Characteristics of bottom dissolved oxygen in Long Island Sound, New York

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Abstract

The variability of bottom dissolved oxygen (DO) in Long Island Sound, New York, is examined using water quality monitoring data collected by the Connecticut Department of Environmental Protection from 1995 to 2004. Self-organizing map analysis indicates that hypoxia always occurs in the Narrows during summer and less frequently in the Western and the Central Basins. The primary factor controlling the bottom DO, changes spatially and temporally. For non-summer seasons, the levels of bottom DO are strongly associated with water temperature, which means DO availability is primarily driven by solubility. During summer, stratification intensifies under weak wind conditions and bottom DO starts to decrease and deviate from the saturation level except for stations in the Eastern Basin. For the westernmost and shallow (<15 m) stations, bottom DO is correlated with the density stratification (represented by difference between surface and bottom density). In contrast, at deep stations (>20 m), the relationship between oxygen depletion and stratification is not significant. For stations located west of the Central Basin, bottom DO continues to decrease during summer until it reaches its minimum when bottom temperature is around 19–20 °C. In most cases the recovery to saturation levels at the beginning of fall is fast, but not necessarily associated with increased wind mixing. Therefore, we propose that the DO recovery may be a manifestation of either the reduced microbial activity combined with the depletion of organic matter or horizontal exchange. Hypoxic volume is weakly correlated to the summer wind speed, spring total nitrogen, spring chlorophyll a, and maximum river discharge. When all variables are combined in a multiple regression, the coefficient of determination \( r^2 \) is 0.92. Surprisingly, the weakest variable is the total nitrogen, because when it is excluded the coefficient \( r^2 \) only drops to 0.84. Spring bloom seems to be an important source of organic carbon pool and biological uptake of oxygen plays a more crucial role in the seasonal evolution of bottom DO than previously thought. Our results indicate that the reassessment phase of the Long Island Sound Total Maximum Daily Load policy on nitrogen loading will most likely fail, because it ignores the contributions of the spring organic carbon pool and river discharge. Also, it is questionable whether the goal of 58.5% anthropogenic nitrogen load reduction is enough.

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1. Introduction

The dynamics of dissolved oxygen (DO) involves complex interactions between physical and biogeochemical processes; i.e., (1) vertical and horizontal mixing, (2) air–water exchange, (3) nutrient loadings and speciation, (4) photosynthesis, (5) sediment and water column oxygen demand, and (6) chemical oxygen demand. These processes can vary semi-independently from one another. It is therefore important to understand how temporal variations in nutrient loadings, phytoplankton blooms, bacterial production and grazing, temperature, and stratification of the water column manifest themselves in bottom water DO depletion. The variability of DO in the water column generally results from the interplay between physical transport and biological consumption of oxygen. Thus, bottom DO gets depleted when rates of consumption exceed rates of supply. Hypoxia, the depletion of DO below 2 or 3 mg/l (Diaz and Rosenberg, 1995; Ritter and Montagna, 1999), is a seasonal phenomenon that occurs in shallow water in most temperate coastal regions (e.g., Hearn and

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Robson, 2001; Buzzelli et al., 2002; Hagy et al., 2004). The occurrence of hypoxia in shallow waters appears to be increasing, and it has been argued that hypoxia is most likely accelerated by human activities (Diaz and Rosenberg, 1995). Diaz and Rosenberg (1995) also noted that no other environmental variable of such ecological importance to estuarine marine ecosystems as DO has changed so drastically and in such a short period of time. Since hypoxia causes numerous economical and ecological losses, i.e., habitat degradation, alteration of food web dynamics, and regime shifts in ecosystem (e.g., Rabalais et al., 2002; Breitburg et al., 2003; Kemp et al., 2005), it is regarded as one of the major global issues in water quality management.

Seasonal hypoxia has been frequently reported around the US coastal areas, for example, in the northern Gulf of Mexico (Justic´ et al., 1996; Rabalais et al., 2002), the Neuse River estuary (Buzzelli et al., 2002), the Chesapeake Bay (Kemp et al., 1992, 2005; Hagy et al., 2004), as well as in certain tributaries (Kuo and Neilson, 1987; Breitburg et al., 2003) and the New York Bight (Swanson and Parker, 1988). Kemp et al. (1992) suggested that any reduction in nutrient loading to the Chesapeake Bay would yield rapid but proportionally smaller increase in oxygen concentration. Hagy et al. (2004) also pointed out that the long-term increase in hypoxia occurred concurrently with the long-term increase in nitrate loading into the Chesapeake Bay. It is believed that nutrient over-enrichment results in the depletion of DO near bottom in shallow waters because the enhanced primary production with coastal eutrophication often leads to problems such as a seasonal formation of hypoxic condition (National Research Council, 2000). Therefore, environmental mitigation efforts have been directed at reducing the amount of nutrient loadings into a system. Kemp et al. (2005) showed that the Susquehanna River concentration of total nitrogen entering the Chesapeake Bay has slightly declined since 1990 due to improved watershed land management (Sprague et al., 2000). However, Hagy et al. (2004) found that more extensive hypoxia was observed in recent years than would be expected from the observed relationship.

Long Island Sound (LIS) (see Fig. 1) has traditionally suffered from hypoxic conditions, which have been observed in the western sound since the early 1970s. Hypoxia in LIS became more severe toward the end of the 1980s (Parker and O’Reilly, 1991). In 1998 the states of Connecticut and New York and the Environmental Protection Agency (EPA) adopted a plan for Phase III Actions for Hypoxia Management, with the aim of managing nitrogen targets through a development of a total maximum daily load (TMDL) (USEPA, 1998). The Long Island Sound TMDL (LIS TMDL) management team recognized that hypoxia is not driven by daily or short-term nitrogen loadings, but may be a function of annual loading rates. As a result, the LIS TMDL is defined as an allowable annual load of nitrogen into the sound. However, O’Shea and Brosnan (2000) suggested that bottom DO in LIS seems to be more associated with thermal stratification than point and non-point nutrient loadings into the western Narrows during the summers of 1963–1999. Numerical model results have also shown that the concentration of DO in the western LIS is primarily driven by stratification (HydroQual Inc., 1995). In addition, Anderson and Taylor (2001) examined several physical and biological processes, and found that bottom DO is mainly driven by physical processes, namely, those controlling the density structure of the water column. There are other previous studies which have found other mechanisms that

![Fig. 1. Bathymetry of Long Island Sound (SS, Stratford Shoal; CA, Cable and Anchor Reef; MS, Mattituck Sill; SB, Smithtown Bay).](image-url)
control DO during summer in LIS, such as horizontal transport of oxygen (Torgersen et al., 1997) and biological uptake (Welsh and Eller, 1991).

Despite efforts to reduce nitrogen loading and upgrade sewage treatment plants, hypoxia has not decreased, but keeps emerging from the Narrows to the Central Basin. This suggests that our current understanding of DO dynamics is incomplete, and besides the mechanisms which have already been identified there may be processes that need to be identified and old ones re-examined. All previous studies have concentrated their efforts on the western sound, but no study has been published to characterize the bottom DO over the whole sound. Our lack of understanding in the variability of DO could be stemming from the lack of examination of the whole sound. In this study, historical hydrographic survey data are reanalyzed to determine temporal and spatial features of bottom DO throughout the sound. We also re-examine the relationship between hypoxia and total nitrogen, plus other variables. The paper is organized in the following manner: Section 2 briefly describes the area of study. The details of data processing, including principal component analysis (PCA) and self-organizing map (SOM) analysis, are given in Section 3. Temporal and spatial variations of the bottom DO including the patterns of SOM analysis are described in Section 4. The bottom DO is examined in relation with the density stratification and temperature. Interannual variability of hypoxic volume is also determined in relation to total nitrogen, wind speed, chlorophyll $a$, and riverine discharge in Section 4. Factors influencing the bottom DO variability including implications for hypoxia management are discussed in Section 5, and results are summarized in Section 6.

2. Study area

LIS is approximately 150 km long and 20 km wide with an average depth of 20 m. It is a weakly stratified system compared to typical estuaries such as the Chesapeake Bay, and a major river is located near the eastern end, which is connected to the Atlantic Ocean through the Race (Fig. 1). The western end is connected to the lower Hudson River via a tidal strait, the East River, where tidal currents exceed 1 m/s (Blumberg and Pritchard, 1997). Owing to complex bathymetry, LIS is made up of four major basins which are separated by various sills and shoals affecting the circulation of bottom waters as shown in Fig. 1. The Eastern Basin lies between Mattituck Sill and the Race forming a narrow and deep channel (≈90 m). The Central Basin, from Mattituck Sill to Stratford Shoal, is characterized by an asymmetrical V-shaped cross section with a deep channel (≈40 m) on the southern side and a gradual slope on the northern. The Western Basin, with a deep channel continuing to the eastern part of the Narrows, is separated by the Cable and Anchor Reef (Vieira, 2000). Tidal currents are strong in LIS, ranging from about 0.5 m/s in the Central Basin to 1 m/s at the eastern end (Vieira, 1990). Freshwater flow enters into the sound from runoff and drainage along the coast of Long Island, New York, and Connecticut. The discharges of three major rivers (i.e., Thames, Housatonic, and Connecticut) comprise most of the freshwater input (90%) into LIS, and the Connecticut River alone contributes more than 70% of the freshwater influx (Lee and Lwiza, 2005).

3. Data and methods

3.1. LIS data

The Connecticut Department of Environmental Protection (CTDEP), Bureau of Water Management, initiated the LIS Ambient Water Quality Monitoring program in January 1991 to establish a database for monitoring water quality in the sound. The monitoring data are collected almost every month including hydrographic and biogeochemical properties: temperature, salinity, density, DO, chlorophyll $a$, nutrients, suspended sediments, and photosynthetically-active radiation (PAR). Hydrographic parameters (temperature, salinity, and density) are measured using a Seabird SBE-19 CTD equipped with fluorometric, PAR and DO sensors. Water samples are also analyzed in a laboratory for biogeochemical parameters. All these properties are measured year-round throughout the sound (as shown in Fig. 2), but are more intensively sampled during the summer season, with up to 49 stations per survey. Most of surveys are done once a month, and two surveys per month are carried out during the summer season (June to August). Because surveys with more than 17 sampling stations became more common after 1994, the analyses in this study are conducted using data collected between 1995 and 2004.

Time series of surface data are constructed by taking water column data available between 2 and 3 m depth in every station, and bottom data are produced by using the data nearest to the bottom. Surface and bottom chlorophyll $a$ data are constructed on the basis of laboratory processed data and filled in with data from a fluorometric sensor. Bottom DO data are also generated primarily with values measured by the Winkler method, and missing data are filled with available DO sensor data, which are calibrated using Winkler titration onboard the survey ship (Kaputa and Olsen, 2000). Temporal gaps in bottom DO, which are less than 2 months, are linearly interpolated only prior to applying optimal interpolation (OI). Time series of summer bottom DO are optimally interpolated on a 0.02° longitude—latitude grid (931 grid-points) in order to identify patterns covering the whole sound. Length scales in OI are determined by using the maximum distance between minimum distances of sampled stations in a given month.

SOM analysis is then applied on the OI data of summer bottom DO, which comprised 70 surveys from June to September for 1995—2004. The volume of hypoxic water is calculated by first determining the thickness of the bottom layer at OI grid-points under hypoxia multiplied by the total affected area. The amount of mean spring total chlorophyll $a$ is determined by multiplying the depth-averaged chlorophyll $a$ concentration by water depth at each OI grid-point and the total surface area of LIS. Since nutrients are only measured continuously at 17 major stations, mean spring total nitrogen is defined as the average of total nitrogen concentration (ammonia,
particulate nitrogen, total dissolved nitrogen, nitrite, and nitrate) in surface water at those stations from February to May.

3.2. Wind and freshwater discharge

In order to estimate the contribution of wind in vertical mixing, we use wind data from Sikorsky Memorial Airport, Bridgeport, Connecticut (WMO ID 72504) to represent the wind condition over the sound. Daily mean wind speed is obtained from National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center (NCDC) historical data archives. Daily measurements are averaged to represent the monthly and summer wind conditions in LIS. In order to determine the effects of freshwater input, monthly freshwater discharge data are retrieved from the US Geological Survey (USGS) website (URL http://nwis.waterdata.usgs.gov/nwis/). Most of freshwater from major rivers entering LIS flows through the Connecticut coast, via the Connecticut River (USGS site number 01184000), the Housatonic River (01205500), and the Thames River which combines the input of the Quinebaug (01127000), the Shetucket (01122500), and the Yantic Rivers (01127500). Monthly discharge rates from these rivers are combined to represent the freshwater discharge into LIS.

3.3. Cluster analysis

3.3.1. Principal component analysis (PCA)

PCA is used to examine the structure of summer DO interannual variability in the bottom waters. The data matrix includes 17 major stations with seven variables, i.e., DO, river discharge, wind speed, bottom temperature, surface total nitrogen, surface chlorophyll $a$, and density stratification. Rows (objects) represent stations repeated over time. From the PCA of all the variables for each station we plot principle components (based on the first two modes) and eigenvectors of the anomalies on the same scale. This type of a plot is commonly known as a bi-plot (Reyment and Joreskog, 1996), and it is useful in examining relationships between several variables simultaneously. However, one has to be careful in interpreting the results with this kind of a matrix, because relationships due to space or time cannot be easily separated.

3.3.2. Self-organizing map (SOM)

Since the DO dynamics might be nonlinear in nature, we apply a nonlinear analysis in addition to the PCA described above. SOM is an artificial neural network based on unsupervised learning (Kohonen, 2001). It is a nonlinear cluster analysis mapping high-dimensional input data onto a two-dimensional output space while preserving the topological relationships between the input data (Liu and Weisberg, 2005). Because SOM is an effective tool in extracting patterns from large data sets, it has been widely used in various fields of studies ranging from sciences to economics (Kaski et al., 1998; Oja et al., 2002). SOM analysis has also been applied to oceanography by Liu and Weisberg (2005) for description of ocean current variability, Richardson et al. (2003) to extract sea surface temperature from satellite data, and Risien et al. (2004) to identify wind regimes. The application of SOM in this study is based on a software package SOM Toolbox 2.0 for Matlab. It is an implementation of the SOM and its visualization in the Matlab computing environment (Vesanto et al., 2000). The SOM Toolbox can be obtained from the Helsinki University of Technology, Finland: URL at http://www.cis.hut.fi/projects/somtoolbox.

4. Results

Fig. 3 shows the time series of bottom DO at stations A4, 09, H2, and J2 located in each basin from the Narrows to

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*Fig. 2. The Connecticut Department of Environmental Protection water quality sampling stations (+) in Long Island Sound (square markers indicate the positions of major stations).*
the Eastern Basin for 1995–2004. It is clearly shown that the variation of bottom DO is mainly dominated by seasonal fluctuations at all stations, i.e., maximum bottom DO in late winter (February to March) and minimum bottom DO in summer (July to September). There is a strong longitudinal gradient in variation of bottom DO from east to west. The range of bottom DO is largest in the Narrows (i.e., 0.1–14.8 mg/l at station A4), and it tends to decrease in an eastward direction toward the Race (i.e., 6.6–12.2 mg/l at station M3). There is no clear indication for long-term trends in increasing or decreasing of bottom DO throughout the sound. However, hypoxic condition (less than 3 mg/l of DO) occurs every summer at station A4, but less frequently as one goes further east to the area near station H2. Hypoxia does not occur at stations H4, H6, and J2 in the Central Basin and all stations in the Eastern Basin for the entire record. The onset and duration of hypoxia differ from station to station and year to year. For instance, hypoxia occurred during the summer of 1996 at stations A4, 09, and H2, while it was not observed at stations 09 and H2 in 1997. Station A4 underwent hypoxic conditions in July and August of 2002, but hypoxia only appeared at station H2 in early August and it was not observed at station 09. Although the occurrence of hypoxia varies spatially and temporally in LIS, it is generally observed at stations in the Narrows, Western Basin, and the nearshore area of the Central Basin.

We use PCA to examine the structure of DO. The first principle component explains 30% of the variability and the second mode explains 29%. The third and fourth modes contain 14% and 10% of the total variance, respectively. When the first two modes are plotted against each other in a bi-plot (as shown in Fig. 4), there is a clear distinction between three groups, i.e., stations from the Eastern Basin, the Narrows, and the rest. The data from the Western and Central Basins are intermingled. The stations in the Narrows are characterized by high total nitrogen and high chlorophyll $a$; the Eastern Basin contains highly oxygenated water, and Central and Western stations are strongly influenced by wind, bottom temperature, stratification and river discharge. The superimposed empirical orthogonal function (EOF) vectors indicate that bottom DO is high where total nitrogen and chlorophyll $a$ are low. All the relationships shown are a function of space, not time. For example, the positive relationship between total nitrogen and chlorophyll $a$ is a spatial one, i.e., both total nitrogen and chlorophyll $a$ decrease with distance from west to east. The temporal relationship between the two variables is negative and the total nitrogen lags approximately a month behind chlorophyll $a$ as shown in Fig. 5.

In order to analyze the variability of DO over the whole sound, SOM analysis was used to detect specific time-dependent patterns of bottom DO, and to quantify which pattern was frequently observed. After several tests, an SOM array size of $4 \times 3$ was selected because it best represents the major features of bottom DO for June to September. The parameters used for the SOM analysis are shown in Table 1 and results of a $4 \times 3$ SOM array are shown in Fig. 6. Each map in the SOM array represents a typical synoptic state within
Fig. 4. A bi-plot of principle components and empirical orthogonal function vectors of bottom dissolved oxygen (DO) in summer, spring chlorophyll \( a \) (CHLA), spring total nitrogen (TN), summer bottom temperature (BT), summer wind speed (WIND), summer density stratification (DS), and spring river discharge (RIVER) at major stations from 1995 to 2004. Stations in the Narrows are represented by N, C is for the Central Basin, W is for the Western Basin, and E is for the Eastern Basin. There is a good separation between the Narrows stations, the eastern stations, and the rest of the sound.

Fig. 5. Time series of surface total nitrogen (dashed line) and surface chlorophyll \( a \) (solid line) for station D3 in the Narrows of Long Island Sound from 1995 to 2004.

The data, constructed from the weights on that particular unit. The unit, often called a node, is indicated in the upper-left corner of each map. The lower numbered maps (the upper-side of the SOM array) exhibit relatively low bottom DO conditions with hypoxic areas while the higher numbered maps (the lower-side of the SOM array) display higher DO levels. All maps indicate strong longitudinal gradients of bottom DO decreasing toward the western sound, which supports the results from PCA. Similar bottom DO patterns are located adjacent to one another and those patterns continuously change across the array. The most dissimilar ones are at opposite ends of the SOM array (i.e., between unit 1 and 12). Once the patterns are characterized, input data are then subjected to SOM unit to find out which patterns they are most similar to. The best matching unit (BMU), or the winning node, can be identified according to the minimum Euclidian distance when that frame is compared to SOM unit. In order to quantify the representation of each unit, relative frequency of occurrence of each pattern is determined as a percentage indicated in the lower-right corner of each map in Fig. 6. The most common bottom DO pattern during summer is unit 1, occurring 27\% of the input data and showing a pattern with the largest area of hypoxic conditions. Its counterpart, unit 12, represents 19\% of the data. There is also a zero frequency at unit 8.

The relative frequency of the input bottom DO data from the BMU evolution can be better viewed monthly, as shown in Fig. 7. A frequency map for each month highlights the variability of the bottom DO through the summer season. The maps were superimposed on the SOM array so that the coordinates of the frequency map correspond to maps of the SOM array. The relative frequency of patterns in a month was also quantified as a percentage and indicated in each map. The frequency of unit mapping for June was mostly limited to the lower-right of the SOM array such as units 9, 11, and 12 with maximum occurrence of 65\% in unit 12. It depicts the bottom DO pattern of early summer with a range of 5.3—8.2 mg/l of DO increasing toward the eastern end. However, the frequency map of July shows that units are relatively spread in the upper and left sides of the array, with maximum occurrence of 30\% at unit 4. It describes the beginning of hypoxic conditions in the Narrows. The most frequent pattern in August is unit 1 with occurrence of 65\%. It shows hypoxic conditions in most of the Narrows and suboxic condition (3.5—4.0 mg/l of DO) over the Western Basin except the areas near station 09. It is interesting to note that unit 3 illustrates the isolated suboxic patch (4—4.5 mg/l of DO) near Smithtown Bay in the Western Basin, which also frequently occurs (35\%). Units 7 and 10 are frequently observed (40\%) in September, which are patterns with a range of 4.2—7.6 mg/l of bottom DO. The frequency map still shows unit 1 (40\% of occurrence) since September data are often collected in the early part of a month. In general, the SOM analysis is consistent with
time series of bottom DO showing that hypoxic conditions appear in July, get fully developed in August, and start to weaken in early September.

To explore the seasonal evolution of DO, the data of bottom DO were analyzed together with temperature, since temperature affects microbial activity and solubility of oxygen. Fig. 8 shows results at stations B3, 15, H2, and K2 from the Narrows to the Eastern Basin. Bottom DO in the Eastern Basin (station K2) is almost saturated throughout the year. For the other basins, the bottom DO follows solubility concentrations only for spring, fall, and winter seasons. During summer the bottom DO starts to be under-saturated in June, and it declines linearly with temperature as the season progresses, until it reaches its minimum when temperature is 19–20 °C in August.

For stations in the Western Basin (station 15) and the Narrows (station B3) the average rate of change of DO with temperature is approximately 1 mg/l per degree centigrade, and the rate decreases to zero for stations in the Eastern Basin. What is intriguing is that although temperature may rise up to about 23 °C, the temperature at which minimum bottom DO is observed (19–20 °C) does not vary much. After reaching the minimum concentration, bottom DO recovers quickly within two weeks, and by October it is almost saturated. At first we thought the recovery was driven by wind mixing, because wind speed picks up at the beginning of the fall season. Upon closer examination of the time of initiation of DO recovery, it was seen that in most cases the recovery starts before the increase in the wind commences. This result is very surprising, because the traditional understanding for the reason for the DO recovery is that it is mainly driven by wind mixing.

Following the examination of the annual evolution of DO, we analyzed the relationship between bottom DO and temperature during summer, i.e., June to August data. Table 2 shows that the correlation between the two variables is significant at all stations, but it tends to be weaker at shallow stations (<15 m), where mean temperature is relatively higher. For example, stations 09, 15, and H2 show weaker correlation coefficients (r) between −0.57 and −0.74, and higher mean temperatures (17.6–17.8 °C). It is interesting to note that station

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialization</td>
<td>Linear (default)</td>
</tr>
<tr>
<td>Training function</td>
<td>Batch (default)</td>
</tr>
<tr>
<td>Map size</td>
<td>4 × 3</td>
</tr>
<tr>
<td>Map lattice</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Map shape</td>
<td>Sheet</td>
</tr>
<tr>
<td>Neighborhood function</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Training length</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1
Self-organizing map (SOM) parameters

Fig. 6. A 4 × 3 self-organizing map (SOM) array of the bottom dissolved oxygen for June to September. The unit of patterns is indicated in the upper-left corner of each map. The relative frequency of units is shown in the lower-right corner of each map as a percentage (%). The bottom dissolved oxygen concentration is contoured every 0.5 mg/l from 2.0 to 8.0 mg/l.
that the export production from surface waters appears to be more important in fueling biological oxygen demand (BOD) in bottom water than allochthonous inputs of organic matter. Hence, we examine the relationship between hypoxia and spring (February to May) primary production, summer (July to August) wind speed, maximum spring discharge, and spring total nitrogen. The volume of hypoxic condition is determined using the OI data. Fig. 10a shows the linear relationship between the maximum hypoxic volume and mean spring total chlorophyll $a$ for the whole sound, which is not significant ($r^2 = 0.19$, $p > 0.05$). Despite having the highest primary production in 2001, the volume of hypoxic condition was less than 1.5% of the total volume, whereas hypoxia occupied about 14% of the sound in 2003 with the lesser primary production. Fig. 10b shows the average of wind speed during summer is negatively correlated with the hypoxic volume, with a coefficient of determination of $r^2 = 0.19$ ($p > 0.05$). Also, Fig. 10b helps to explain why the year 2001 appears to be an odd year. The mean summer wind speed in 2001 was medium, i.e., wind mixing minimized the effect of spring biomass production, whereas the weak wind in 2003 could not overcome stratification. Therefore, the combined effect of spring primary production and wind mixing in summer is an important factor in determining the maximum volume of hypoxic condition. Although hypoxia in other estuaries is strongly associated with freshwater input (e.g., Kemp et al., 2005). Fig. 10c indicates that there is a weak negative relationship between the maximum volume of hypoxia and the amount of freshwater discharge into LIS, $r^2 = 0.18$ ($p > 0.05$). The relationship is worse with the mean spring total nitrogen yielding $r^2 = 0.11$ ($p > 0.05$). Fig. 10 clearly illustrates that the individual relationship for every variable we have considered with hypoxic volume is weak. Next we decided to examine the combined effect of all the variables. Multiple linear regression using spring chlorophyll $a$, summer wind speed, spring river discharge and spring total nitrogen produces a strong relationship with $r^2 = 0.92$ ($p < 0.01$) as shown in Fig. 11. When total nitrogen is removed the coefficient of determination drops slightly to $r^2 = 0.84$ ($p < 0.01$). Surprisingly, the largest change is detected when river discharge is excluded, with the coefficient of determination dropping to $r^2 = 0.31$ ($p > 0.05$).

5. Discussion

The SOM analyses (Figs. 6 and 7) have revealed that unit 1, i.e., the severe hypoxic condition, is the most frequently occurring pattern during summer in LIS. It is interesting to note that there is a region near station 09, the shallowest station, showing a higher concentration of DO compared to surroundings. Table 2 shows the highest mean temperature with a weak correlation of bottom DO and Fig. 9 exhibits the strongest relationship of bottom DO with density stratification at station 09. This means that vertical mixing tends to play an important role in the variability of DO at shallow stations. In contrast, unit 3 demonstrates the suboxic patch (4–4.5 mg/l of DO) near Smithtown Bay in the Western Basin, which exhibits
the lower DO compared to surroundings. In the central area of the Western Basin near stations F3 and E1, bottom water with a range of 3–4 mg/l of DO was observed in August of 1995, 1997, 1999, 2001, and 2004 (not shown). It is possible that the bottom water becomes stagnant due to the complex bathymetry because these stations are located along the deep channel (w40 m) in the Western Basin which is separated by shoals (see Fig. 1). Its location coincides with that of a cold water pool that usually occurs in the bottom of the Western Basin during summer (e.g., Gay et al., 2004; Crowley, 2005). Hence, the bottom water is likely to be isolated from surroundings and inhibited from vertical mixing with oxygenated water.

Previous studies (HydroQual Inc., 1995; O’Shea and Brosnan, 2000; Anderson and Taylor, 2001) have shown that stratification or vertical mixing was an important contributing factor to the variability of bottom DO in the western LIS. However, this characteristic is not universal to all stations in LIS. Only stations such as A4, 09, 15, and H2 exhibit a strong relationship between bottom DO and stratification (see Fig. 9). This implies that bottom DO is indirectly related with bottom temperature but has no functional relationship with stratification at deep stations. Solubility seems to control bottom DO in the Eastern Basin (see Fig. 8). Fig. 4 suggests that the

![Graph](image-url)

**Fig. 8.** The relationship between the bottom dissolved oxygen (mg/l) with bottom temperature (°C) at stations B3, 15, H6, and K2. The solid line indicates the mean solubility and dotted lines are the maximum and minimum solubility depending on salinity.

**Table 2**

Correlation coefficients between bottom temperature (BT) and bottom dissolved oxygen (BDO), and mean temperature for the summer season (June to August)

<table>
<thead>
<tr>
<th>Region</th>
<th>Station</th>
<th>Depth (m)</th>
<th>Correlation coefficient between BDO and BT</th>
<th>Mean temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrows</td>
<td>A4</td>
<td>38.6</td>
<td>-0.66 (p &lt; 0.01)</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>18.0</td>
<td>-0.76 (p &lt; 0.01)</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>19.8</td>
<td>-0.80 (p &lt; 0.01)</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>32.4</td>
<td>-0.87 (p &lt; 0.01)</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>40.9</td>
<td>-0.89 (p &lt; 0.01)</td>
<td>16.5</td>
</tr>
<tr>
<td>Western Basin</td>
<td>09</td>
<td>9.1</td>
<td>-0.58 (p &lt; 0.01)</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>38.1</td>
<td>-0.89 (p &lt; 0.01)</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>15.3</td>
<td>-0.57 (p &lt; 0.01)</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>19.7</td>
<td>-0.83 (p &lt; 0.01)</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>40.9</td>
<td>-0.87 (p &lt; 0.01)</td>
<td>16.6</td>
</tr>
<tr>
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<td>H2</td>
<td>13.9</td>
<td>-0.74 (p &lt; 0.01)</td>
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</tr>
<tr>
<td></td>
<td>H4</td>
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<td>-0.88 (p &lt; 0.01)</td>
<td>17.3</td>
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<tr>
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<td>-0.79 (p &lt; 0.01)</td>
<td>16.5</td>
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<tr>
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<td>27.3</td>
<td>-0.86 (p &lt; 0.01)</td>
<td>17.7</td>
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<td>72.6</td>
<td>-0.82 (p &lt; 0.01)</td>
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Fig. 9. The relationship between the density stratification (DS) calculated as a difference between surface and bottom values (kg/m³), and the saturation of bottom dissolved oxygen as a percentage (%) for June to August. The name of the station is indicated in the upper-left and the correlation coefficient ($r$) is shown in the upper-right or the lower-left. A solid line indicates the linear relationship when the slope is significantly different from zero ($p < 0.05$).
factors involved in controlling summer bottom DO differ from region to region in LIS. This longitudinal gradient may stem from the differences in primary production, nutrient, hydrographic properties and dynamics. For example, nitrogen loading from sewage treatment plants in the densely populated areas around the western LIS may stimulate primary production. The longitudinal distributions of DO and other scalar properties (e.g., nutrients, temperature, and salinity) possibly occur through the advection of fronts and the processes involved in exchange with adjacent water (Lee and Lwiza, 2005). Therefore, findings in previous studies may be insufficient to adequately describe the variability of bottom DO for the whole sound.

Our results indicate that the bottom DO begins to be undersaturated in June, which coincides with the maximum density stratification and weak wind speed. This supports what was observed by Welsh and Eller (1991) about the period of oxygen depletion being associated with the period of stratification. However, the stronger density stratification observed at deep stations is not strongly associated with changes in bottom DO. Undoubtedly stratification hinders transport of oxygen to the bottom layer, but intensification of stratification does not necessarily result in further depletion of oxygen. Hence, biological uptake is more likely a major factor that controls the variability of DO at deep stations during summer. Nutrient concentrations in LIS clearly affect the upper limit of phytoplankton biomass, which accumulates during the spring bloom (Riley, 1952). The influence of nutrients on the onset of spring blooms, however, may be diminished during warmer winters. The long-term data set of the CTDEP indicates that during abnormally warm winters (i.e., 1998–2000), there is little if any detectable spring bloom and nutrient concentrations remain elevated from January to March in LIS (see Fig. 5). Such years tend to be associated with weak hypoxia. Phytoplankton contribute to BOD in several ways. When DO demand exceeds gross photosynthetic production under low light conditions, and phytoplankton continue to respire, they become oxygen consumers rather than producers (Cole et al., 1992). Therefore, at night phytoplankton below the photic zone can become a major component of the BOD (Jensen et al., 1990). In addition, since they are the major food source for herbivores, they indirectly fuel BOD by the zooplankton. Jensen et al. (1990) showed that the combined effect of phytoplankton and bacteria may account for 64—83% of total community BOD. Hence, processes which stimulate primary production and vertical export of particulate organic carbon (POC) to bottom waters will enhance BOD at depth and contribute to hypoxia.

Fig. 10. The relationship between the maximum hypoxic volume as a percentage (%) and (a) mean spring (February to May) total chlorophyll $a$ for the whole sound (ton), (b) mean summer (July to August) wind speed (m/s), (c) maximum spring (February to May) discharge into Long Island Sound (m$^3$/s), and (d) mean spring (February to May) total nitrogen (mg/l), from 1995 to 2004. The solid lines indicate the least-squares fit from linear regression and the coefficient of determination ($r^2$) is shown in the upper-right.
Ducklow, 1994a). Anderson and Taylor (2001) also showed bacterial biomass can be influenced by grazing (Shiah and Ducklow, 1994b) demonstrated that substrates become limiting when higher temperatures allow faster maximum bacterial growth, because cells require greater rates of substrate supply. When temperature exceeds 20 °C, rates of microbial production and respiration slow down because organic matter gets depleted. However, it is not clear how the timing of organic matter depletion would coincide with 20 °C every year. Another, alternative, explanation is that bacterial biomass can be influenced by grazing (Shiah and Ducklow, 1994a). Anderson and Taylor (2001) also showed that bacterial biomass in LIS reaches maximum values in July and early August, and consequently becomes low and relatively constant thereafter in bottom waters.

Examining the role of bacterial biomass in regulating DO as discussed above is important, because the recovery from minimum DO levels in late summer or early fall has generally been accepted to be a result of increased wind mixing from summer low. However, our study shows that the increase of bottom DO from the minimum usually begins in mid-August, well before the wind speed starts to increase. This shows that the recovery is not necessarily driven by increased mixing. It seems to support the argument of bottom DO budget being driven by one or a combination of the following: (1) reduced bacterial activity, (2) leakage of oxygen from the surface layer due to background diffusion, and (3) horizontal exchange.

Practical implications of understanding DO dynamics are finding ways of reducing the frequency and the extent of hypoxia to the minimum. Our results show that hypoxic volume is weakly correlated to summer wind speed, spring total nitrogen, spring chlorophyll $a$, and maximum river discharge. We used spring values for total nitrogen and chlorophyll $a$ because that is when maximum concentrations of chlorophyll $a$ occur, implying maximum contribution to the organic carbon pool. Maximum river discharge was applied in order to represent major flood events. Interannual variability of total nitrogen has the weakest coupling because nitrogen concentrations are driven by the phytoplankton biomass (see Fig. 5). At first the fact that maximum river discharge is negatively correlated to the hypoxic volume is surprising because we thought high volume of freshwater input would lead to strong stratification, thus cutting off the bottom water early in spring. However, the negative correlation seems to indicate that extreme river discharge events may act to enhance estuarine circulation, which brings in more oxygen to the bottom water. What is even more intriguing is that the river discharge which had a weak correlation ($r^2 = 0.18$) with hypoxic volume had the largest impact when excluded from multiple regression. Since the combined effect of all four factors produces a very strong correlation, it underscores the fact that these factors interact and may act synergistically to influence the DO balance in ways we have yet to fully understand.

The results may explain also why recently LIS has experienced severe hypoxic conditions despite efforts in waste management plans. The LIS TMDL management initiative calls for a reassessment phase whereby response to nitrogen reduction is evaluated. Interannual variability in summertime bottom DO confounds this assessment and necessitates an evaluation of factors controlling this interannual variability. Since the TMDL goals (not just for LIS, but most regions experiencing hypoxia in the United States) are based on only one factor (nitrogen load) and ignore other important factors, the regional management teams will most probably continue to be frustrated by not being able to accurately evaluate the response. The variability of the combined effect of late winter and spring total nitrogen, spring chlorophyll $a$, spring river discharge, and summer wind condition can explain more than 90% of the variability in summertime hypoxia in LIS. We want to emphasize that this does not mean that regulating nitrogen load is not important. It is the only choice we have because we have no control on the other variables. However, in order to be able to properly assess the

Fig. 11. Multiple linear regression showing the relationship between the maximum hypoxic volume as a percentage (%) and the combined effect of four variables from Fig. 10: (1) mean spring total chlorophyll $a$ for the whole sound (CHLA), (2) mean summer wind speed (WIND), (3) maximum spring discharge into Long Island Sound (RIVER), and (4) mean spring total nitrogen (TN). The solid line represents the least-squares best fit from linear regression with the coefficient of determination ($r^2$) shown in the upper-right.
response of the ecosystem to nitrogen reduction, we first must have a systematic way of accounting for the effect introduced by the interannual variability of other factors. It is tempting to think that if we know the amount of nitrogen in the water then we can determine primary production, but the coupling between nutrients and phytoplankton biomass is strongly influenced by meteorological forcing. As mentioned earlier, it has been shown that warm winters can adversely affect spring blooms (Keller et al., 1999, 2001; Oviatt et al., 2002). Also, our results show that efforts toward reducing nitrogen loading so far have not had any impact on the frequency or severity of hypoxia. This indicates that nitrogen levels in LIS during late winter and spring are still too high to limit primary production. In order to meet the TMDL goal to succeed, nitrogen levels have to be lowered such that they can measurably reduce the organic carbon pool.

This study has shown that processes involved in the dynamics of DO are more complicated and they often interact all year around. Water quality data collected on weekly to monthly basis as in most of research programs are probably inadequate because the residence time of particles in LIS is of the order of a few days (Aller and Cochran, 1976). In addition, it has been shown that, at the highest observed BOD rates, DO in bottom waters would be completely depleted in less than 3 days (Anderson and Taylor, 2001). Therefore, in order to understand the mechanisms controlling the dynamics of DO in LIS better, future research work needs to include other areas (tidally dominated and non-tidally dominated), and surveys should be conducted at higher frequency to capture those processes that occur at timescales on the order of days. There are still uncertainties in biological uptake, for example, sediment oxygen demand since benthic communities may account for the higher proportions of the BOD (Aller, 1994), and the role of grazing on bacteria. Previous modeling efforts (e.g. HydroQual, Inc., 1995) have mainly focused on the physics (mixing and stratification) and simple oxygen balance with biological consumption rates that need to be re-evaluated.

6. Summary

The variability of bottom DO has been examined in relation to temperature and density stratification over the whole sound. No clear indication is shown in long-term increase or decrease of bottom DO, but there is a strong longitudinal gradient in variation of bottom DO from east to west. SOM analysis demonstrates that hypoxia occurs in the Narrows every summer and is less frequently observed in the Western Basin. Hypoxia, however, does not develop at some stations in the Central Basin or at any station in the Eastern Basin for the entire record. Contrary to previous studies, for the first time we have shown that there is a large spatial variability in the primary factor which controls the bottom DO. For example, the westernmost and shallow stations are largely affected by density stratification, whereas biological processes possibly dominate the variability of bottom DO at other stations (except the Eastern Basin where DO is controlled by solubility). Second, our results indicate that the variability of hypoxic volume is a function of primary production in spring which acts as a source of organic carbon pool. Third, we have shown that although the hypoxic condition is initiated by strong stratification and weak wind speed, its recovery is not necessarily controlled by increased mixing. We propose three mechanisms that might be responsible for abetting recovery: horizontal exchange, background vertical diffusion and diminished microbial activities. While the first mechanism can act alone to bring in oxygenated water to a hypoxic location, the latter two have to act in tandem. Last but not least, this analysis has exposed a major flaw in the current TMDL policy evaluation. Neglecting the influence of spring bloom production and basing the policy on nitrogen load alone makes it difficult for the management teams to evaluate the response. Therefore, there is a need to include those biogeochemical processes missing in the current models, e.g. role of spring bloom, microbial activity in the water column and the sediment and diagenetic mobilization, and to determine how they interact with physical factors (especially advection) and the competition between vertical mixing and stratification.

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