1. OVERVIEW

Dissolved oxygen is essential for the survival of many types of marine life, and the concentration of dissolved oxygen serves as an important indicator of ecosystem condition. Changes in the dissolved oxygen indicator can reflect the direct effects of tides, stratification of the water column, and other types of physical forcing as well as the indirect effects of nutrient pollution, which decreases the amount of oxygen available through decomposition and respiration. The Narragansett Bay Estuary Program analyzed and compared the extent and duration of concentrations of dissolved oxygen that fell below water quality thresholds between 2001 and 2015.

Acute low levels of dissolved oxygen—a condition termed hypoxia—occur most frequently in the urbanized northern portions of Narragansett Bay and in small embayments where tidal flow is restricted. Urbanization and land development around the upper Bay increased greatly from the Industrial Revolution in the mid-1800s to the present, bringing increases in nutrient pollution. Excess nutrients encourage phytoplankton blooms, which can lead to hypoxia when the phytoplankton decompose. Other stressors on dissolved oxygen in bottom waters of the Bay include high amounts of precipitation and river flow, which increase stratification of the water column leading to reduced mixing of oxygen-rich surface waters with deeper waters, and warmer temperatures, which reduce the amount of oxygen dissolved in the water and increase stratification.

In 2015, dissolved oxygen concentrations in bottom waters were high. Analysis of data revealed high variability from year to year, potentially linked with summer precipitation and freshwater runoff. In dry years with low precipitation and river flow, oxygen concentrations were high. In wet years with high precipitation and river flow, oxygen concentrations were low, and hypoxia was widespread in the northern bottom waters of the Bay.

2. INTRODUCTION

Dissolved oxygen in the water column is critical to sustain water quality and marine life in Narragansett Bay. The concentration of dissolved oxygen depends on a complex mix of biological, chemical, and physical processes. Sources of dissolved oxygen include mixing with the atmosphere, photosynthesis, and circulation with more oxygenated waters. Sinks of dissolved oxygen include respiration within the water column and sediments, and mixing and circulation with less oxygenated waters. Low levels of dissolved oxygen that stress or kill marine organisms are known as hypoxia. Bottom water hypoxia can occur when excess nutrients cause phytoplankton or algae to bloom, which depletes the water of oxygen when the phytoplankton or algae consume oxygen during the night (respiration) and when they die and sink into deep waters and are decomposed by bacteria.

Dissolved oxygen concentration is the measure of how much oxygen (mg/L) is in a quantity of water. Dissolved oxygen sources are mostly in the upper water column, whereas sinks are throughout the water column and concentrated below the pycnocline (where water density increases rapidly with depth). Hypoxia is defined as low levels of dissolved oxygen concentrations that stress or kill marine organisms (USEPA 2000, Miller et al. 2002, Saarman et al. 2008). Hypoxia occurs when oxygen levels are drawn down and not readily replenished. According to the United States Environmental Protection Agency (USEPA 2000), unacceptable chronic impacts to aquatic life
occur at dissolved oxygen values below 4.8 mg/L, unacceptable acute impacts occur at oxygen values below 2.3 mg/L, and between these two values the intensity and duration of hypoxia must be examined. These criteria were based on standards necessary to protect marine juvenile and adult organisms (USEPA 2000). Since larvae are more sensitive to dissolved oxygen than juveniles or adults, Rhode Island designed their regulations to protect larvae using a 1-day exposure of less than 2.9 mg/L (RIDEM 2010).

Hypoxia can be driven by many factors, including eutrophication, which is the excess loading of nutrients and the subsequent increase in the supply of organic matter. If nutrient input to an estuary increases, primary production usually increases. The excess primary production of organic matter leads to an increase in respiration, which decreases oxygen within the water column. If sub-pycnocline/bottom water cannot mix with surface waters, or gets trapped in silled or small embayments due to lack of circulation or mixing, new oxygen (from the atmosphere, circulation or mixing, or photosynthesis) introduced into the area is much reduced. Therefore, as respiration continues, oxygen levels are driven down (Bergondo et al. 2005, Deacutis et al. 2006, Saarman et al. 2008, Codiga et al. 2009). During the summer months, warm waters support high productivity and respiration rates. In addition, the Bay is often stratified with a layer of relatively warm and lower salinity surface water overlying colder and saltier deep water (Codiga et al. 2012). This stratification can isolate the bottom waters from sources of oxygen near the surface (the atmosphere or phytoplankton production of oxygen). Biochemical reactions and respiration in both the water column and the sediments remove oxygen from the waters. This oxygen demand, coupled with warm waters and density stratification, increases the risk of hypoxic conditions in the summer months. The warming climate may also lead to higher hypoxia risk in coastal regions, as warmer water holds less oxygen and contributes to increases in respiration rates (USEPA 2016).

Wet weather tends to increase freshwater discharge to an estuary, enhancing stratification due to the density differences of water, which decreases mixing. This results in increased likelihood of hypoxic events following rainstorms. Usually acute hypoxic events (< 2.9 mg/L) are relatively short-lived and may have only localized effects, but chronic hypoxia (2.9-4.8 mg/L) may have lasting effects on the organisms that inhabit the region.

Hypoxic conditions have been widely studied in estuaries that experience eutrophication, with notable United States examples including the Gulf of Mexico, Chesapeake Bay, and Long Island Sound (Diaz 2001). Coastal hypoxia is a global issue, and it may result in changes to the food web, which may have lasting socioeconomic and environmental effects (Rabalais et al. 2014). Benthic habitats can be affected (see “Benthic Habitat” chapter), and migration by mobile organisms out of affected areas commonly occurs due to hypoxia. Many of these changes can also be linked to changes in nutrient inputs (Rabalais et al. 2014), which may alter the phytoplankton community and shift trophic interactions (Turner et al. 1998). In 2003, a large fish kill, caused by severe hypoxia, occurred in Greenwich Bay, prompting public outcry and accelerating plans to reduce point source nutrient inputs to Narragansett Bay (RIDEM 2003). Managers also sought to expand the Narragansett Bay Fixed Site Monitoring Network to include 13 sites measuring for dissolved oxygen among other water properties. Funding from the National Oceanic and Atmospheric Administration Bay Window Program was instrumental in expanding the network. Key partners in the network include the Rhode Island Department of Environmental Management, University of Rhode Island’s Graduate School of Oceanography, Narragansett Bay National Estuarine Research Reserve, and the Narragansett Bay Commission. These monitoring data are fundamental to establishment of the hypoxia index presented in this report.
3. METHODS

To analyze hypoxia, the Narragansett Bay Estuary Program utilized data from 10 fixed sites throughout the Bay taking bottom dissolved oxygen measurements as part of the Narragansett Bay Fixed Site Monitoring Network (NBFSMN 2016). Those measurements were used to calculate the annual Hypoxia Index, a combined measure of the degree or intensity bottom water dissolved oxygen levels below a fixed threshold and how long dissolved oxygen stayed below the threshold; the Hypoxia Index has been used to identify the areas of the Bay that experience the most severe hypoxia (Codiga 2008, Codiga et al. 2009). In addition, data from a spatial survey were analyzed to examine the spatial and vertical extent of low oxygen values throughout the Providence River estuary, upper Bay, and upper West and East Passages using data from 4 to 7 surveys during each of the summer seasons (June–September) for a total of 58 surveys from 2005 through 2015 (Prell et al. 2016). The spatial survey profiles show the geographic extent of low dissolved oxygen as well as the vertical structure to demonstrate how dissolved oxygen levels change within the water column.

A. Hypoxia Index

The Hypoxia Index utilizes summer bottom water dissolved oxygen data from the Narragansett Bay Fixed Site Monitoring Network (NBFSMN) to quantify spatial and temporal changes in dissolved oxygen. Sensors located 0.5 or 1 meter above the seafloor collected the dissolved oxygen records for bottom waters every 15 minutes in units of mg/L oxygen concentration (NBFSMN 2016). Data from 10 mooring sites were analyzed individually for 2001 to 2015 (Table 1; Figure 2) using the seasonal period May 15 through October 14. From 2001 to 2005, a relatively small number of sites were monitored, mostly in the Providence River estuary and upper Bay. From 2006 to 2015 most or all of the 10 sites were sampled (Table 2).

To identify and quantify individual hypoxic events, the Hypoxia Index applies an algorithm, known as a moving window trigger, to track low dissolved oxygen events in a time series (Codiga 2008, Codiga et al. 2009). The algorithm determines the start and end time for each individual event and its deficit-duration, which is measured as the area below the threshold in the time series of observed concentrations (Figure 1). The deficit-duration is a reflection of both the intensity of the event (concentration difference from the threshold, during the event) and its duration (time that the concentration is lower than the threshold). The moving window trigger algorithm applies a 9-hour trigger duration and 24-hour minimum event duration. Deficit-duration is measured in units of mg l\(^{-1}\) day. As an example of the meaning of the deficit-duration units, consider that if an individual hypoxic event has oxygen concentration that falls below the threshold by an amount 2 mg l\(^{-1}\), and remains there for a duration of 3 days, it has a deficit-duration of 6 mg l\(^{-1}\) day.

To assess hypoxic events, we used three fixed oxygen thresholds: 4.8 mg l\(^{-1}\), 2.9 mg l\(^{-1}\), and 1.4 mg l\(^{-1}\); however, to be consistent with RIDEM water quality standards only the 2.9 mg l\(^{-1}\) threshold is presented in this report (see Codiga et al. 2009 and Codiga 2016, for the complete data set). The Hypoxia Index differs from the metric used by RIDEM (SAIC 2006). In particular, exceedances of the state criteria do not use the same 24-hour minimum event duration and 9-hr trigger duration used by the moving window trigger. Detailed inter-comparisons of results from the two methods, applied to the same measurement records, reveal that they lead to qualitatively similar findings (Codiga et al. 2009).
Figure 1. Schematic showing computation of the Hypoxia Index, relative to a given threshold (red dashed horizontal line), from the time series of near-bottom dissolved oxygen measurements (blue line) at a single mooring site. The index is the total area beneath the threshold level. It is the season-cumulative deficit-duration of all individual hypoxic events (this schematic shows three events) during the mid-May to mid-October analysis period.

We computed multi-site average annual Hypoxia Index results, using the fixed sites grouped by geographic location throughout Narragansett Bay (Figure 2):

- **Providence River and Upper Bay** group (PRUP)
- **Upper West Passage** group (UWP)
- **Upper East Passage** group (UEP)
- **Greenwich Bay** group (GRBY)
- **Mount Hope** group has one site.

Table 1. Acronyms for each site name and site group (shaded) and water depth relative to mean low water. Sensors are located 0.5–1 meter (1.6–3.3 feet) from the bottom.

<table>
<thead>
<tr>
<th>Group</th>
<th>Site</th>
<th>Acronym</th>
<th>Water Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRUB</td>
<td>Bullock’s Reach</td>
<td>BR</td>
<td>6</td>
</tr>
<tr>
<td>PRUB</td>
<td>Conimicut Point</td>
<td>CP</td>
<td>7</td>
</tr>
<tr>
<td>PRUB</td>
<td>North Prudence</td>
<td>NP</td>
<td>11</td>
</tr>
<tr>
<td>UWP</td>
<td>Mount View</td>
<td>MV</td>
<td>7</td>
</tr>
<tr>
<td>UWP</td>
<td>Quonset Point</td>
<td>QP</td>
<td>7</td>
</tr>
<tr>
<td>UEP</td>
<td>Poppasquash Point</td>
<td>PP</td>
<td>8</td>
</tr>
<tr>
<td>UEP</td>
<td>T-Wharf</td>
<td>TW</td>
<td>6</td>
</tr>
<tr>
<td>GRBY</td>
<td>Greenwich Bay</td>
<td>GB</td>
<td>3</td>
</tr>
<tr>
<td>GRBY</td>
<td>Sally Rock</td>
<td>SR</td>
<td>4</td>
</tr>
<tr>
<td>MH</td>
<td>Mount Hope</td>
<td>MH</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 2. Site locations for the Hypoxia Index. Arrows indicate river discharge to the Bay, with size of the arrow representing relative discharge volume (from Codiga 2016).

The Hypoxia Index, referred to as the cumulative deficit, is determined for each individual site and each year as the sum of all deficit-durations for all individual hypoxic events (2.9 mg l$^{-1}$ threshold) that occur there during the mid-May to mid-October period. Uncertainty in the Hypoxia Index is assessed for a given site by determining the typical probability of an event at that site during those times of year and the typical intensity of an event at that site, based on the statistics of all sampled years at that site. Gaps in sampling, when field sensors were not operating or data did not meet quality standards, typically comprise about 10 to 40 percent of the mid-May to mid-October period (Table 2).

<table>
<thead>
<tr>
<th>Site</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>100</td>
<td>75</td>
<td>79</td>
</tr>
<tr>
<td>CP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP</td>
<td>62</td>
<td>81</td>
<td>65</td>
</tr>
<tr>
<td>MV</td>
<td></td>
<td></td>
<td>73</td>
</tr>
<tr>
<td>QP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW</td>
<td></td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>GB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td></td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>MH</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Percent of time during mid-May to mid-October analysis period with valid near-bottom dissolved oxygen values at each of the 10 sites in each of the 15 years. Asterisks indicate records with less than 55 percent valid values, which were not included in the analysis. Blanks indicate sites that were not sampled in a given year.
### B. Spatial Survey

The spatial surveys used in this analysis were initiated in 2005 using Sea-Bird 19 Plus SEACAT profilers. Three boat groups sampled about 77 sites covering 150 square kilometers (58 square miles) in the Providence River, Greenwich Bay, and the East and West Passages of Narragansett Bay (Figure 3). The surveys focused on the warm summer months near neap tides when the risk of hypoxia was believed to be greatest. Because dissolved oxygen exhibits little diurnal variability below the pycnocline (an area in the water column where density rapidly increases with depth), the surveys were conducted in the morning hours irrespective of tidal phase. Tidal excursions in Narragansett Bay are small compared to the scale of the survey, so we have not attempted any correction for tidal phase. The data were calibrated and organized to produce an internally consistent and documented, interpolated (0.5 meter or 1.6 feet) dataset of temperature, salinity, and dissolved oxygen. The dataset has 58 surveys at about 77 sites over eleven years (2005–2015) and contains 4,154 individual profiles (Prell et al. 2015, 2016).
Inter-annual variations in oxygen concentrations are strongly related to freshwater runoff into Narragansett Bay (Codiga et al. 2009). Accordingly, the impact of freshwater runoff was assessed using the daily discharge from the Blackstone, Pawtuxet, and Taunton Rivers (as measured by USGS gauges) along with the long-term data of Ries (1990) to calculate the total freshwater flux to the Bay during the summer (June, July, August, September; abbreviated JJAS). Annual departures from the long-term median (2005–2015) were used with annual salinity to define wet years (Prell et al. 2016).

4. STATUS AND TRENDS

A. Hypoxia Index

We report the status of hypoxia in Narragansett Bay based on conditions in the most recent years (2013–2015) using Hypoxia Index results from individual sites (Figure 4) and multi-site average Hypoxia Index results (Figure 5).

The individual site results in 2013–2015 make clear two dominant aspects that are generally applicable to other years. The first aspect is pronounced inter-annual variability. The Hypoxia Index was higher in 2013 than in 2014 or 2015 at all sites, and substantially so at most sites (Figure 4). This inter-annual variability is notably far larger than uncertainties in the Index values due to sampling gaps. The increases in the 2013 Index values over those of 2014 and 2015 were generally similar at all sites, indicating they result from a process with Bay-wide influence. Hypoxia was likely more severe in 2013 than in 2014 and 2015 because 2013 had wetter than average spring and summer conditions, while 2014 and 2015 were drier.
The second dominant characteristic was a down-Bay gradient, in which the Hypoxia Index generally decreased from north to south (Figures 4 and 5). This was a persistent feature, with very few exceptions, in any given year and is more pronounced in wet years. The Hypoxia Index decreased toward the south from Bullock’s Reach to Conimicut Point to North Prudence in the Providence River and Upper Bay group (PRUB); from Mount View to Quonset Point in the Upper West Passage group (UWP), except 2014, when they were similar in magnitude; and from Poppasquash Point to T-Wharf in the Upper East Passage group (UEP).

The results for the Hypoxia Index, using the 2.9 mg l$^{-1}$ threshold, were typically less than 30 mg l$^{-1}$ day with a maximum of about 60 mg l$^{-1}$ day (Figure 4). During the drier years of 2014 and 2015, the Index was effectively zero everywhere except for in GRBY. During the wet year of 2013, the Index included elevated results for GRBY, PRUB, MH, and the northern site (MV) in UWP, and the other sites in the Bay were zero or very near to zero (no hypoxic events using the 2.9 mg l$^{-1}$ threshold).
Figure 4. Hypoxia Index for individual sites within each site group, relative to threshold 2.9 mg l^{-1} day. Years with substantially higher than average river runoff during June to September (Table 4) are
marked by gray vertical bars. To improve clarity by reducing overlap of lines and symbols, symbols from each site are systematically offset a small distance horizontally relative to those of other sites in the frame. Error bars are obscured by the data points; uncertainties are due to gaps in the time series because of sensor malfunction or data not meeting quality standards.

Figure 5. Hypoxia Index averaged over all sites within each site group, relative to threshold 2.9 mg l\(^{-1}\) day. Shown as in Figure 4.

The Estuary Program analyzed the results from all years of data, using the multi-site mean Hypoxia Index values for the 2.9 mg l\(^{-1}\) threshold, in an attempt to discern trends. However, the possible presence of trends extending over multiple years was difficult to discern due to the relatively large inter-annual variability. This fundamental characteristic of the dataset sharply limited the confidence that can be placed in conclusions regarding trends (Figure 5).

These results did illustrate the pattern that higher Hypoxia Index values occurred in wetter conditions (Figures 4 and 5). The years with higher than typical runoff (2003, 2006, 2009, 2011, and 2013) appeared as local maxima in the Hypoxia Index, generally at all sites. There was no strong evidence for a long-term trend that was comparable in magnitude, over the 15-year period, to the inter-annual variability. This was true whether examining all years together, wet years alone, or dry years alone.
B. Spatial Survey

The spatial survey data for the summers of 2005 to 2015 were used as a point of comparison to the Hypoxia Index. The summer of 2015 was characterized by relatively low freshwater flux, high salinity, and a low percent area of hypoxia (Tables 3 and 4; Figures 6c and 6d). To illustrate the spatial extent of hypoxic waters, representative maps of bottom water and minimum dissolved oxygen on August 12 of 2015, a dry year with a minimal area of hypoxia waters, were compared to August 4 of 2009, a wet year with a large area of hypoxic waters (Figure 6). In general, the spatial pattern remained similar throughout the surveys: hypoxic waters typically occurred in the Seekonk and Providence Rivers and Greenwich Bay, expanding to the Upper and Middle West Passage during more extreme events.

The lowest dissolved oxygen values typically occurred at the bottom, but during intervals of high river flux and stratification the minimum levels of dissolved oxygen were often measured near the pycnocline, which was typically at a depth of 4 to 6 meters (13 to 20 feet). This pattern was especially evident in the dredged shipping channel in the Providence River and the eastern upper Bay (Figures 6a and 6b). During low hypoxic intervals, the bottom and minimum maps were virtually identical as no mid-water minimum developed (Figures 6c and 6d). On the maps, areas of higher dissolved oxygen surrounded by lower dissolved oxygen typically indicate shallow sites that were within the mixed layer and thus more highly oxygenated. This pattern was evident on the margins of the Providence River above Conimicut Point, where a number of shallow sites did not change from bottom to minimum maps (Figures 4, 6a, and 6b). During intervals of high hypoxia, the low dissolved oxygen extended over the upper Bay and down the West Passage to Quonset Point. The East Passage, south of Poppasquash Point, remained largely oxygenated (Figures 6a and 6b).

The average bottom dissolved oxygen for different parts of the Bay in 2015 was slightly higher (about 0.2 mg/L) compared to the 2005–2015 average (Table 3; Figure 7), and the percent area covered by hypoxic bottom water (5.6 percent) during the summer (July, August, September: JAS) was among the lowest observed during the past decade (Tables 3 and 4; Figure 9). Although the average bottom dissolved oxygen did not change substantially from long-term averages (compare Figures 7 and 8), the average minimum bottom dissolved oxygen in 2015 was higher (Table 3).

Table 3. Summary of the average bottom dissolved oxygen and the average minimum dissolved oxygen for 2015 compared to the long-term (2005–2015) averages for different areas of the Bay. All units are mg/L.

<table>
<thead>
<tr>
<th>Year</th>
<th>Seekonk and Providence Rivers</th>
<th>Upper Bay</th>
<th>Greenwich Bay</th>
<th>Lower Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average – Min.</td>
<td>Average – Min.</td>
<td>Average – Min.</td>
<td>Average – Min.</td>
</tr>
<tr>
<td>2015</td>
<td>3.6</td>
<td>2.1</td>
<td>4.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Long-term Average (2005-2015)</td>
<td>3.4</td>
<td>0.9</td>
<td>4.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Figure 6. The spatial extent of bottom water (left column: 6a, 6c) dissolved oxygen and minimum (right column: 6b, 6d) dissolved oxygen in a highly hypoxic survey (top row: 6a, 6b; August 4, 2009) and a minimally hypoxic survey (bottom row: 6c, 6d; August 12, 2015). Dissolved oxygen categories
correspond to the three thresholds (4.8, 2.9, and 1.4 mg/L) used RIDEM to identify chronic and acute hypoxia.

Table 4. Summary statistics for all summer (June, July, August, September: JJAS) surveys during each survey year. Wet years, based on river flux, shaded in grey. DO is dissolved oxygen.

<table>
<thead>
<tr>
<th>Year</th>
<th>River Flux Departure m³/s</th>
<th>Average Surface Salinity %/00</th>
<th>Average Surface Temp. °C</th>
<th>% Area with Bottom DO &lt; 2.9 mg/L JJAS</th>
<th>Average % DO Surface Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>-10</td>
<td>28.0</td>
<td>23.2</td>
<td>5.3</td>
<td>101</td>
</tr>
<tr>
<td>2006</td>
<td>26</td>
<td>23.7</td>
<td>22.0</td>
<td>27.1</td>
<td>96</td>
</tr>
<tr>
<td>2007</td>
<td>-13</td>
<td>27.7</td>
<td>21.1</td>
<td>2.9</td>
<td>91</td>
</tr>
<tr>
<td>2008</td>
<td>-4</td>
<td>26.5</td>
<td>23.1</td>
<td>17.6</td>
<td>91</td>
</tr>
<tr>
<td>2009</td>
<td>44</td>
<td>24.3</td>
<td>21.6</td>
<td>29.8</td>
<td>101</td>
</tr>
<tr>
<td>2010</td>
<td>-17</td>
<td>27.6</td>
<td>24.2</td>
<td>17.4</td>
<td>105</td>
</tr>
<tr>
<td>2011</td>
<td>25</td>
<td>25.3</td>
<td>23.6</td>
<td>13.7</td>
<td>107</td>
</tr>
<tr>
<td>2012</td>
<td>-5</td>
<td>27.6</td>
<td>23.7</td>
<td>12.2</td>
<td>97</td>
</tr>
<tr>
<td>2013</td>
<td>23</td>
<td>23.9</td>
<td>23.0</td>
<td>18.0</td>
<td>107</td>
</tr>
<tr>
<td>2014</td>
<td>-17</td>
<td>27.9</td>
<td>23.6</td>
<td>3.7</td>
<td>101</td>
</tr>
<tr>
<td>2015</td>
<td>-8</td>
<td>28.4</td>
<td>23.4</td>
<td>5.6</td>
<td>88</td>
</tr>
</tbody>
</table>

The minimum bottom water dissolved oxygen observed at each site and the mean bottom water levels for each site and its standard deviation over all surveys revealed bottom conditions throughout the Bay. Of the 77 sites, 11 sites (14 percent) had mean bottom water dissolved oxygen < 2.9 mg/L and 67 sites (87 percent) had a minimum observed dissolved oxygen of < 2.9 mg/L.
Figure 7. The distribution of average (solid symbols) and minimum (open symbols) dissolved oxygen concentrations in bottom water for sites in each region of Narragansett Bay in 2015 surveys. Sites are shown in the graph from north (left) to south (right). The north-to-south gradient in dissolved oxygen is attributable to differences between East and West Passages, shallow sites, and low dissolved oxygen in coves and embayments at different latitudes. Dashed lines indicate the three thresholds (4.8, 2.9, and 1.4 mg/L) used by EPA and RIDEM to identify chronic and acute hypoxia. Bars indicate standard deviation for mean dissolved oxygen.
Figure 8. The distribution of average (solid symbols) and minimum (open symbols) dissolved oxygen concentrations in bottom water for sites in each region of Narragansett Bay averaged over all surveys (2005-2015). Shown as in Figure 7.

Although the average dissolved oxygen values (Figures 7 and 8) show large-scale spatial gradients in the Bay, they do not capture the temporal and spatial variability. To document these patterns, we
mapped the bottom dissolved oxygen and calculated the area of each dissolved oxygen class (Figure 9). The percent area of hypoxic bottom water (<2.9 mg/L) during the summer (July, August, September: JAS) exhibited significant intra- and inter-annual variability. Typically, less impairment occurred in June, which tended to have lower water temperatures. The area of hypoxic bottom waters ranged from over 40 percent in sporadic extremes in 2006, 2008, 2009, and 2013 to only a few percent, especially in June and September.

Figure 9. Percent of the survey area considered hypoxic (<2.9 mg/L) from 2005 to 2015. Each bar represents a survey. Only July, August, and September surveys are shown.

5. DISCUSSION
The Hypoxia Index and the spatial survey both showed that a down-Bay increase in dissolved oxygen concentrations is an annual trend. This down-Bay increase starts with the lowest concentrations in the Providence River estuary and the Seekonk River and the highest concentrations at the southern end of Narragansett Bay (Figures 4, 5, and 6). The down-Bay gradient has been interpreted (Codiga et al. 2009, Codiga 2012) as the result of two interacting influences. First, the most-concentrated nutrient loading thought to be driving hypoxia is located to the north in Providence River estuary and upper Bay regions. Second, the residual circulation is counterclockwise (Rogers 2008), thus moving the oxygen-depleted waters originating in the north toward the westward and southward directions. Similarly, the spatial survey showed a down-Bay gradient in which the long-term mean bottom water dissolved oxygen concentration ranged from 1.2 mg/L at Providence River site to 6.3 mg/L at the shallow West Passage site (Figure 8). While clear, the down-Bay gradient is irregular, reflecting the variety of depths and location of sites in coves and embayments (Figure 8). The water depth of the sites affected the variability of mean bottom dissolved oxygen, with shallow sites in the Providence River showing higher than expected levels and Greenwich Bay showing especially low minimum dissolved oxygen.

The data revealed low bottom water dissolved oxygen in problem areas including the Providence-Seekonk River estuary, upper Bay, Greenwich Bay, upper West Passage, and Mount Hope Bay fixed sites (Deacutis et al. 2006, Melrose et al. 2007, Codiga et al. 2009, Prell et al. 2016). The data also showed that the Providence River estuary periodically suffered from acute hypoxia, although the minimum dissolved oxygen concentration was not always at the bottom of the water column (Deacutis et al. 2006, Melrose et al. 2007). In the upper Bay, the minimum dissolved oxygen value was often observed near the pycnocline (Deacutis et al. 2006, Melrose et al. 2007, Prell et al. 2016).

A decrease of bottom water hypoxia with distance down the Bay followed the gradient of anthropogenic inputs to Narragansett Bay (Oviatt et al. 2002, Murray et al. 2007, Oviatt 2008). Those issues may, in certain cases, be compounded by neap tides, which decrease water circulation, particularly in restricted areas such as the Providence River estuary and Greenwich Bay (Bergondo et al. 2005). However, the link between hypoxia and neap tides has not been supported by regression analyses (Codiga et al. 2009, Codiga 2012).

Both the Hypoxia Index and the spatial survey showed that hypoxia was low for the recent dry years of 2014 and 2015 and that there was a strong pattern of intra- and inter-annual variability in the amount of hypoxia measured each year (either from May to October or June through September). The Hypoxia Index levels in 2014 and 2015 were similar to previous dry years of 2004 and 2007 (Figure 5). The Hypoxia Index showed that hypoxic events tended to occur in the Providence River-Upper Bay (PRUB), Upper West Passage (UWP), and Greenwich Bay (GRBY) during wet years, with Greenwich Bay showing significant hypoxic events in dry years as well (Figures 4 and 5).

Similarly, the area of hypoxic bottom waters in the spatial survey also appeared to be correlated to the freshwater flux with wet years having a higher area of hypoxic waters (Table 4; Figure 9). The greater area of hypoxic waters in 2010 was likely related to warmer temperatures, while the cause of the higher area of hypoxic waters in 2008 was unclear (Table 4). The area of hypoxic bottom water approximately doubled between the dry (8 percent) and wet (19 percent) years, while the departure from mean river flux changed from -10.6 m$^3$/s to 29.5 m$^3$/s (Table 4).

The mechanism by which wetter conditions make hypoxia more severe is not fully understood. It is known that higher-than-average runoff contributes to stronger stratification, which can enhance
hypoxia by impeding re-aeration through reduced vertical mixing (Codiga 2012). Wet years are also thought, by some, to increase nutrient loads that drive hypoxia. The relative importance of these two processes, and possible influence of differing rates or patterns of circulation during wet and dry years, is a topic that will require additional research.

The Hypoxia Index and the spatial survey are different but complementary methods, using different data and different temporal scales. The Hypoxia Index uses an extensive array of temporal data with data collected every 15 minutes from May to October, but it does not have high spatial resolution, given that there are just 10 fixed sites used by the Index. Conversely, the spatial survey has more spatial resolution (both horizontally and vertically) with 77 sites, but it focuses on only 5 or 6 survey days each summer, providing low temporal resolution. We conducted an initial analysis comparing these methods in the Providence River estuary. The Hypoxia Index results for two sites (Bullocks Reach-BR and Conimicut Point-CP) had a strong correlation to the spatial extent of hypoxia using the spatial survey (Figure 10). There is a need to expand this analysis and complete correlations for other sites in the Bay to assess the strength of correlations in a manner that captures inter-annual variability.
Figure 10. Top: Comparison of Hypoxia Index at two sites (Bullocks Reach, BR: black diamonds and lines; Conimicut Point, CP: blue diamonds and lines) and spatial survey (red squares and lines) using a threshold of 2.9 mg/L. Bottom: Correlation of Hypoxia Index for BR (red) and CP (black) with spatial survey at the 2.9 mg/L threshold.
An additional comparison used the minimum dissolved oxygen in select wet years (2006, 2009, and 2013) and dry years (2007, 2014, and 2015) (Figure 11). The minimum dissolved oxygen value for each Narragansett Bay Fixed Site Monitoring Network site was only a single 15-minute value for the entire season and may not be reflective of the season. The year 2013 had higher than average precipitation and runoff, while 2014 and 2015 were drier than typical, with less runoff than normal, leading to higher Hypoxia Index results in 2013 than in 2014 and 2015. This pattern is also apparent in other wet years (Figures 4 and 5).
Figure 11. Minimum dissolved oxygen values for all Narragansett Bay Fixed Site Monitoring Network sites for the dry years of 2007, 2014, 2015 (top) and for the wet years of 2006, 2009, and 2013 (bottom). The sites are presented by Narragansett Bay sections.
An important context for examining trends in hypoxia is that wastewater treatment facilities have been upgrading over the past decade and continue to upgrade, significantly reducing the nutrient loads thought to drive hypoxia. Wastewater treatment facilities in the Bay and watershed have reduced nitrogen loading by 57 percent from the 2000–2004 period to the 2013–2015 period (see “Nutrient Loading” chapter). The response time of the system to nutrient load reductions is not well understood, so it is possible that the recent results of the Hypoxia Index and spatial survey reflect weakening hypoxia (results for 2014 and 2015 were the lowest on record) as a result of reduced nutrient loads. However, those years were also dry, and the spatial survey and Hypoxia Index results from earlier dry years (Figures 4, 5 and 9) were comparable to results from 2014 and 2015. Consequently, it is too early to conclude that Bay hypoxia is weakening due to reduced nutrient loads. There may be a significant time lag between nitrogen reduction and the biological response of the systems (e.g., organic matter production, decomposition, and oxygen depletion). It will be necessary to monitor and analyze the coming few years before such a conclusion may be supported or refuted. In particular, much will be learned from the next year that is wetter than average. In the event that during an upcoming wetter than normal year the Hypoxia Index is substantially lower, as compared to earlier wet years, it would be evidence that a long-term reduction in hypoxia has occurred.

Warming temperatures are an expected consequence of climate change (see “Temperature” chapter). Warming temperatures will result in higher rates of primary production and respiration and also contribute to the stratification of the water column, which prevents mixing of bottom water with the surface (USEPA 2016). Respiration would continue to decrease dissolved oxygen concentrations and less vertical mixing could exacerbate hypoxic conditions. This would increase the consumption of dissolved oxygen, and reduce dissolved oxygen concentrations towards hypoxic conditions.

Another predicted effect of climate change is the increased frequency of intense storms (RI EC4 STAB 2016, USEPA 2016; see “Precipitation” chapter). These storms can lead to higher pulses of river runoff, causing more nutrient loading and salinity-induced stratification. The addition of nutrients and stratification can set up the same hypoxic conditions noted with warming temperatures. Analysis of stratification concluded that climate-driven changes will be due to increases of river runoff more than increases in temperature (Codiga 2012).

Local hypoxia researchers (Codiga 2012) have noted that weather in May and June sets up the severity of hypoxia for the remainder of the summer. If river runoff pulses occur in May and June, hypoxic events could increase through throughout the summer, even if no further pulses occur. This type of situation happened in 2013, when June was very wet and the rest of the summer was very dry, but bottom water dissolved oxygen concentrations were very low. It may have also happened during years with higher than average river flow and higher than average stratification (2003, 2006, 2009, etc.) (Codiga et al. 2009). There is a relationship between stratification and hypoxia but it has limits (Codiga 2012), possibly because strong stratification is due to high runoff reducing the flushing time, decreasing the time nutrients stay in the system. Further investigation into these processes is needed.
6. DATA GAPS AND RESEARCH NEEDS

A major gap with the Narragansett Bay Fixed Site Monitoring Network and spatial survey is the lack of resource commitment (e.g., funding and personnel) to continue these field monitoring and data processing efforts. The NBFSMN and spatial survey require constant equipment maintenance and costly upgrades.

Synthesis studies are needed to further explore the different temporal and spatial scales of dissolved oxygen variability and their relationships to the physical structure of the water column. Integration of the spatial patterns with the temporal data from the fixed sites in the Bay is needed to assess how well the sites reflect the larger geographic distribution of dissolved oxygen. The combined datasets could also include a comprehensive study of river runoff, nutrient flux, stratification, and hypoxia. This would further an understanding of the physical forcing responsible for hypoxia. Phillipsdale Dock, the URI Graduate School of Oceanography dock, and the two new sites in Mount Hope Bay should be included in this analysis.

Warming waters due to climate change may worsen hypoxia in the Bay under certain conditions. Further research into the interactions between dissolved oxygen and water column temperature, pH, and other properties would help us better understand how the changing climate may affect dissolved oxygen levels in Narragansett Bay.

Another research need is to incorporate the findings of recent hydrodynamic modeling efforts with the data discussed here. The combination of the dissolved oxygen data and modeling efforts may provide a better understanding of how hydrodynamic properties of the Bay are influenced by physical forces, such as wind, precipitation, and river flow, and how dissolved oxygen levels respond.

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8. REFERENCES


Kiernan S., D. Murray, W. Prell, and C. Deacutis. 2014. Dissolved Oxygen Profiles and Monitoring in Narragansett Bay Quality Assurance Project Plan. Water Resources Division, Rhode Island Department of Environmental Management, 235 Promenade Street, Providence, Rhode Island 02908


RIDEM. 2013. Fixed Site Monitoring Stations and Data in Narragansett Bay. Bay Assessment and Response Team (BART). http://www.dem.ri.gov/bart/stations.htm


USEPA. 2016. Climate change vulnerability scoring report: risks to clean water act goals in habitats in the Northeast. EPA Contract # EP-C-14-017.