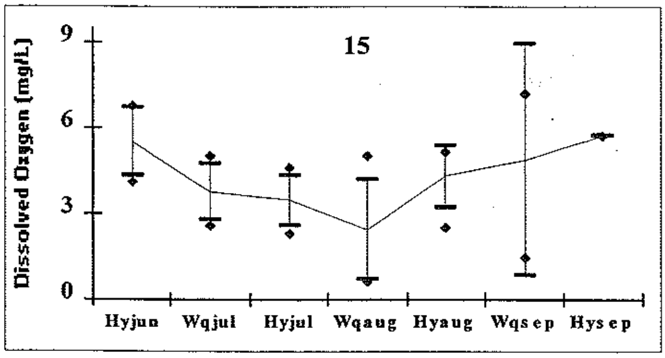
Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
02	4	5	5	5	5	4	3
03	4	5	5	5	5	4	4
04	3	3	5	5	5	2	1
05	4	5	5	5	5	4	2
06	4	4	5	5	5	3	1
07	2	3	5	5	5	2	0
08	4	4	5	5	4	3	0

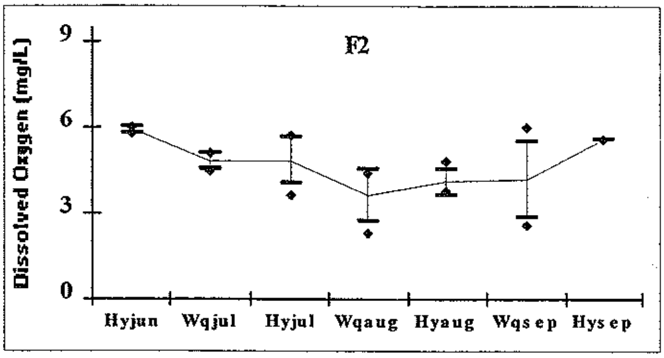
Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◊), by survey.

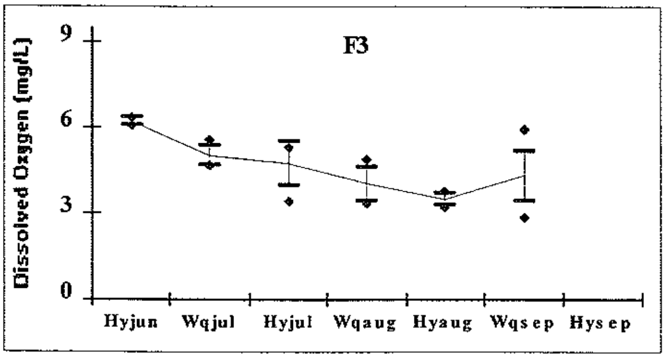
Western Basin

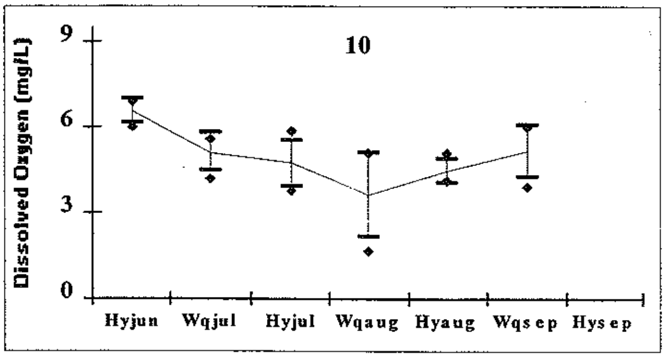


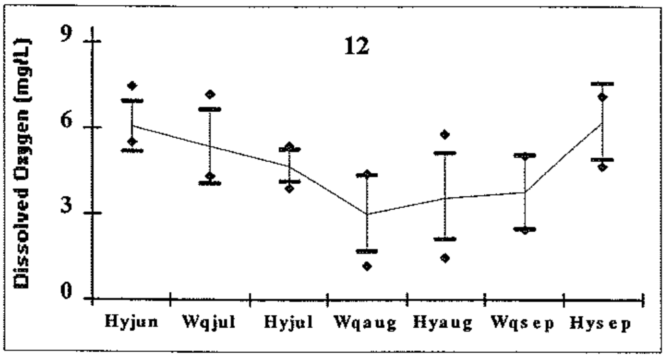








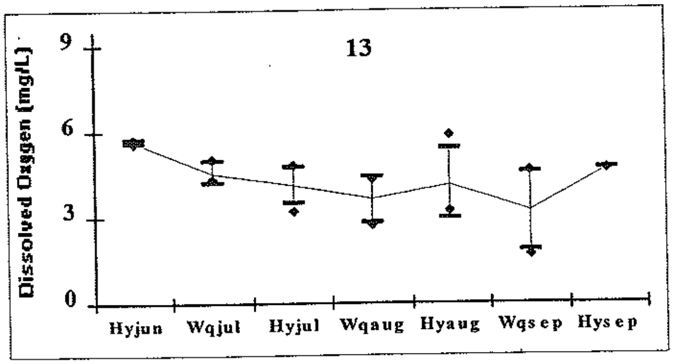


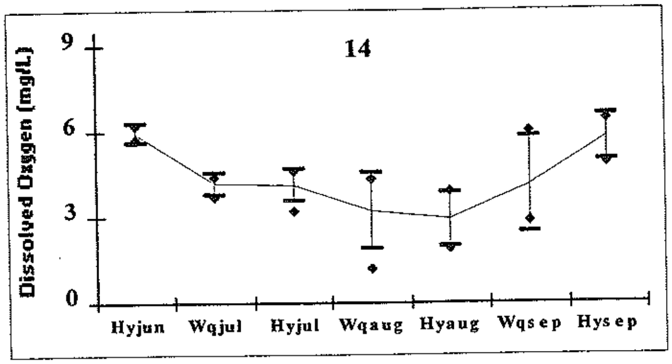


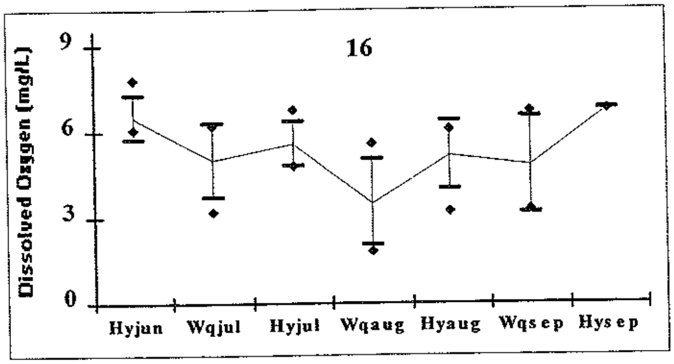
Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
09	5	5	5	5	5	5	2
E1	4	4	5	5	5	5	1
15	5	4	5	5	5	5	1
F2	4	4	5	5	4	5	1
F3	4	7	5	8	5	8	0
10	4	4	5	5	5	4	0
12	5	4	5	5	5	3	3

Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (⋄), by survey.

Western Basin



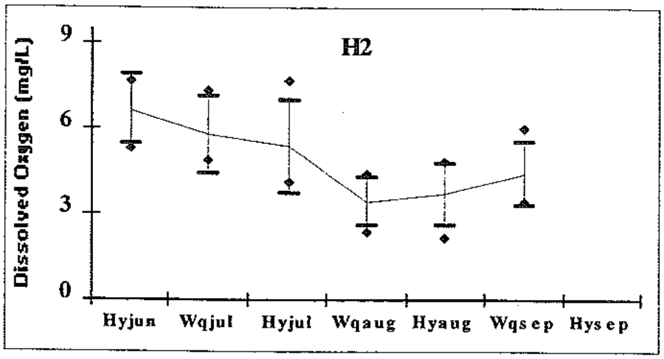


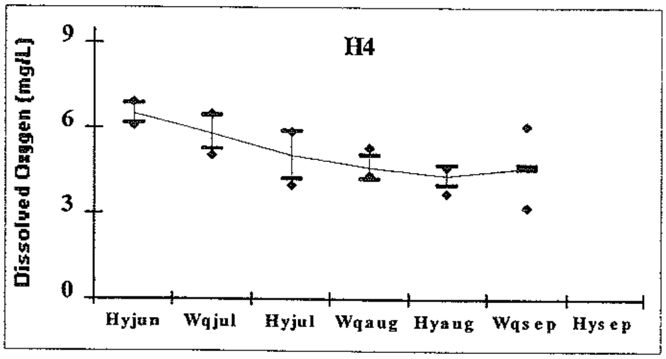


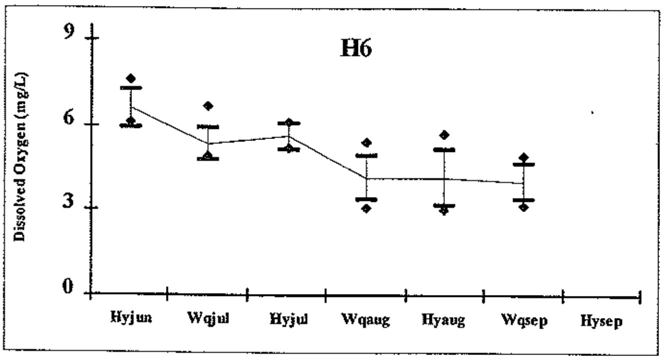
Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
13	2	3	5	5	4	4	1
14	2	3	5	5	5	3	3
16	5	4	5	5	5	4	1

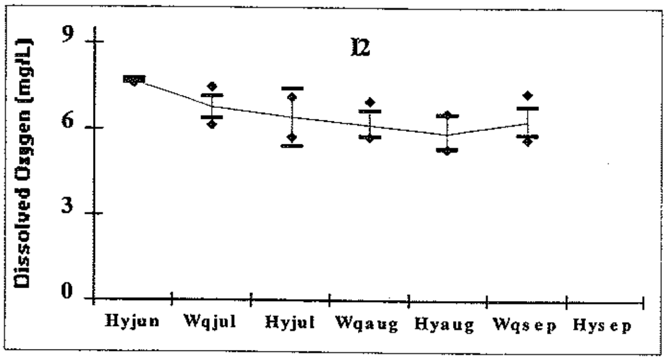
Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◇), by survey.

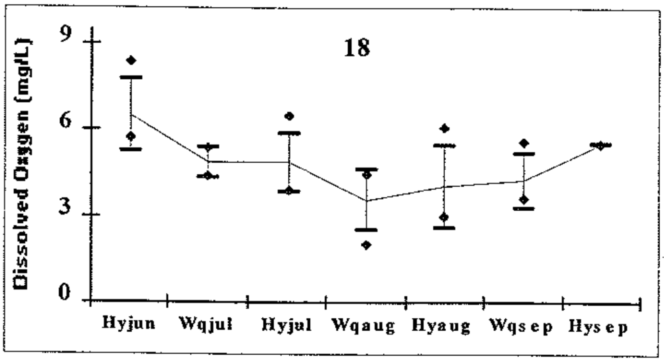
Central Basin

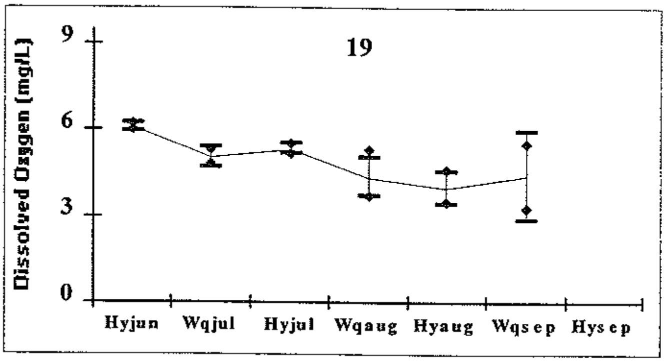


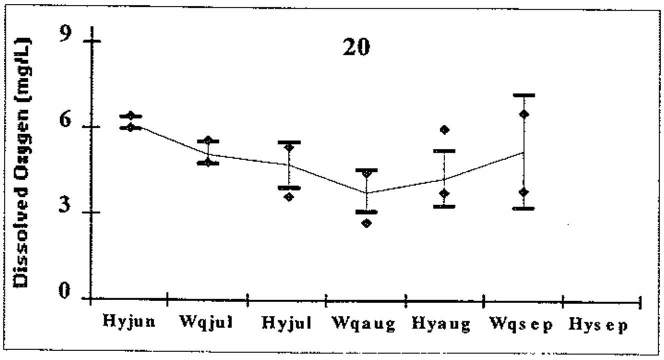








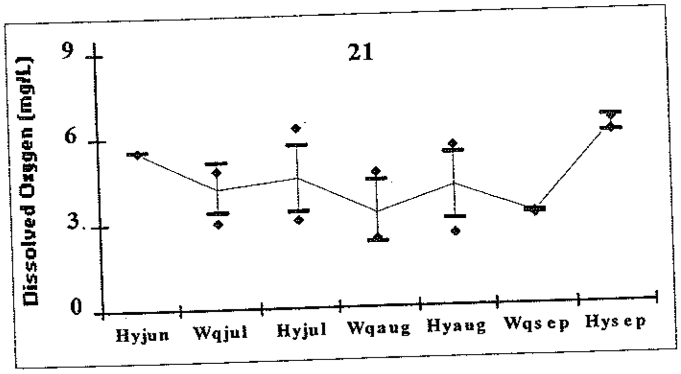


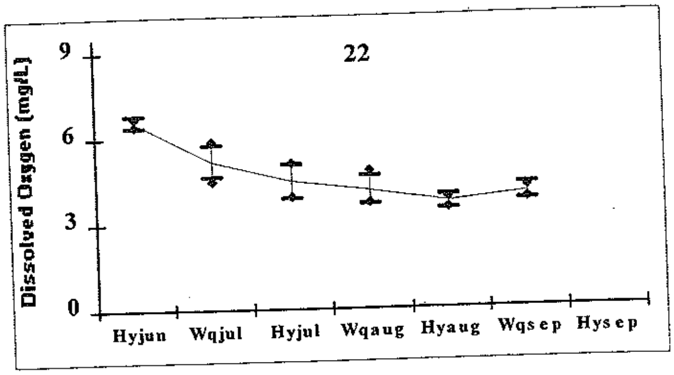


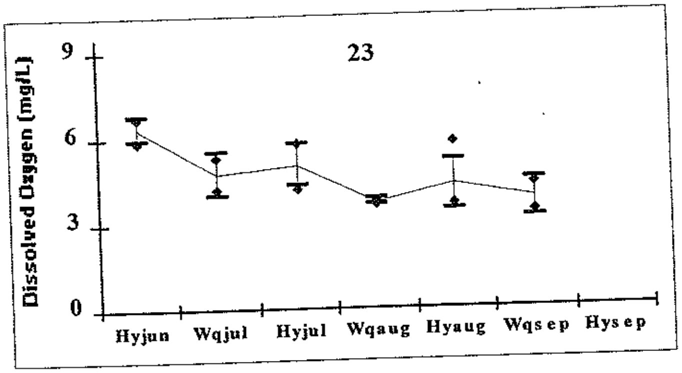
Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
H2	3	3	4	4	4	4	0
H4	4	5	5	5	5	5	0
H6	4	8	3	8	5	8	0
I2	2	8	2	8	4	8	0
18	4	3	5	5	4	4	1
19	2	2	3	5	3	2	0
20	3	3	4	5	5	2	0

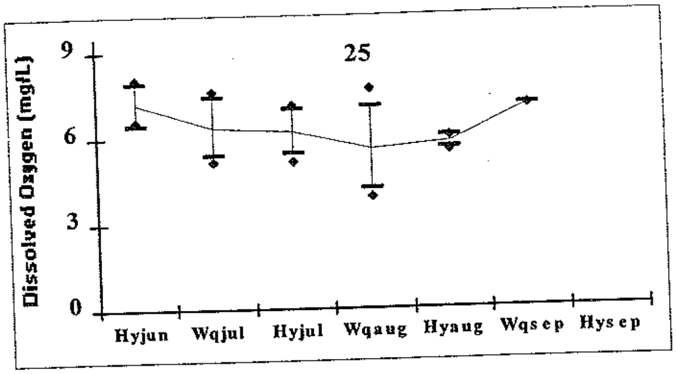
Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◇), by survey.

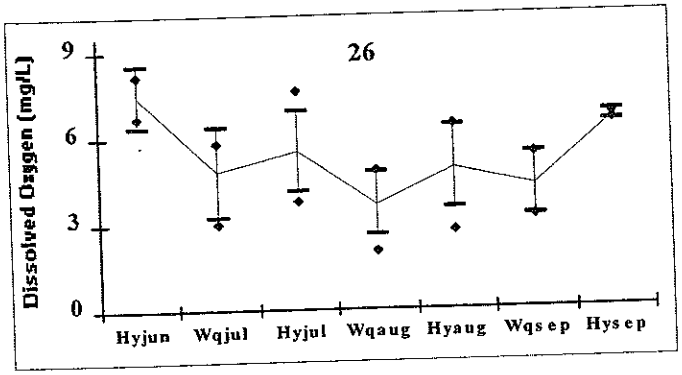
Central Basin

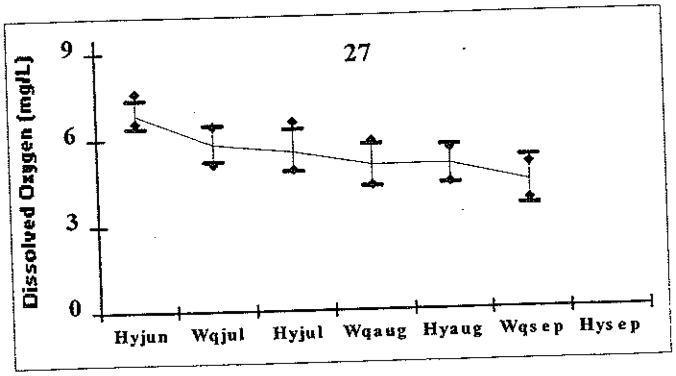


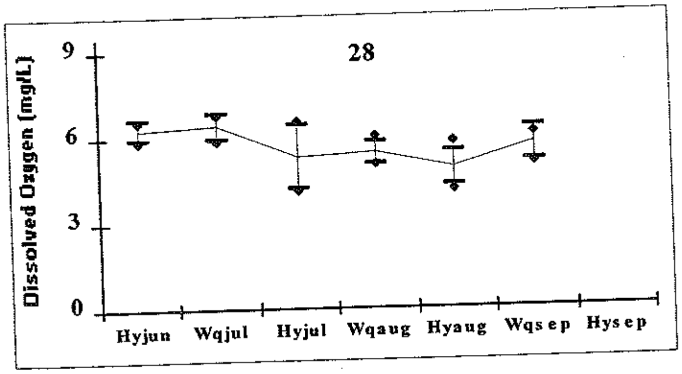








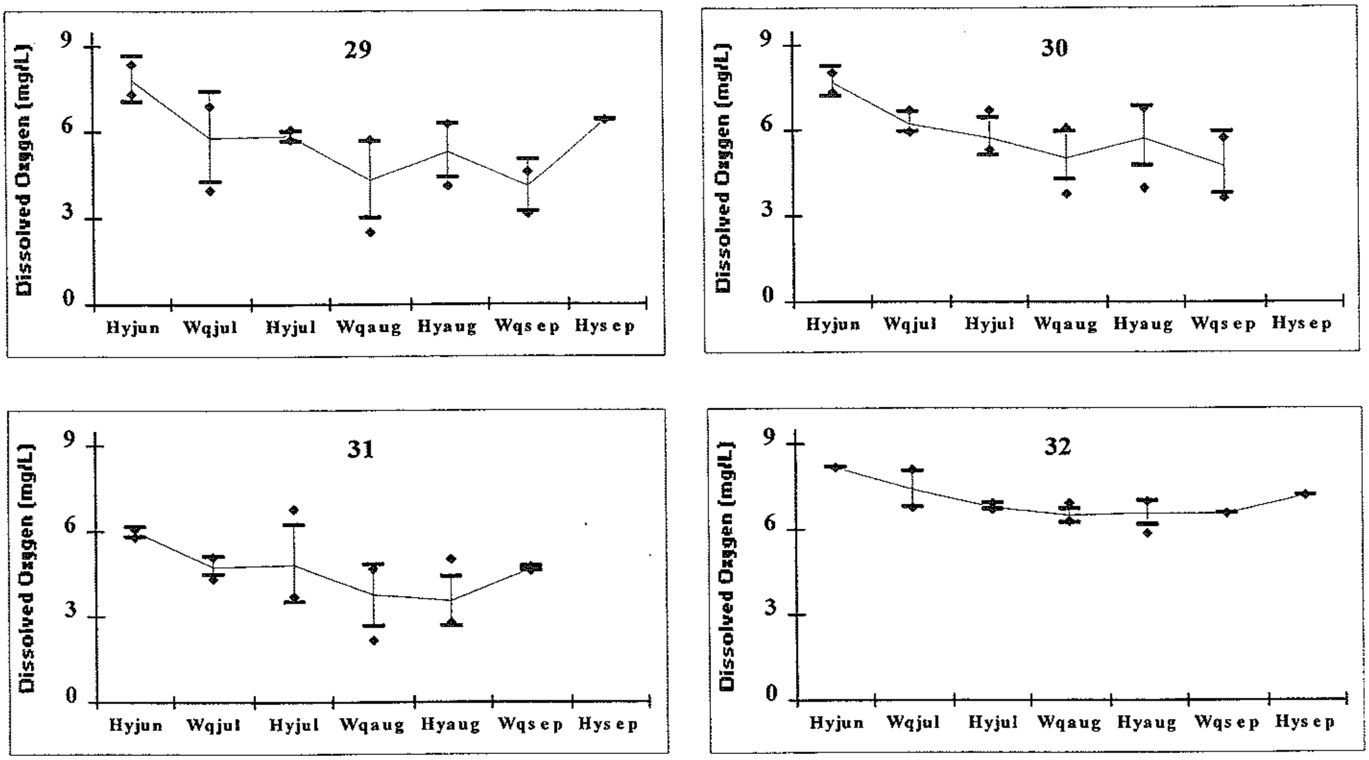




Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
21	1	4	5	4	5	2	2
22	2	4	4	4	2	2	0
23	3	2	5	3	5	2	0
25	3	4	4	5	4	1	0
26	2	3	5	5	5	3	2
27	4	3	4	5	4	2	0
28	3	3	4	5	5	3	0

Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◇), by survey.

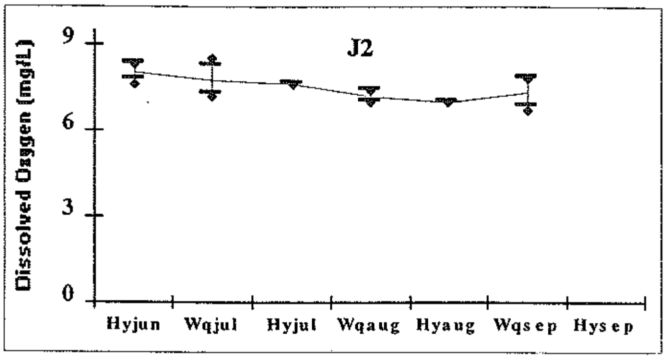
Central Basin

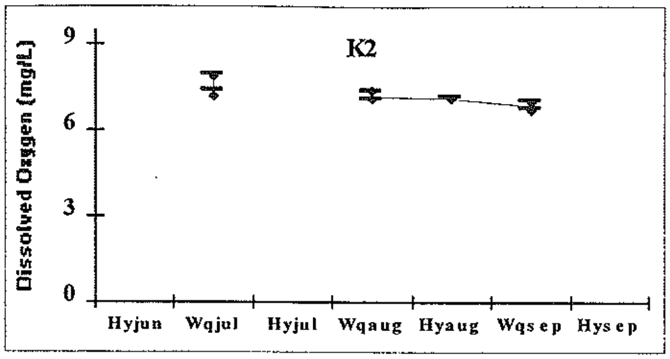


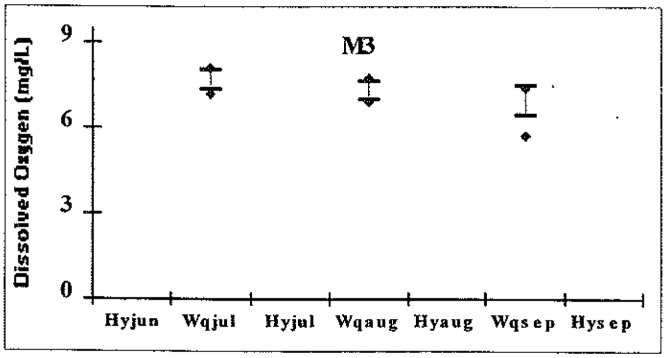
Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
29	2	3	4	4	4	3	1
30	2	4	4	5	5	3	0
31	4	5	4	5	5	3	0
32	1	3	3	5	5	1	1

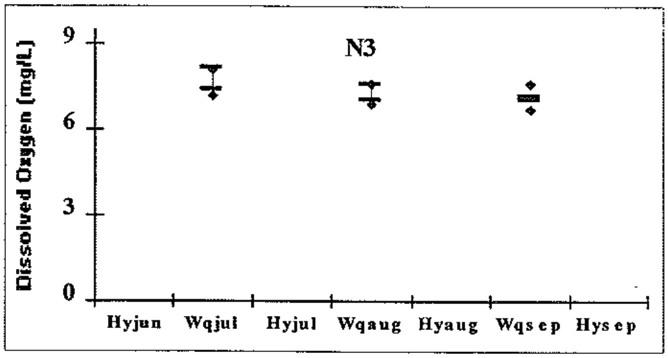
Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◊), by survey.

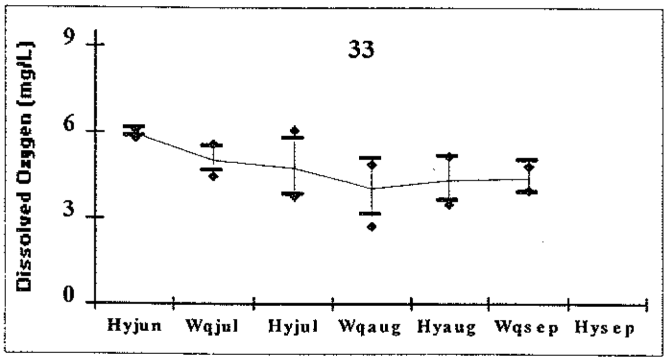
Eastern Basin

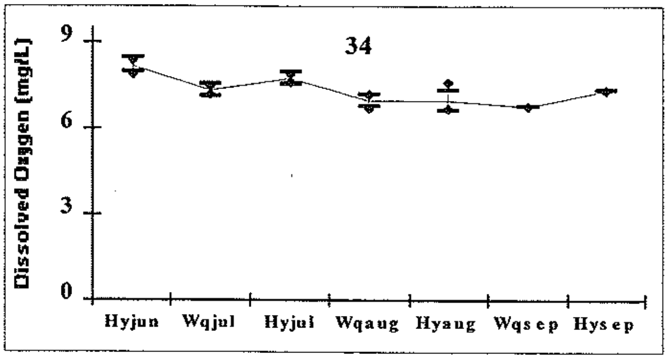


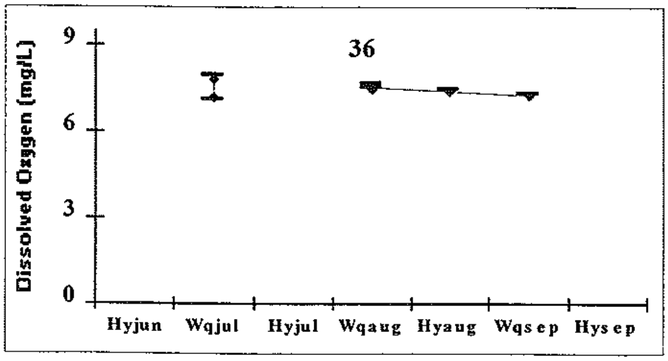












Station Name	Hyjun	Wqjul	Hyjul	Wqaug	Hyaug	Wqsep	Hysep
J2	4	5	1	4	1	4	0
K2	0	5	0	4	1	4	0
M3	0	8	0	8	0	8	0
N3	0	4	0	4	0	4	0
33	4	5	4	5	5	2	0
34	3	2	2	4	5	1	1
36	0	2	0	2	1	1	0

Mean bottom dissolved oxygen (--), the standard deviation about the mean (I), and high and low values (◇), by survey.

APPENDIX C

STATION AND AREA MAPS:

Maps of Long Island Sound for Each Cruise Showing
1) Stations Sampled and 2) Dissolved Oxygen
Distribution by Surface Area

1991 – 1998

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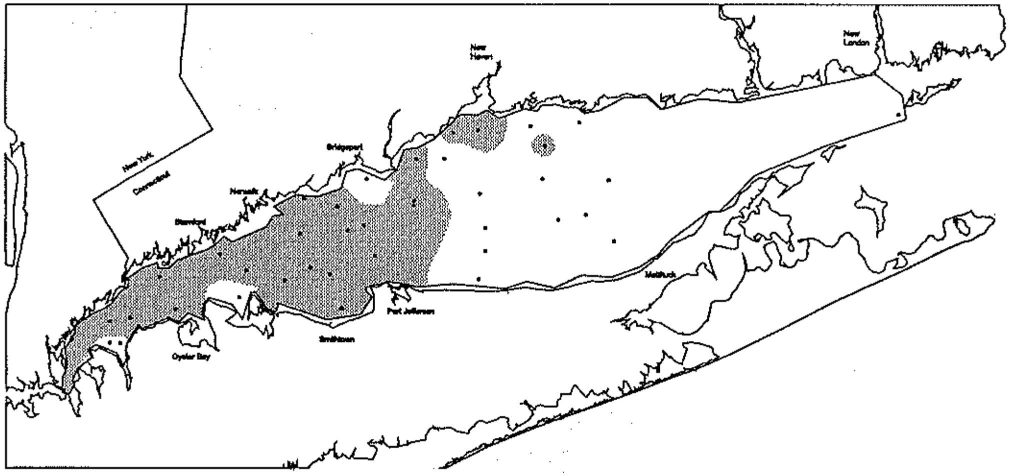
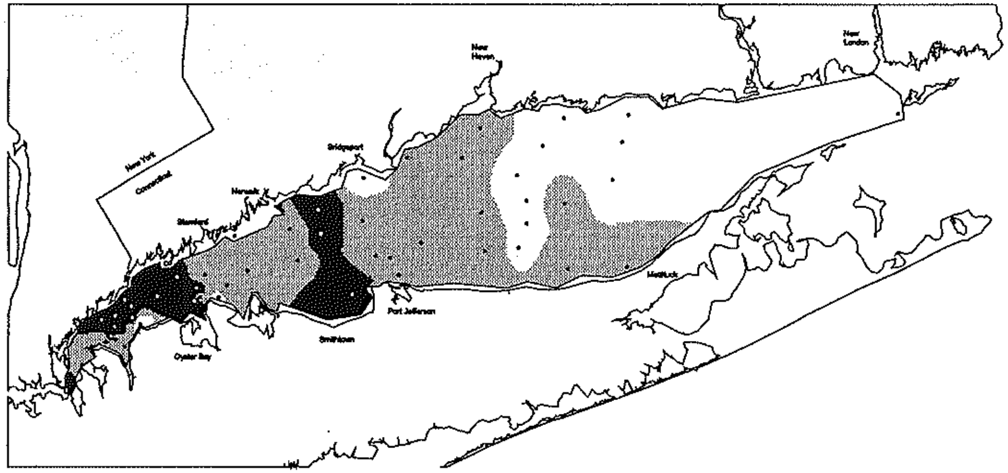
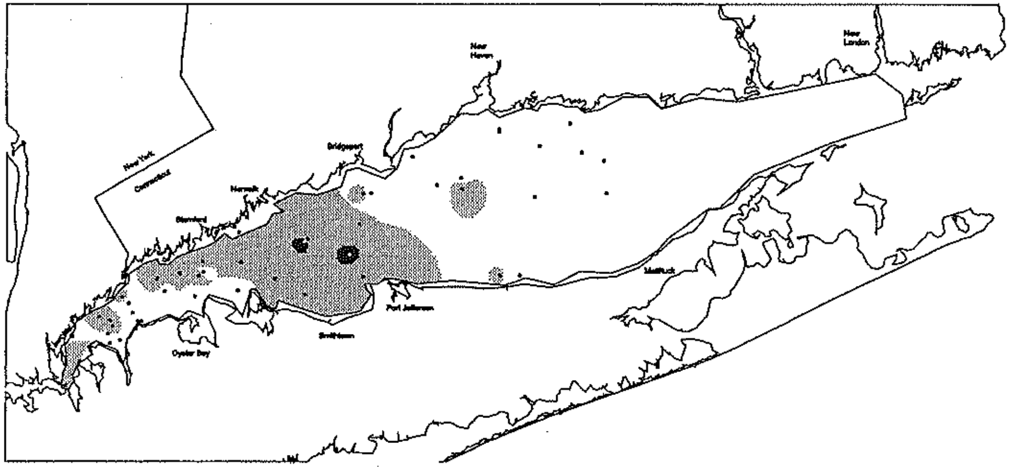


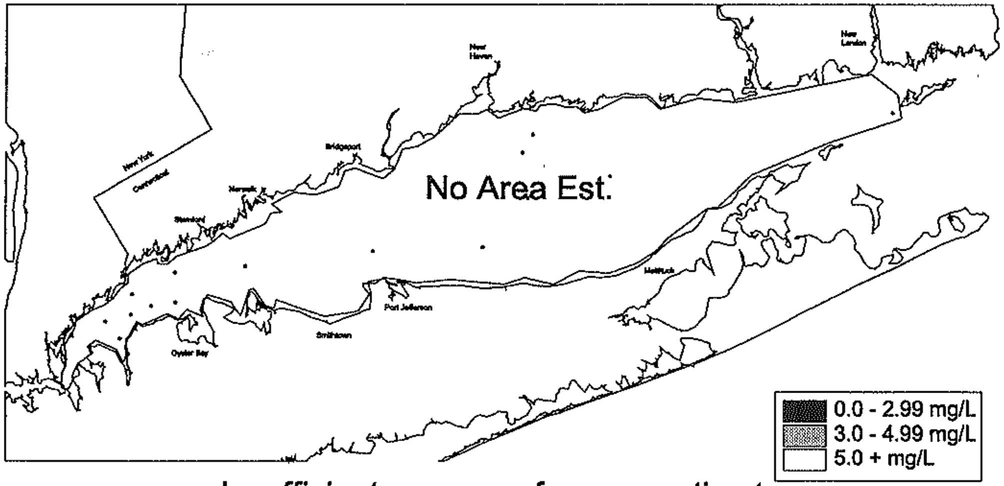
WQJUL91
July 8 - 18, 1991



WQAUG91
July 29 - August 13, 1991



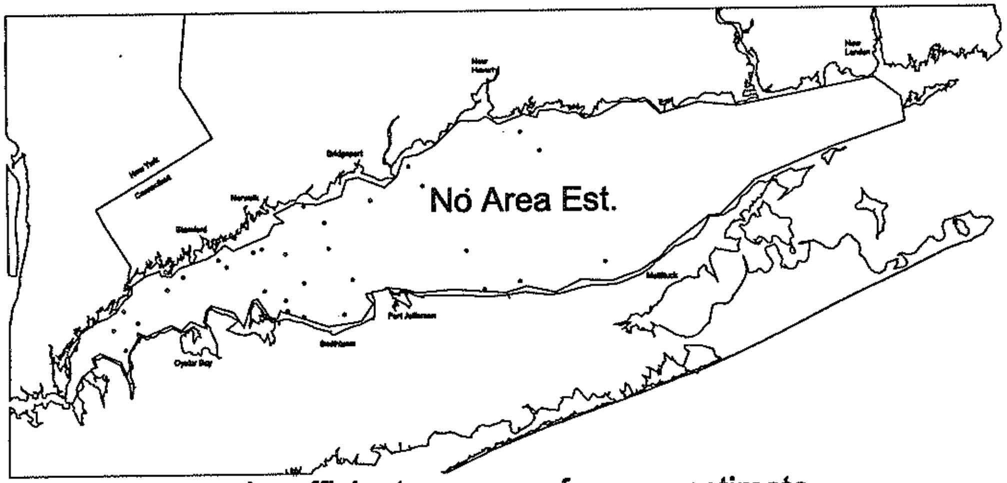
HYAUG91
August 21 - 28, 1991



WQSEP91
September 4 - 12, 1991

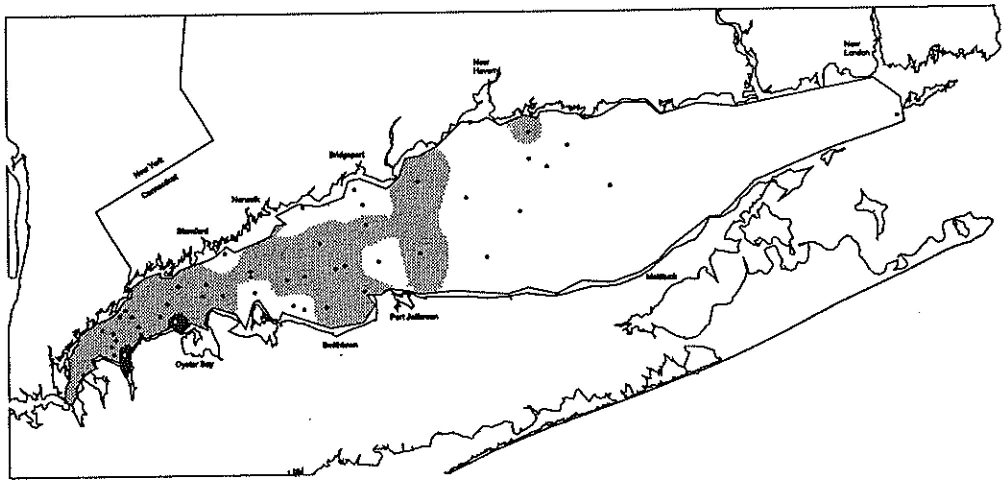
Insufficient coverage for area estimate
No hypoxia recorded

HYJUN92
June 29 - July 2, 1992

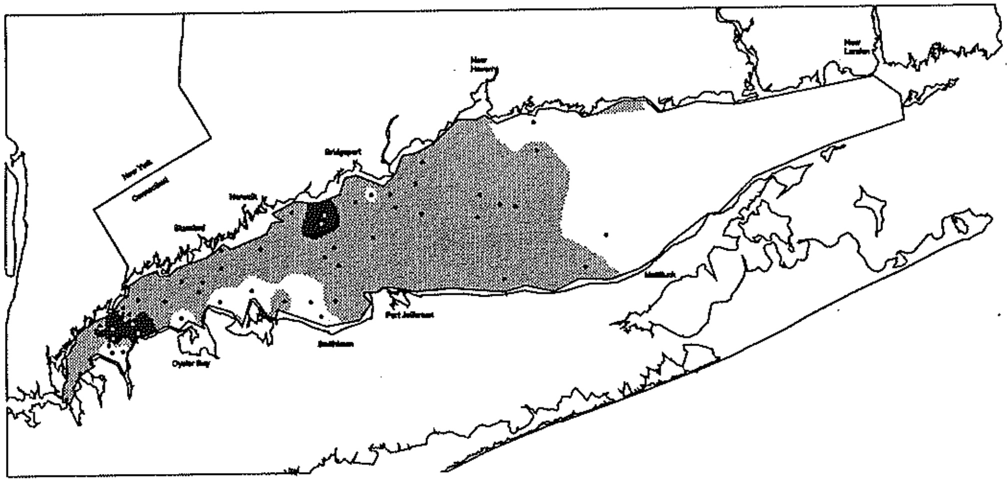


Insufficient coverage for area estimate
No hypoxia recorded

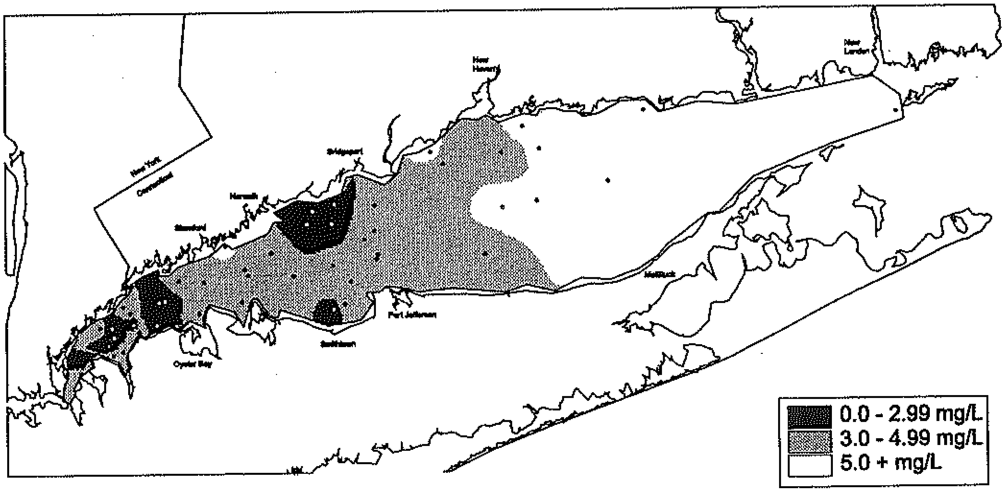
WQJUL92
July 7 - 20, 1992



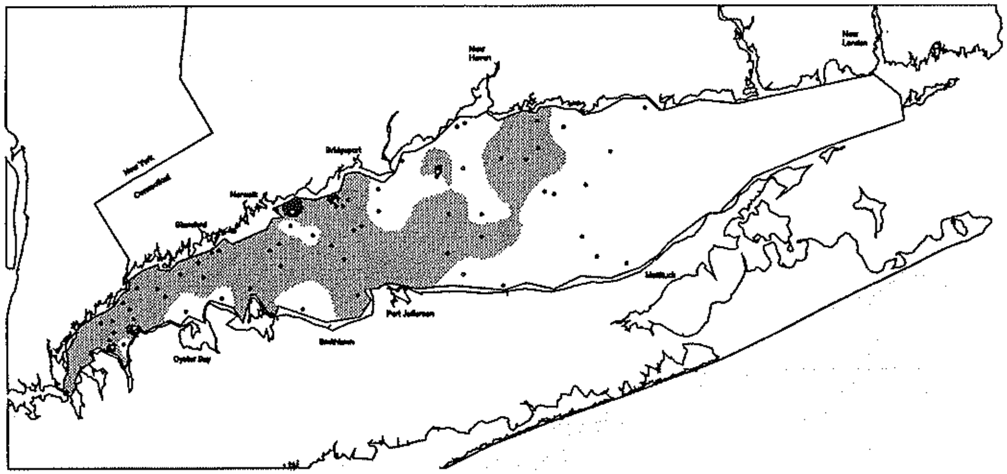
HYJUL92
July 27 - 30, 1992



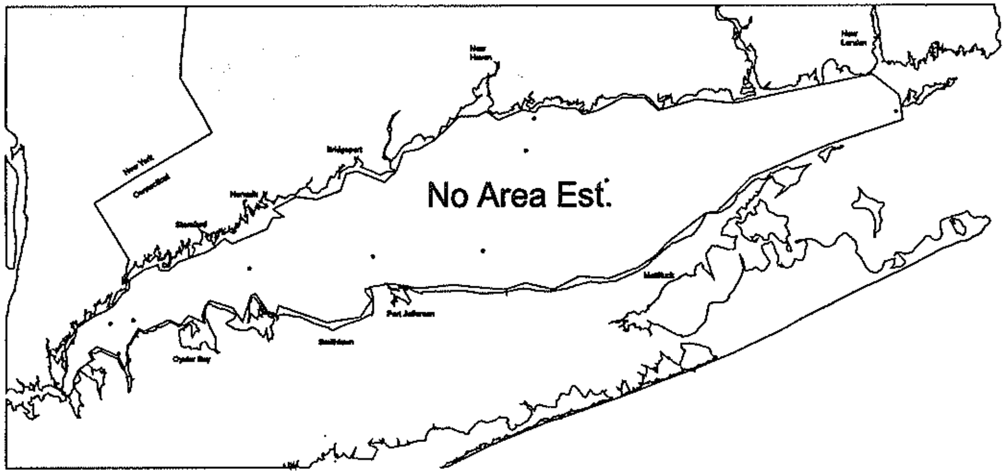
WQAUG92
August 5 - 13, 1992



HYAUG92
August 17 - 28, 1992



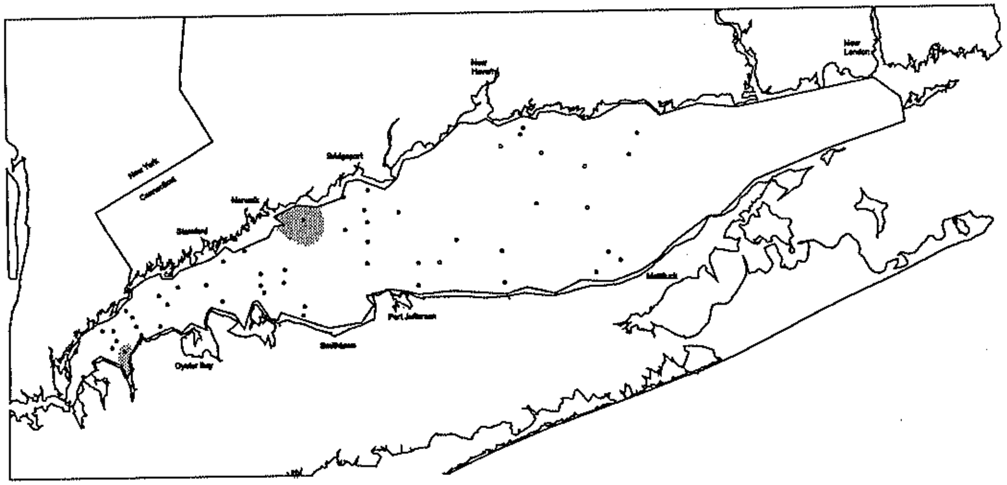
WQSEP92
September 1 - 9, 1992



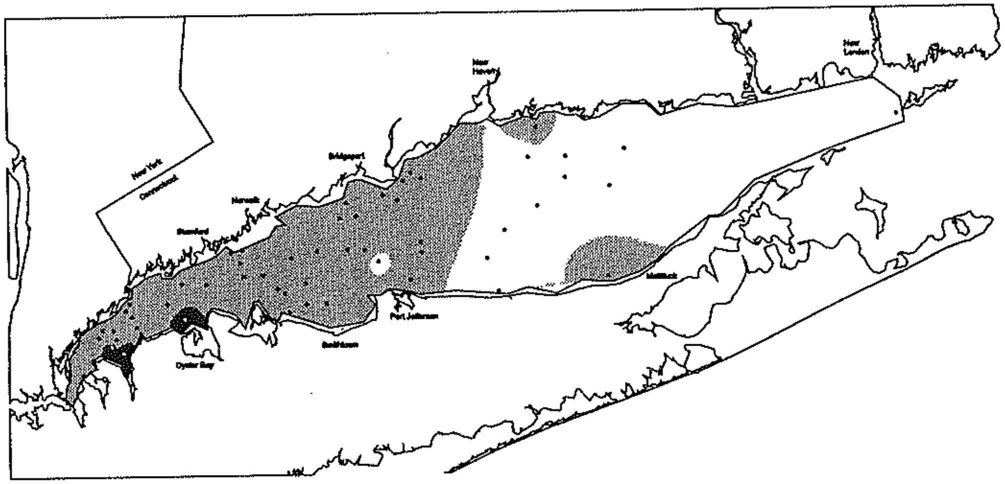
Insufficient coverage for area estimate
No hypoxia recorded

■ 0.0 - 2.99 mg/L
▨ 3.0 - 4.99 mg/L
☐ 5.0 + mg/L

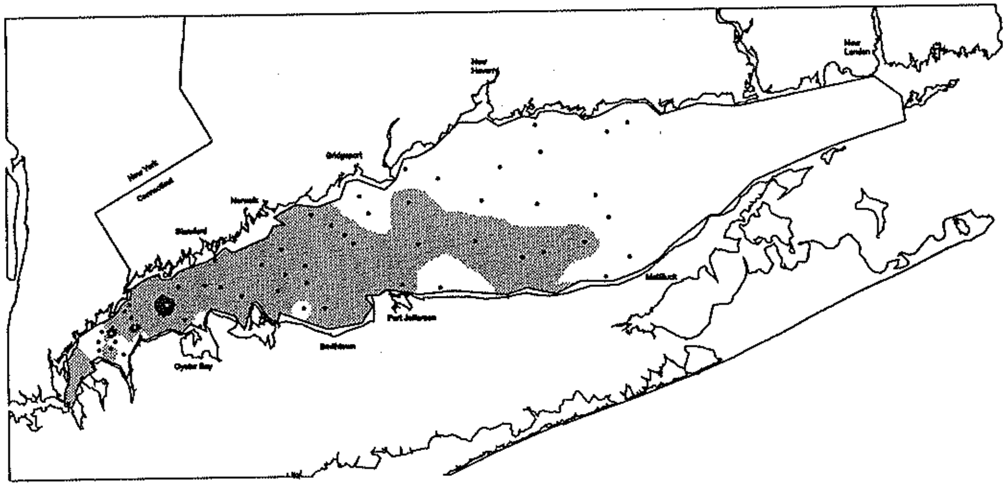
HYJUN93
June 28 - July 2, 1993



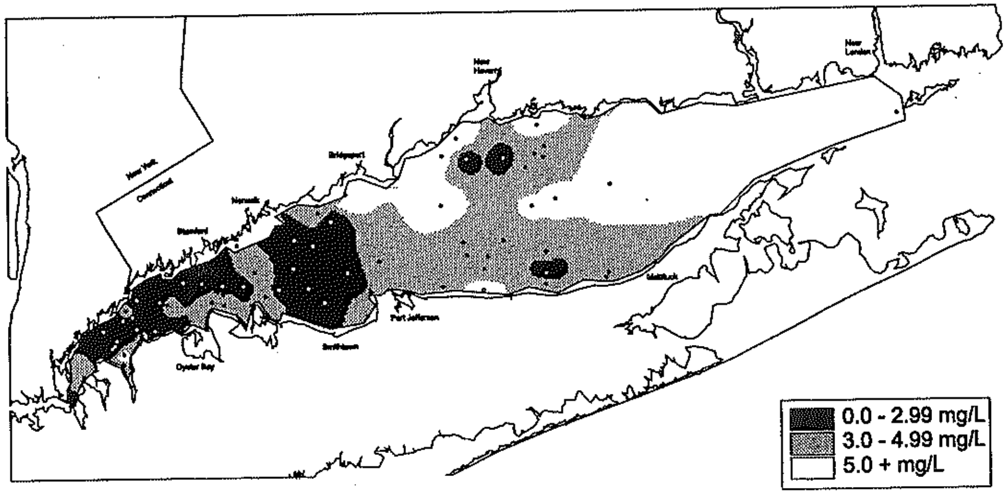
WQJUL93
July 7 - 15, 1993



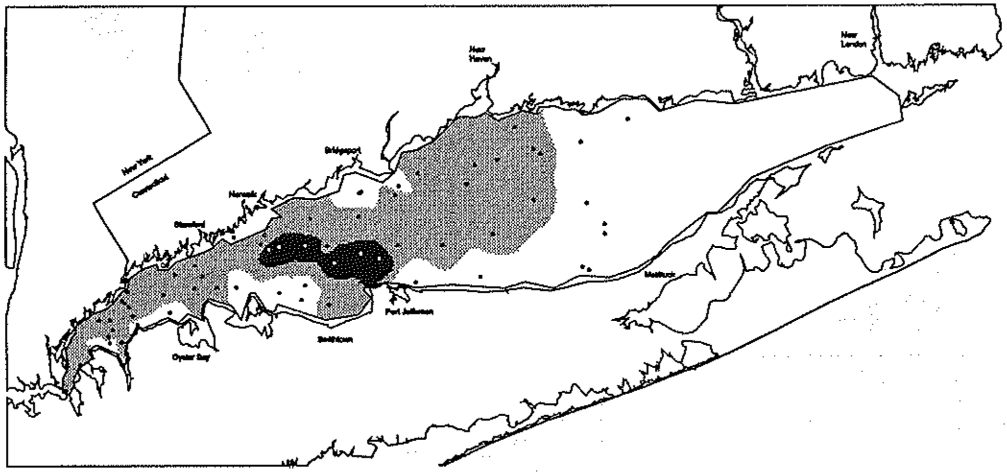
HYJUL93
July 26 - 29, 1993



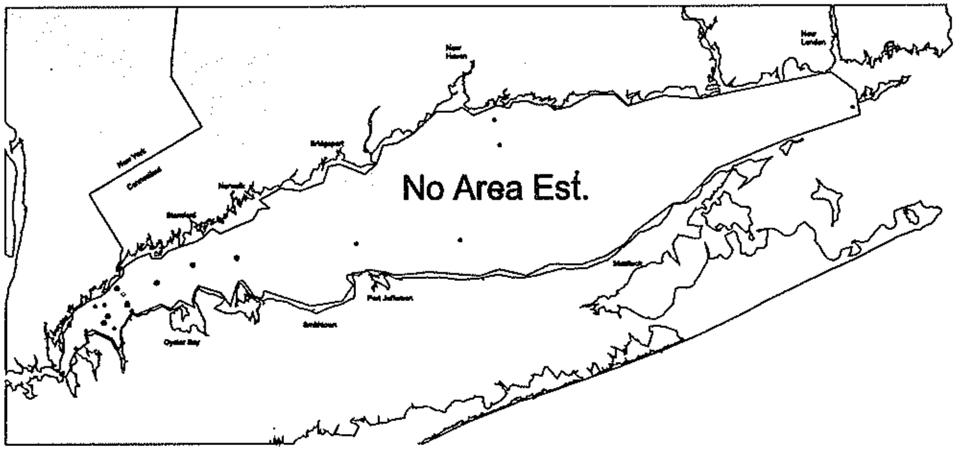
WQAUG93
August 2 - 12, 1993



HYAUG93
August 17 - 26, 1993



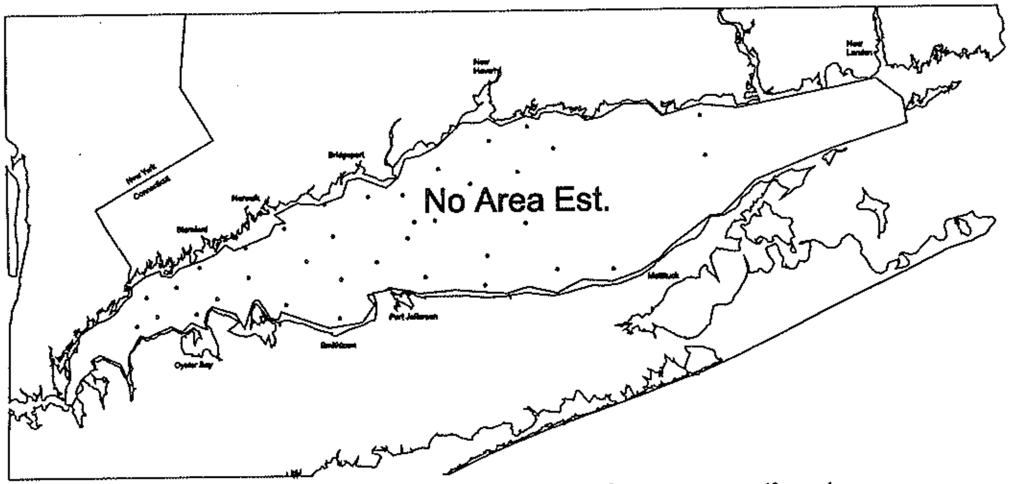
WQSEP93
September 7 - 9, 1993



Insufficient coverage for area estimate
Hypoxia present in Narrows

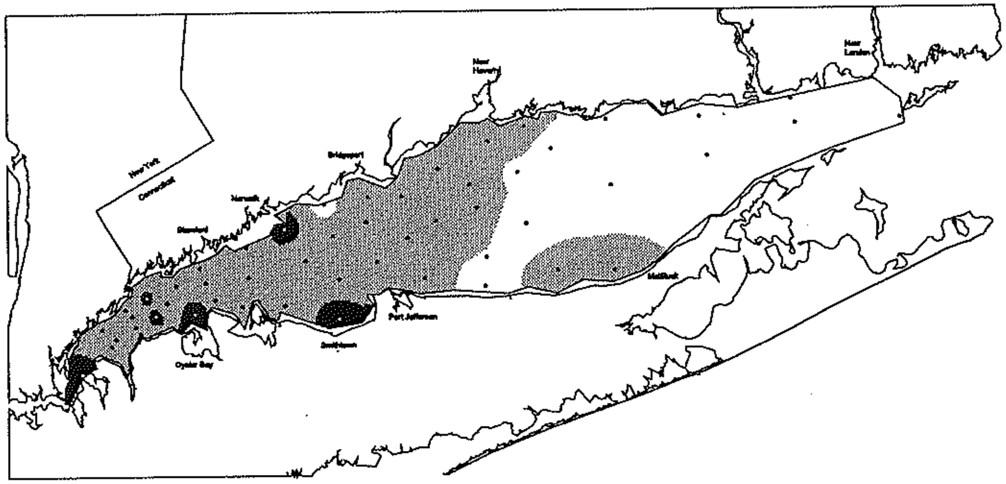
■ 0.0 - 2.99 mg/L
▨ 3.0 - 4.99 mg/L
☐ 5.0 + mg/L

HYJUN94
June 21 - 23, 1994

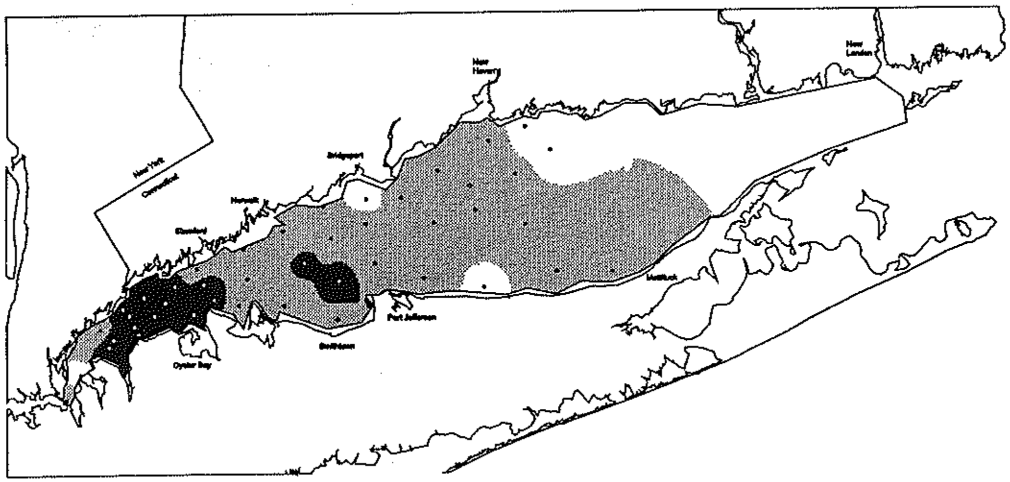


Insufficient coverage in Narrows for area estimate
No hypoxia recorded

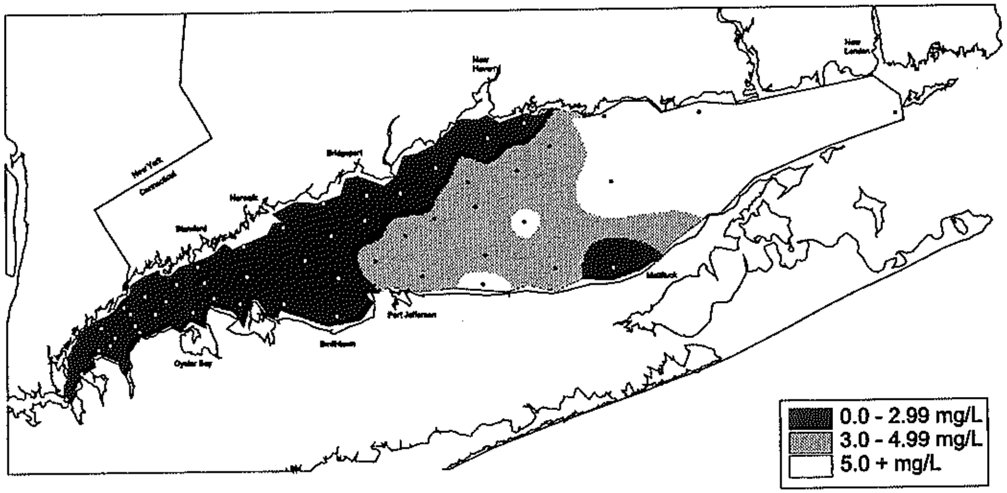
WQJUL94
July 5 - 11, 1994



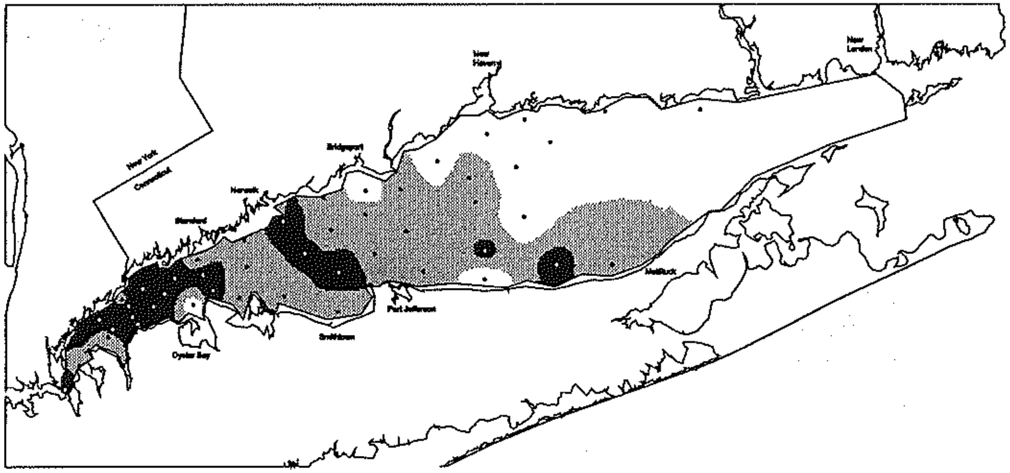
HYJUL94
July 20 - 22, 1994



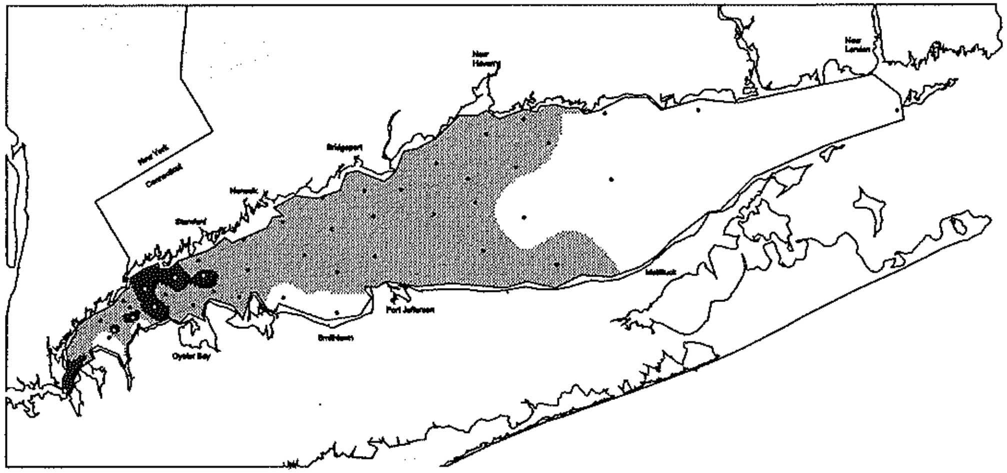
WQAUG94
August 1 - 4, 1994



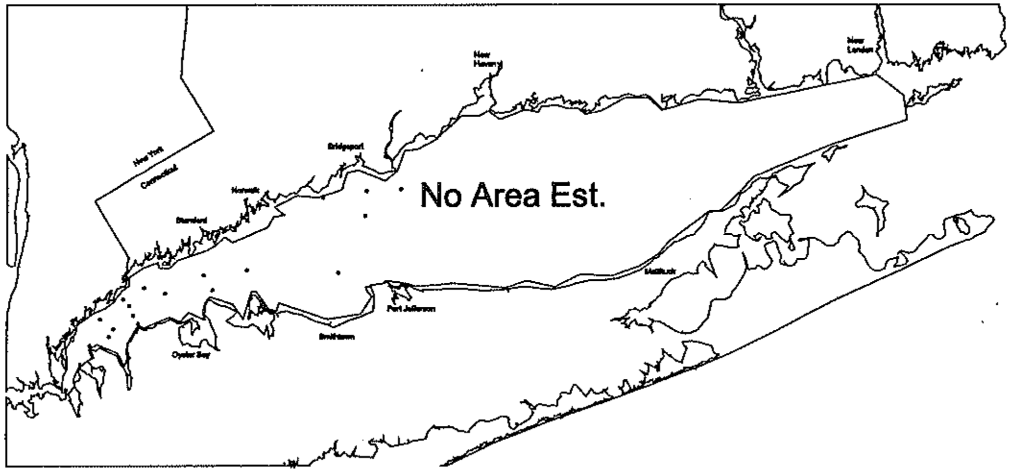
HYAUG94
August 16 - 18, 1994



WQSEP94
August 29 - September 1, 1994



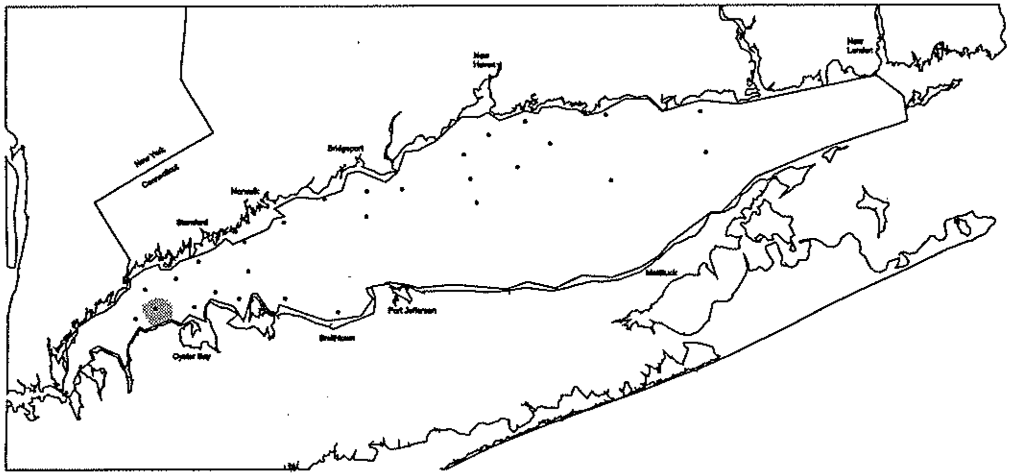
HYSEP94
September 7 - 8, 1994



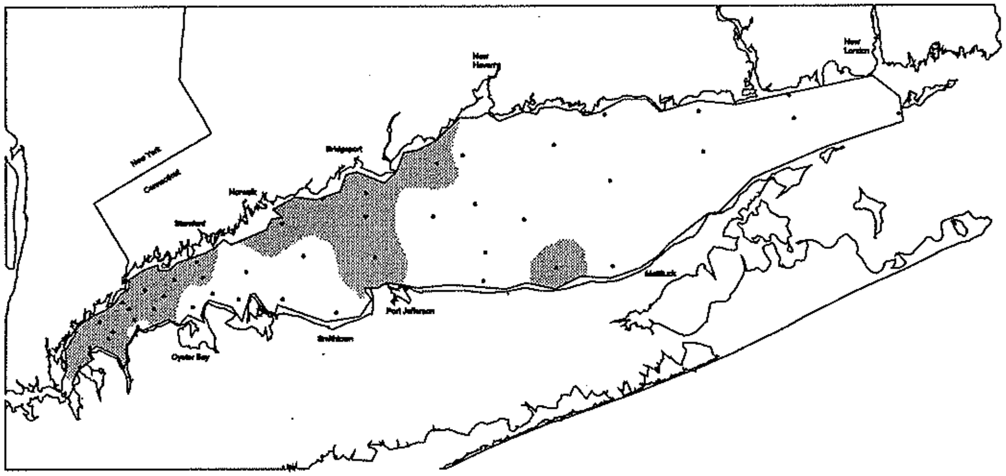
Insufficient coverage for area estimate
No hypoxia recorded

■ 0.0 - 2.99 mg/L
▨ 3.0 - 4.99 mg/L
□ 5.0 + mg/L

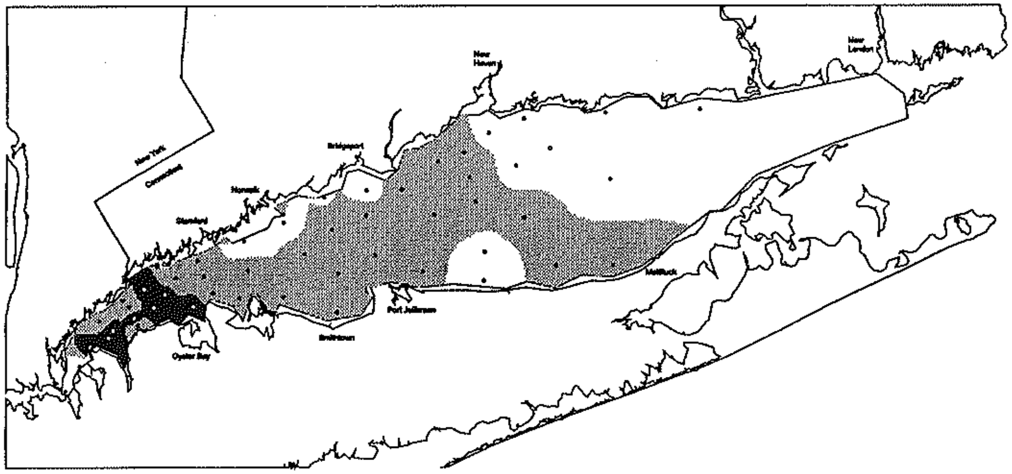
HYJUN95
June 22 - 27, 1995



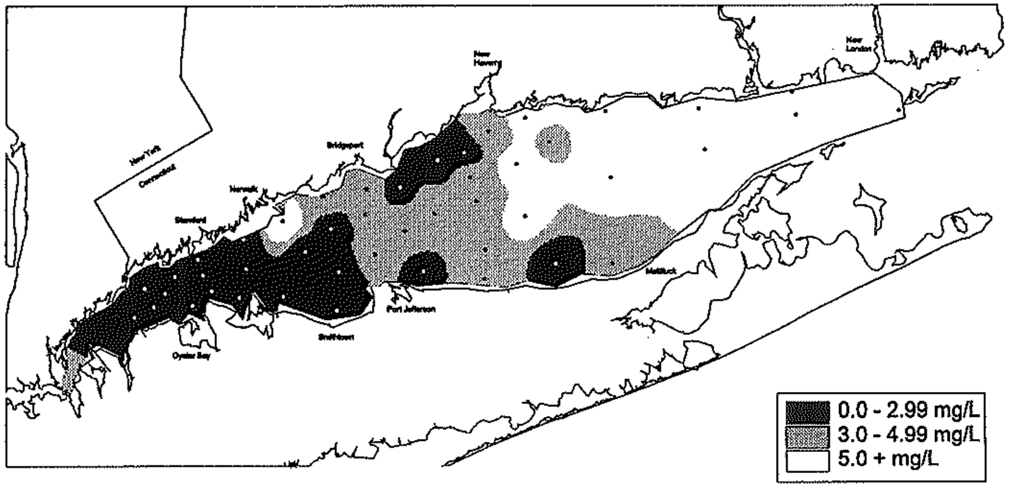
WQJUL95
July 6 - 11, 1995



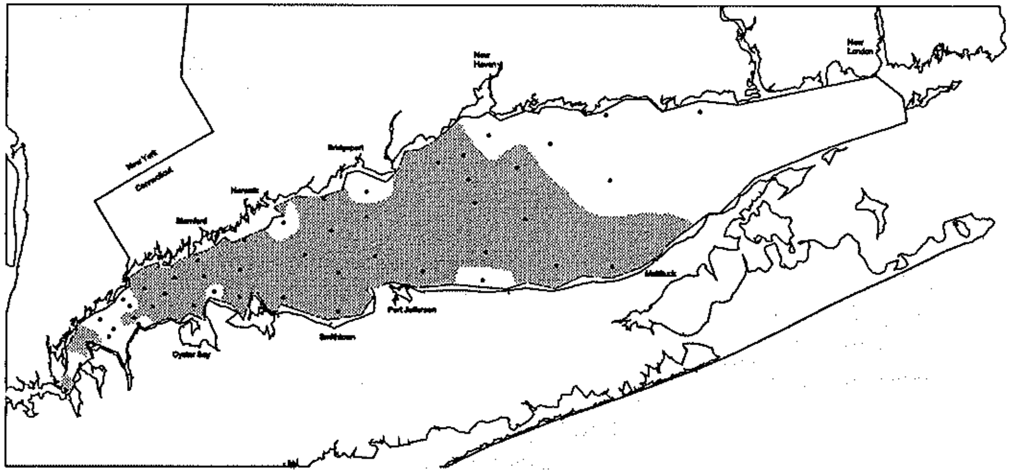
HYJUL95
July 18 - 20, 1995



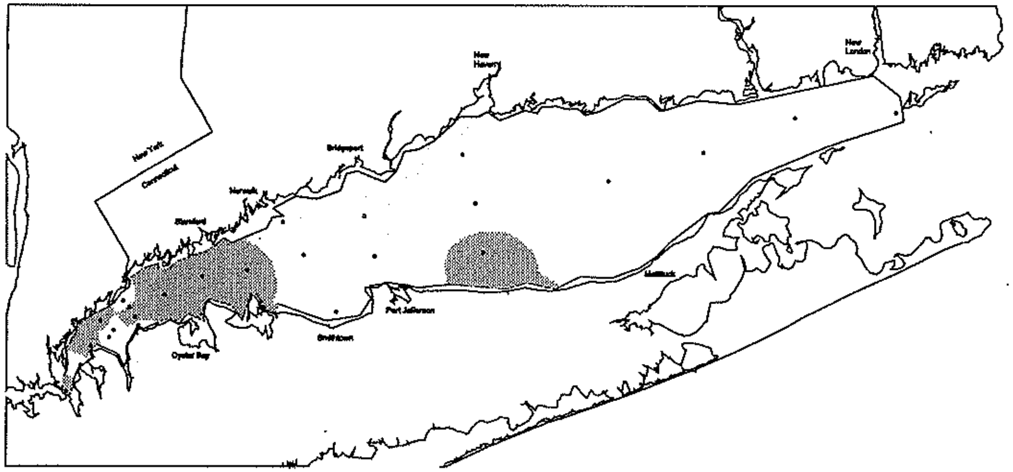
WQAUG95
July 31 - August 4, 1995



HYAUG95
August 14 - 16, 1995

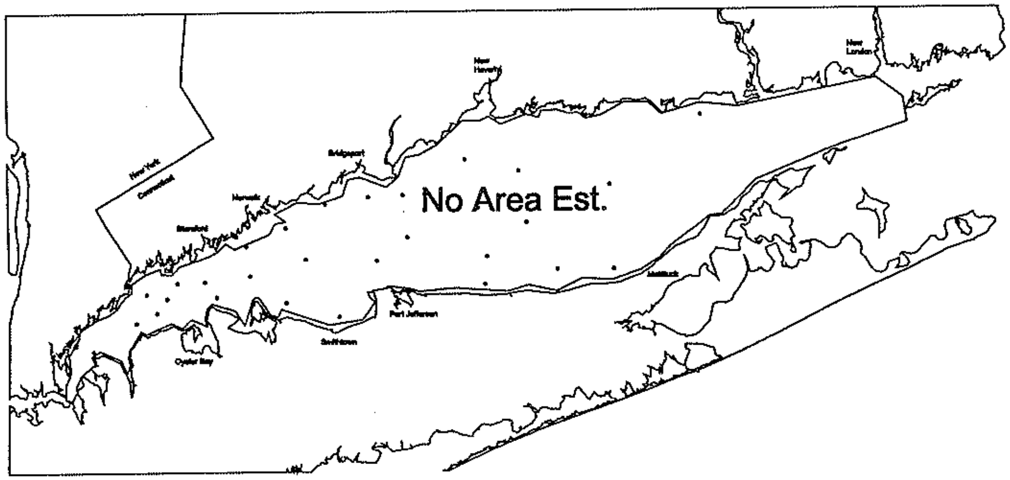


WQSEP95
September 5 - 12, 1995



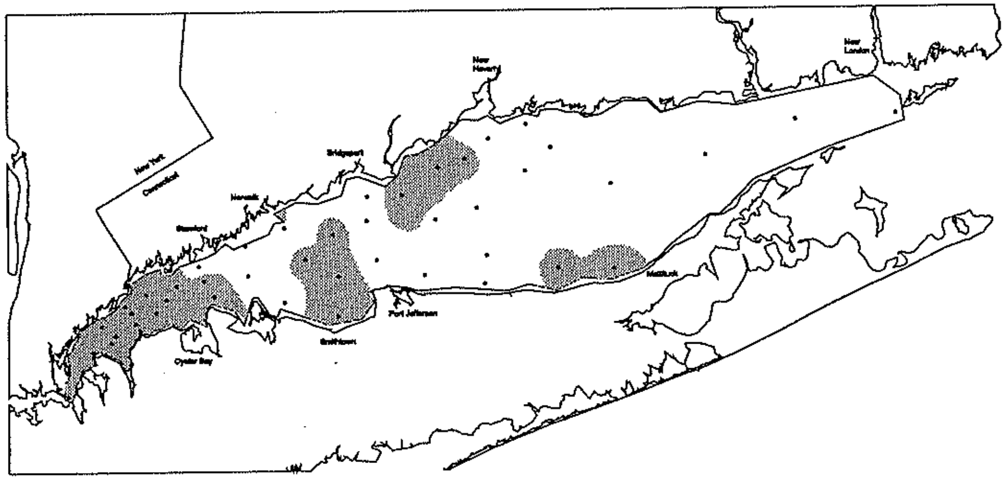
■ 0.0 - 2.99 mg/L
▨ 3.0 - 4.99 mg/L
☐ 5.0 + mg/L

HYJUN96
June 25 - 27, 1996



Insufficient coverage in Narrows for area estimate
No hypoxia recorded

WQJUL96
July 8 - 11, 1996



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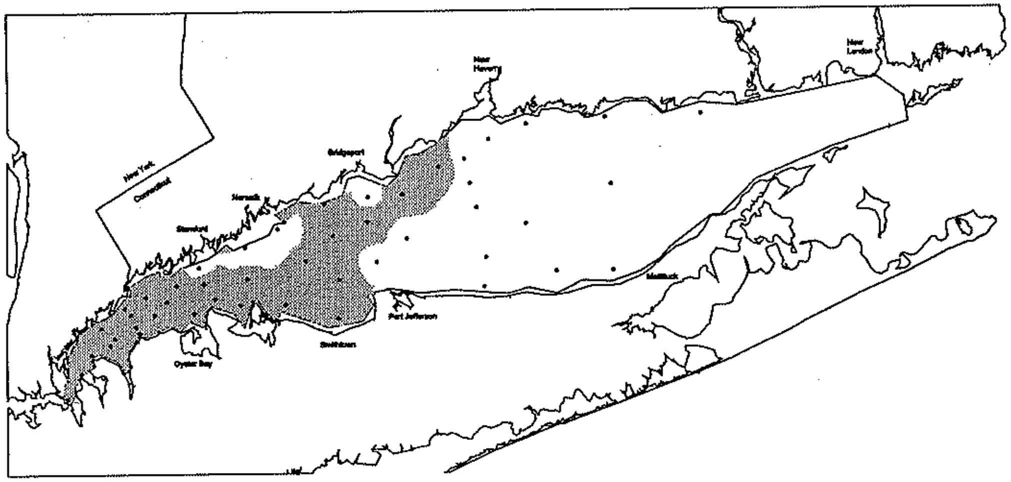
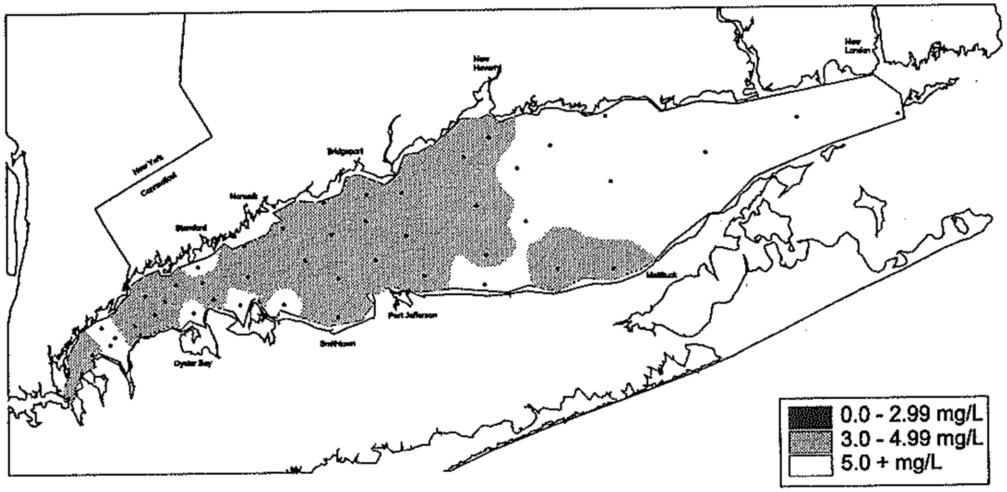
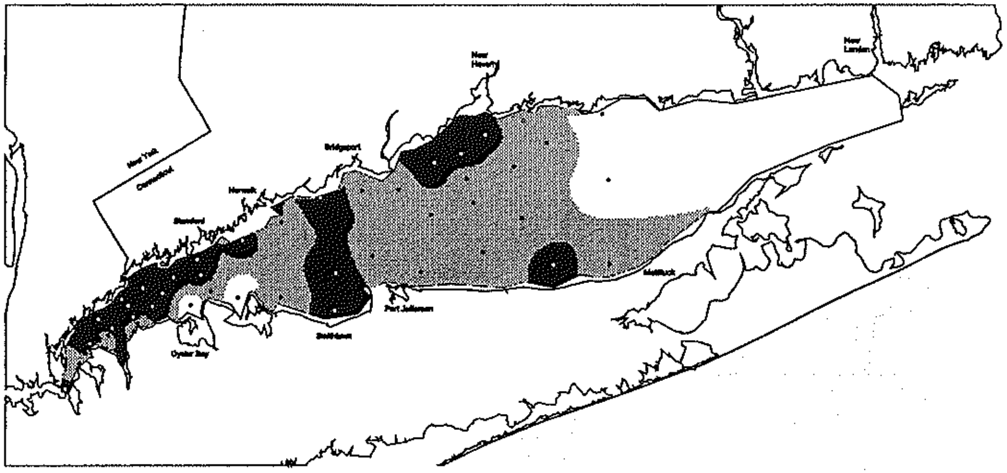
July 23 - 25, 1996



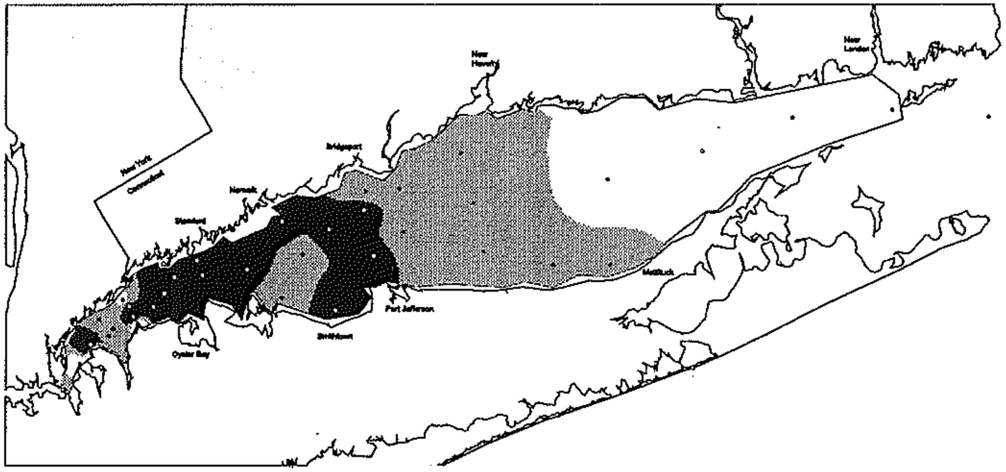
WQAUG96
August 5 - 8, 1996



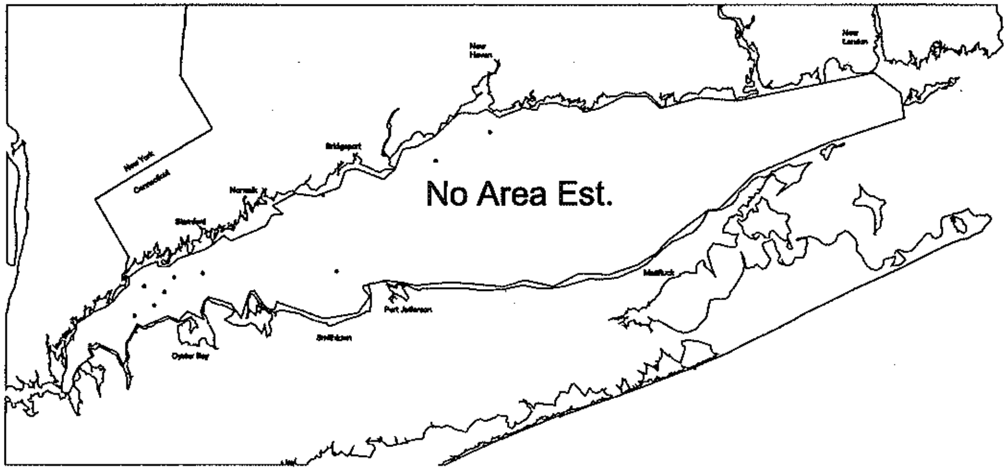
HYAUG96
August 20 - 22, 1996



WQSEP96
September 3 - 6, 1996



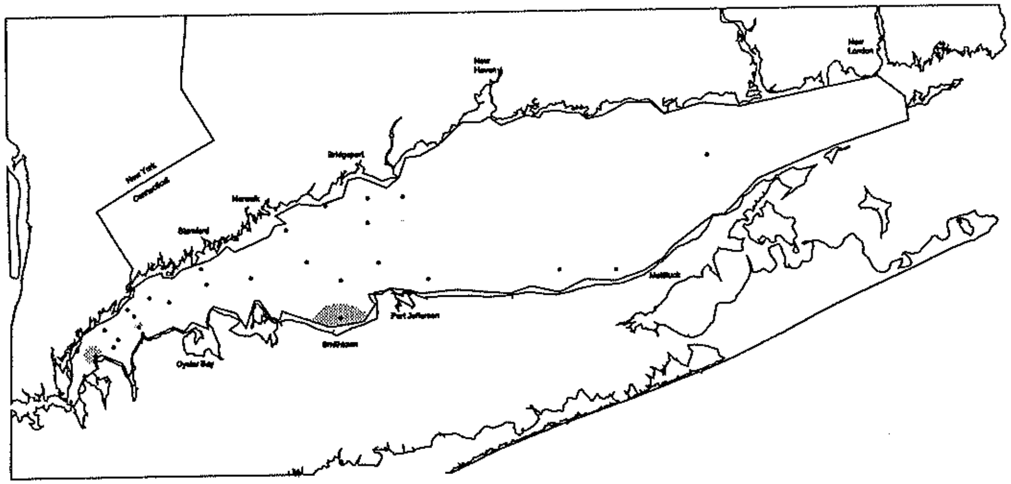
HYSEP96
September 20, 1996



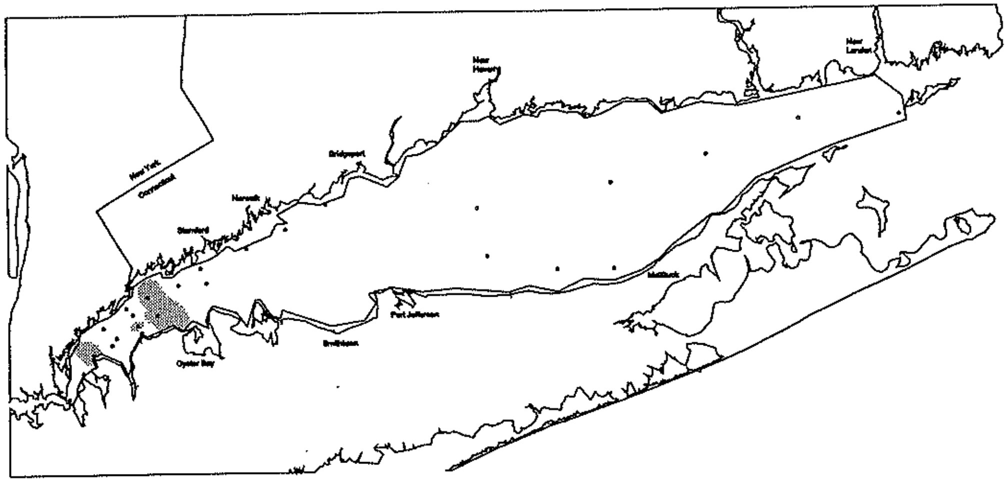
Insufficient coverage for area estimate
No hypoxia recorded

▨ 0.0 - 2.99 mg/L
▨ 3.0 - 4.99 mg/L
☐ 5.0 + mg/L

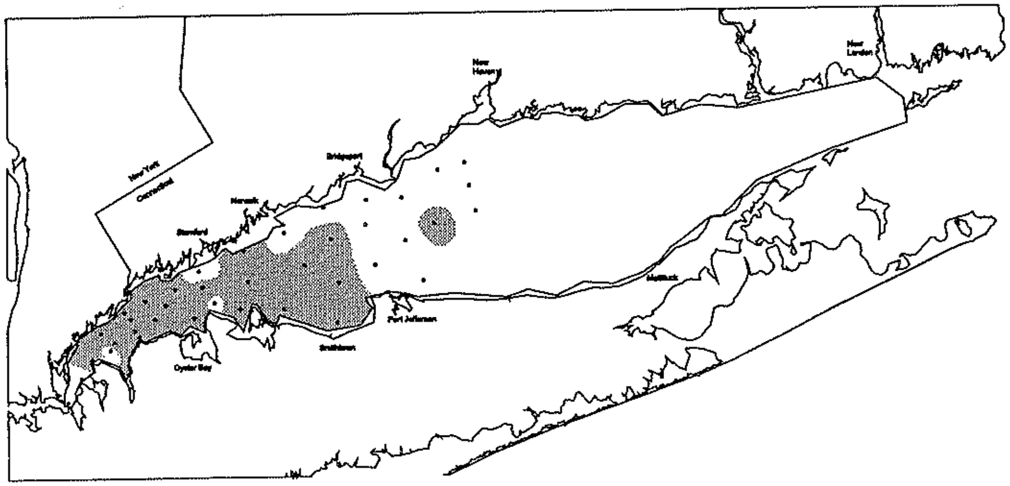
HYJUN97
June 27 - 30, 1997



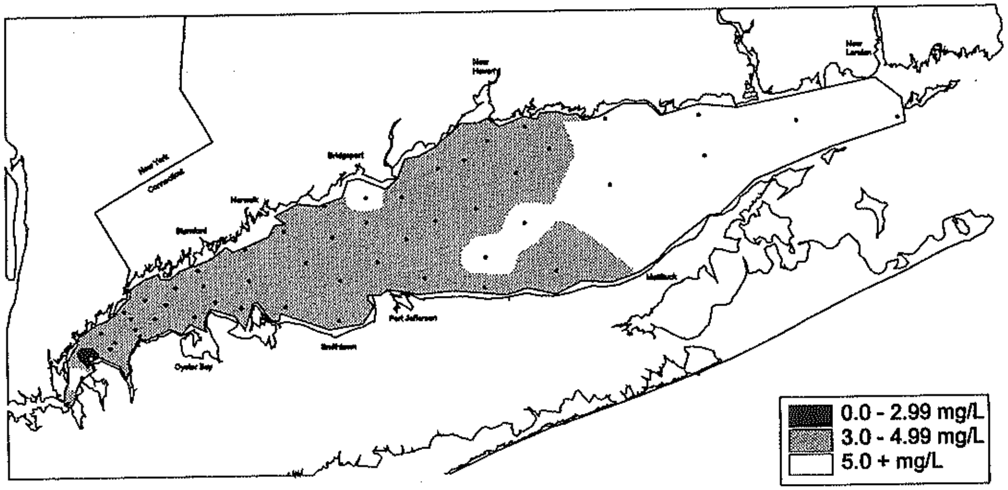
WQJUL97
July 8 - 9, 1997



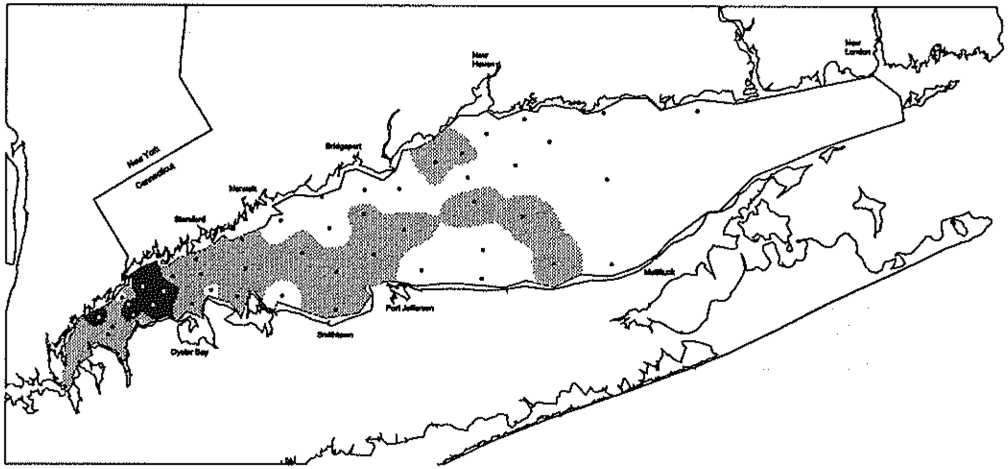
HYJUL97
July 22 - 24, 1997



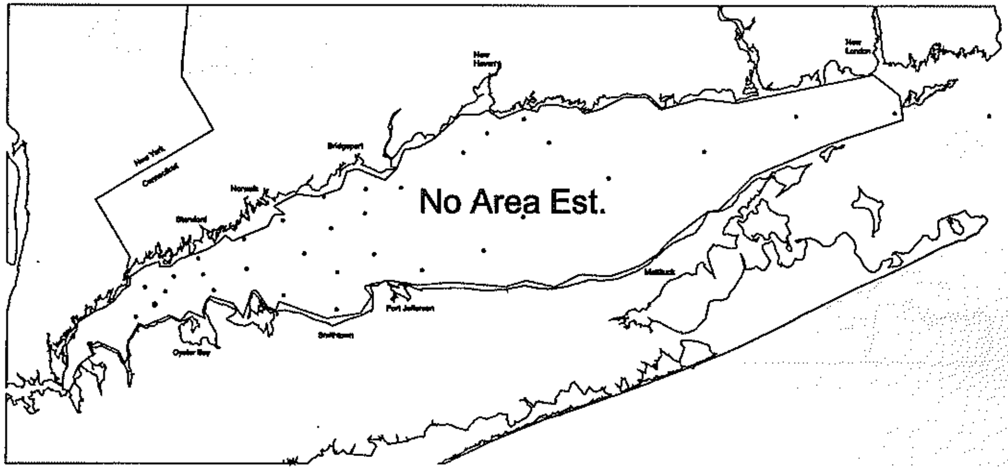
WQAUG97
August 4 - 7, 1997



HYAUG97
August 19 - 22, 1997

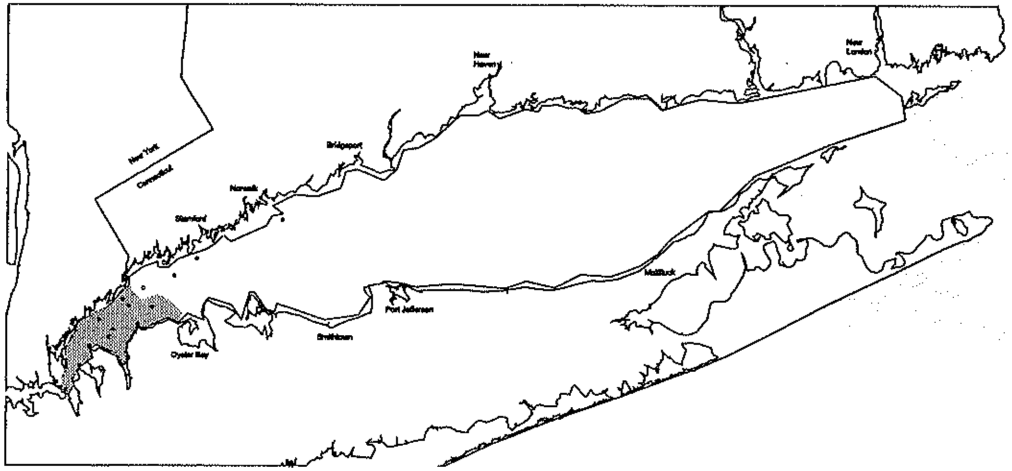


WQSEP97
September 2 - 5, 1997



Insufficient coverage in Narrows for area estimate
Hypoxia present in Narrows

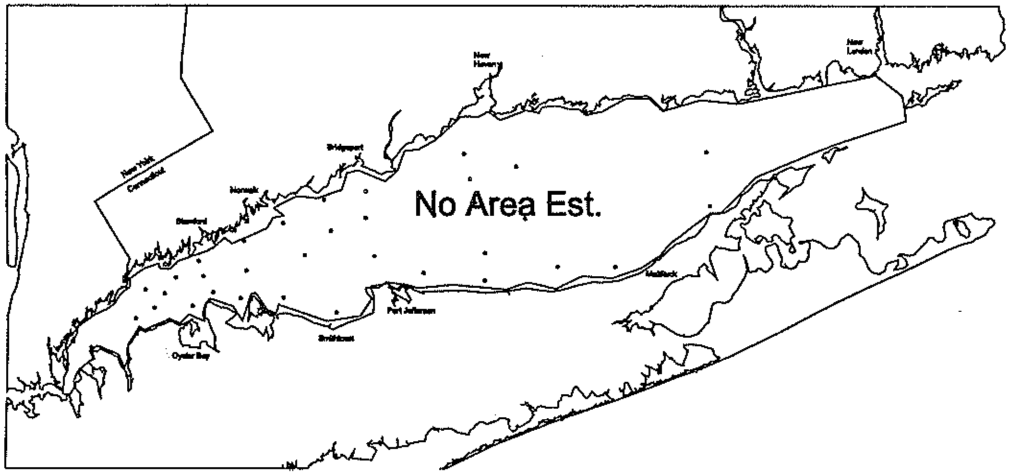
HYSEP97
September 17, 1997



Area estimate valid only for Narrows

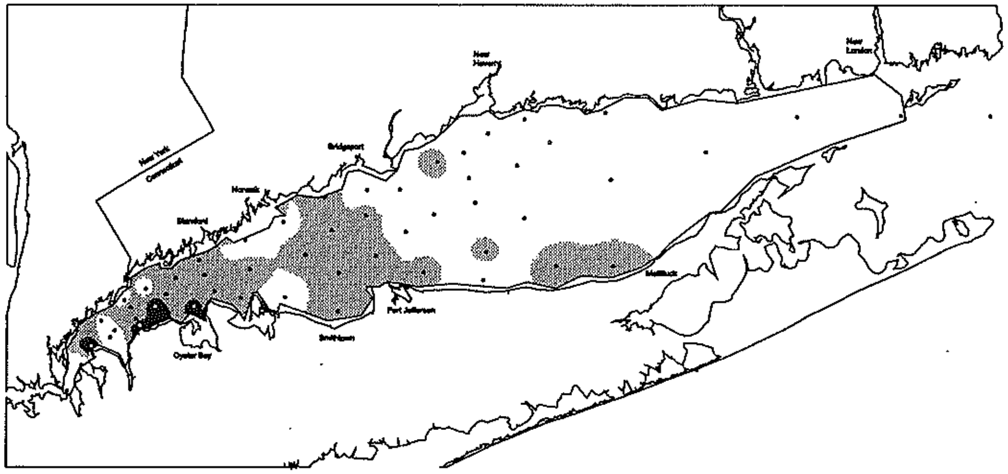
- ■ 0.0 - 2.99 mg/L
- ▨ 3.0 - 4.99 mg/L
- ☐ 5.0 + mg/L

HYJUN98
June 24 - 26, 1998

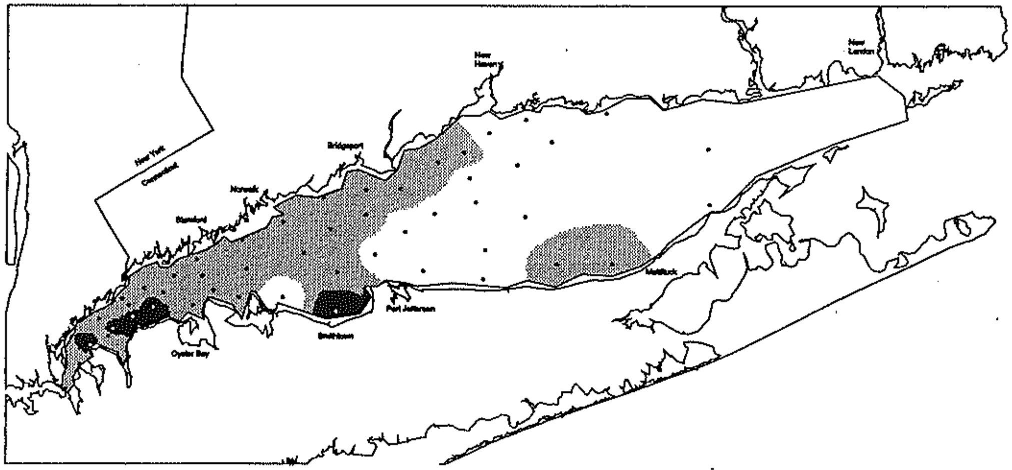


Insufficient coverage in Narrows for area estimate
No hypoxia recorded

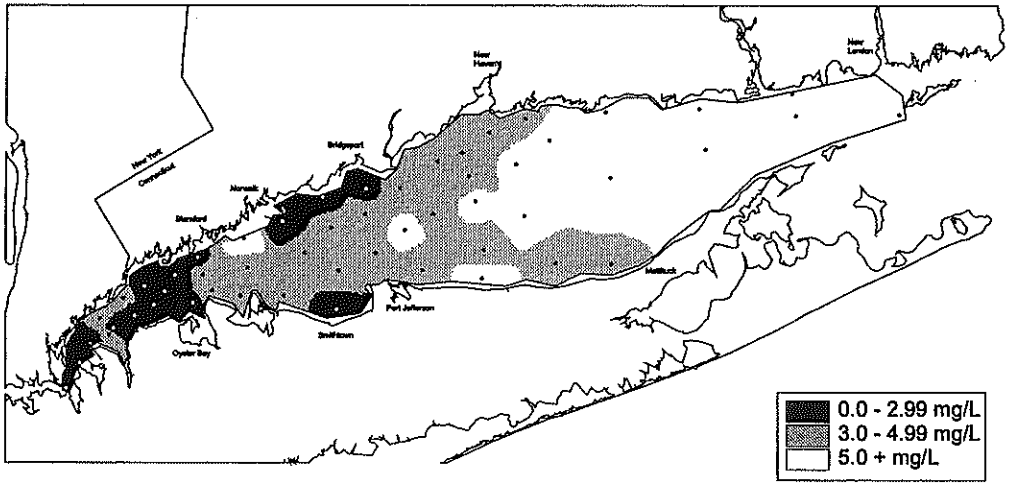
WQJUL98
July 6 - 9, 1998



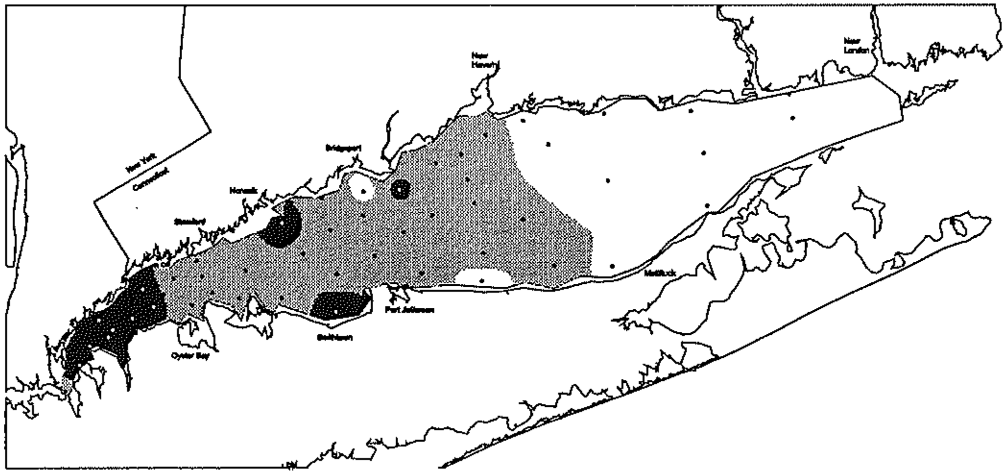
HYJUL98
July 21 - 23, 1998



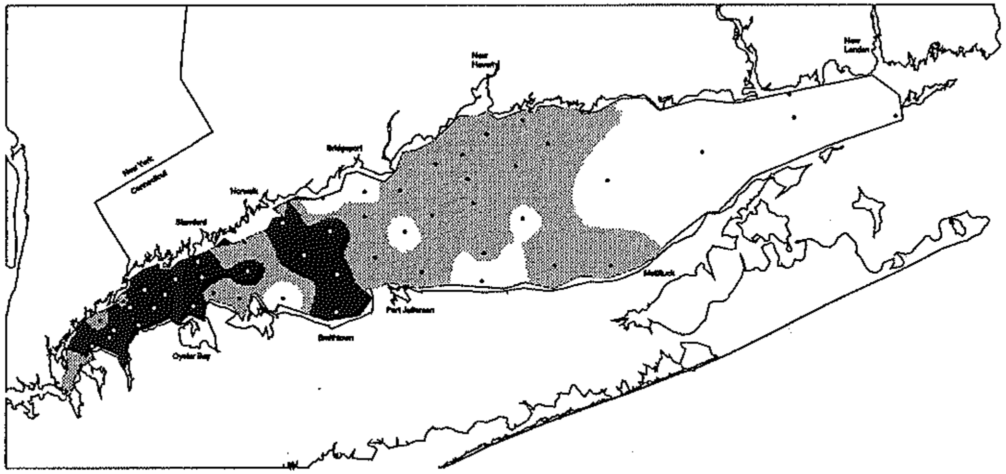
WQAUG98
August 3 - 6, 1998



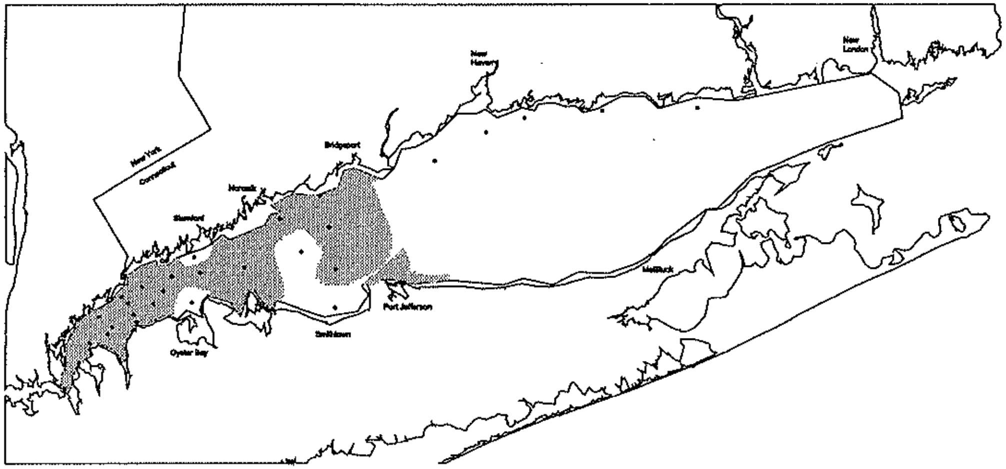
HYAUG98
August 17 - 21, 1998



WQSEP98
August 31 - September 3, 1998



HYSEP98
September 15 - 17, 1998



■ 0.0 - 2.99 mg/L
▨ 3.0 - 4.99 mg/L
☐ 5.0 + mg/L

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