State of Narragansett Bay and Its Watershed
2017 Technical Report

Bay Ecosystem Condition Indicators

CHAPTER 15: DISSOLVED OXYGEN

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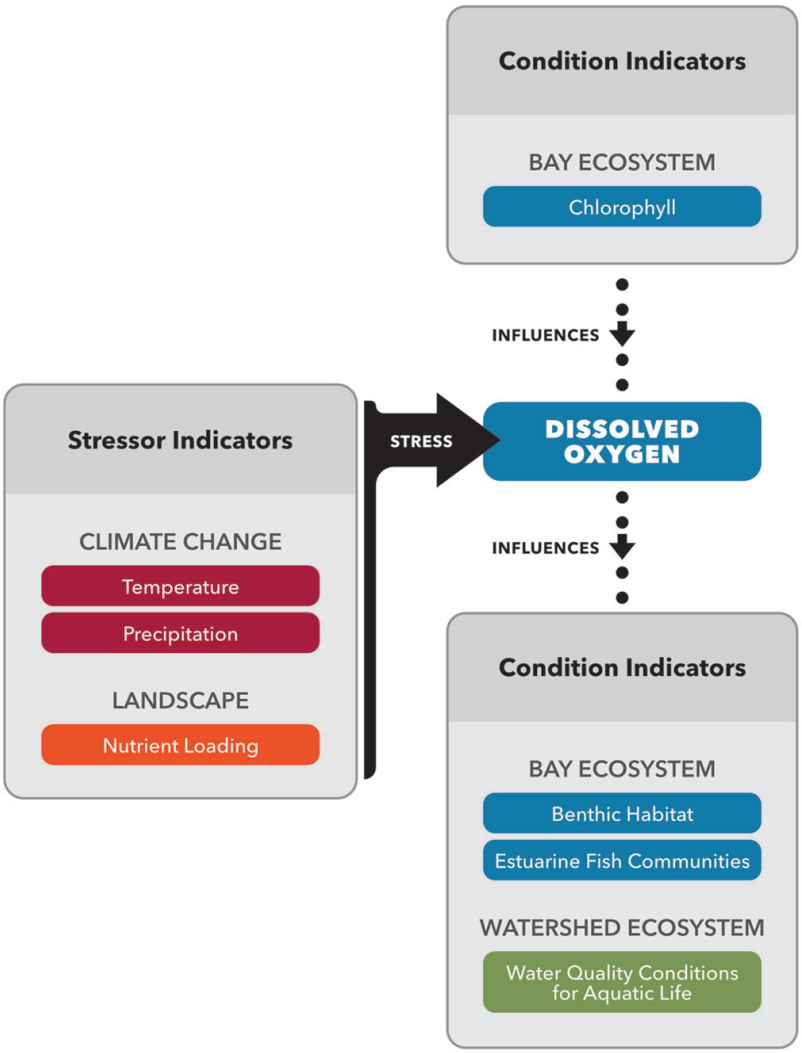
NARRAGANSETT BAY ESTUARY PROGRAM

Overview



BACKGROUND

- Dissolved oxygen is essential for the survival of many types of marine life, and thus it serves as an important indicator of ecosystem condition. Dissolved oxygen concentrations are influenced directly by oxygen generation (photosynthesis) and consumption by living organisms (in particular, bacteria). In addition, dissolved oxygen is influenced by many other factors such as water temperature, exchange with the atmosphere as driven by winds, and exchange with nearby waters as governed by currents and mixing (processes shaped by precipitation-driven riverine inputs that promote distinct water layers, and by tidal conditions). Excessive nutrient loading can lead to depletion of dissolved oxygen by stimulating the growth of large amounts of phytoplankton (indicated by chlorophyll concentrations) and macroalgae. As the phytoplankton and macroalgae decay, bacterial

consumption can deplete dissolved oxygen, stressing organisms, especially those that are unable to move out of the oxygen-depleted area. Both Rhode Island and Massachusetts assess estuarine waters for impacts by nutrient enrichment and/or oxygen depletion to protect aquatic life.

KEY FINDINGS

- ***Status:*** In 2013 to 2015, the lowest bottom water oxygen concentrations were recorded in the Providence and Seekonk Rivers, as well as in Greenwich Bay, with concentrations elsewhere generally increasing throughout the bay southward and eastward. Bay-wide, hypoxia was variable year to year, with low oxygen concentrations in 2013 when summer precipitation and river flow were higher than typical, and relatively high oxygen concentrations in 2014 and 2015 which were drier than typical. Observed hypoxia characteristics from 2013 to 2015 were typical of conditions seen since focused measurement programs began, in the early 2000s.
- ***Trends:*** Data from 2005 to 2015 revealed high variability from year to year, linked to spring/summer precipitation and river flow. Relative to these interannual changes, long-term trends were not sufficiently pronounced to be identified well by the measurements.

Introduction

Dissolved oxygen (DO) 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. 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). Sources of dissolved oxygen include mixing with the atmosphere, photosynthesis, and exchange with more-oxygenated waters through circulation and mixing. Sinks of dissolved oxygen include respiration within the water column and sediments, and exchange with less oxygenated waters through circulation and mixing.

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 depleted and not readily replenished. According to the United States Environmental Protection Agency (USEPA 2000), unacceptable chronic impacts to aquatic life occur at dissolved oxygen concentrations below 4.8 mg/l, while unacceptable acute impacts to adult and juvenile species occur at levels below 2.3 mg/l for at least 24 hours. Between these two values the intensity and duration of hypoxia must be examined to determine habitat suitability. Because larvae are more sensitive to dissolved oxygen than juveniles or adults, the Rhode Island Department of Environmental Management (RIDEM) adopted criteria calculated from USEPA (2000) guidance to protect larvae from a 24-hour exposure of less than 2.9 mg/l in bottom waters during the recruitment season (RIDEM 2010). Both Massachusetts and Rhode Island assess estuarine waters for impacts from nutrient enrichment and depleted oxygen concentrations. Of the state-assessed estuarine waters, approximately 50 percent were identified as impacted by nutrient enrichment and/or depleted oxygen levels (see "Water Quality Conditions for Aquatic Life" chapter). This translates to 37 percent of all estuarine waters in the Rhode Island and Massachusetts portions of Narragansett Bay. These areas are located in the northern sections of the Bay (the Upper West Passage, Greenwich Bay, Upper Narragansett Bay, Providence River Estuary, Mount Hope Bay, and the Taunton River).

Hypoxia is influenced by many factors, including excessive nutrient loading, respiration/decomposition, and stratification. Excessive nutrient loading causes phytoplankton or macroalgae to bloom, which, when the phytoplankton or macroalgae consume oxygen (respiration) and when they die and sink into deep waters and are decomposed,

depletes the water of oxygen. If sub-pycnocline/bottom water cannot mix with surface water, or gets trapped in silled or small embayments due to lack of circulation or mixing, consumption of oxygen can exceed oxygen introduced to the area (from the atmosphere, photosynthesis, or circulation) and the waters can become oxygen depleted. As respiration and decomposition continue, 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 density stratified, meaning there are distinct layers with relatively warm and lower salinity surface water overlying colder and saltier deep water (Codiga 2012). Wet weather tends to increase freshwater discharge to an estuary, which increases nutrient loading and further enhances stratification due to the density differences of water, leading to decreased mixing. This results in increased likelihood of hypoxic events following rainstorms, as stratification can isolate the bottom waters from sources of oxygen near the surface. 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).

Hypoxic conditions have been widely studied in estuaries that experience eutrophication, with notable examples including the Gulf of Mexico, Chesapeake Bay, and Long Island Sound (Diaz 2001, Bricker et al. 2007, USEPA 2012). Coastal hypoxia is a global issue, and it may result in changes to the food web that have lasting socioeconomic and environmental effects (Bricker et al. 2007, USEPA 2012, 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).

By the mid to late 1980s, researchers established that bottom waters in the Providence-Seekonk River Estuary and the upper portions of Narragansett Bay experienced periods of low oxygen during the summer months (e.g., Pilson and Hunt 1989, Doering et al. 1990). The low dissolved oxygen contributed to changes in the benthic community (Germano and Rhoads 1989; see "Benthic Habitat" chapter) and resulted in periodic fish kills. During the 1990s, managers and researchers strived to implement management actions to mitigate hypoxic events, such as reducing nitrogen loading (specifically ammonium, and later, total nitrogen) from wastewater treatment facilities (see "Wastewater Infrastructure" and "Nutrient Loading" chapters). In 2003, a large fish kill, caused by severe hypoxia, occurred in Greenwich Bay, prompting public outcry and accelerated plans to reduce point source nutrient inputs to Narragansett Bay (RIDEM 2003). Following the fish kill, managers also sought to expand the Narragansett Bay Fixed Site Monitoring Network to include thirteen sites measuring dissolved oxygen and other properties.

This chapter analyzes bottom water dissolved oxygen concentrations in Narragansett Bay using two separate methods–a Hypoxia Index and Spatial Surveys–to assess the duration, intensity, and spatial extent of hypoxic events in the Bay. The analysis using the Hypoxia Index focuses on the growing season (May to October) from 2001 to 2015, while the analysis using the Spatial Surveys targets the summer season (June through September) from 2005 to 2015.

Methods

To analyze dissolved oxygen concentrations and hypoxia, the Narragansett Bay Estuary Program employed two methods:

- ***Hypoxia Index:*** The Hypoxia Index, using data from the Narragansett Bay Fixed Site Monitoring Network (NBFSMN), combines measures of the amount or magnitude that bottom water dissolved oxygen concentrations fell below a fixed threshold, and how long they 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). It provides a tool to consistently characterize hypoxia across the bi-state estuarine waters of the Bay.
- ***Spatial Surveys:*** The Estuary Program analyzed the spatial distribution of bottom water dissolved oxygen concentration using data collected by the Day Trippers, which is a collaborative sampling effort involving several organizations (Prell et al. 2015, 2016).

These efforts have two separate methodologies (detailed below) and generate results which may not be consistent with each other. The Status and Trends section of this chapter is divided into two parts to separately report the results for each method. Status was based on the most recent data – 2013 to 2015

for the Hypoxia Index and 2015 for the Spatial Survey. Trends were determined using the entire dataset for both metrics. Additional methods are available upon request.

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 to 1 meter (1.6 to 3.3 feet) above the seafloor collected the dissolved oxygen records for bottom waters every 15 minutes in units of mg/l (or mg l-1) (NBFSMN 2016). Data from ten of the fixed stations were analyzed individually for 2001 to 2015 (Table 1; Figure 1) using the seasonal period May 15 through October 14, building on work done previously (Codiga 2008, Codiga et al. 2009). May through October is the WWTFs subject to advanced nitrogen removal are required to do so (see "Nutrient Loading" chapter). 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 ten 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 each time series (Codiga 2008, Codiga et al. 2009). The start (or end) of an event is identified when the concentration falls below (or rises above) the 2.9 mg/l threshold for longer than a "trigger duration" to avoid mistakenly identifying short-duration excursions below (or above) the threshold as starting (or ending) an event. Due to tidal processes, such short-duration excursions are common, lasting less than about six hours or one-half the dominant tidal period (M2, lunar semidiurnal), so the algorithm used a trigger duration of nine hours (Codiga 2008, Codiga et al. 2009). An individual event is identified when a start and end are detected with sub-threshold concentration for a duration of at least 24 hours between them. The algorithm determines the event deficit-duration, which is the area below the threshold in the time series of observed concentrations (Figure 2). The deficit-duration is a reflection of both the intensity of the event (amount or magnitude by which concentration falls below the threshold during the event) and its duration (time that the concentration is lower than the threshold).

Deficit-duration is measured in units of mg/l day (mg l-1 day). As an example of the meaning of the deficit-duration units, consider that if an individual hypoxic event has an oxygen concentration that falls below the threshold by an amount of two mg/l, and remains there for a duration of three days, it has a deficit-duration of six mg/l day.

To characterize hypoxic conditions, three fixed oxygen thresholds were used, as motivated by RIDEM water quality standards: 4.8 mg/l, 2.9 mg/l, and 1.4 mg/l; however, only the 2.9 mg/l threshold results are presented in this chapter to focus on acute hypoxia (see Codiga et al. 2009 and Codiga 2016 for the complete analysis). The Hypoxia Index differs from the regulatory metric used by RIDEM to evaluate the different allowable exposure periods associated with each DO threshold/criteria (SAIC 2006). The Hypoxia Index events can start or end at any time during the day, while the RIDEM metric

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

Site Group	Site	Acronym	Water Depth (m)
PRUB	Bullock's Reach	BR	6
PRUB	Conimicut Point	CP	7
PRUB	North Prudence	NP	11
UWP	Mount View	MV	7
UWP	Quonset Point	QP	7
UEP	Poppasquash Point	PP	8
UEP	T-Wharf	TW	6
GRBY	Greenwich Bay	GB	3
GRBY	Sally Rock	SR	4
MH	Mount Hope Bay	MH	5

determines exceedances based on daily, midnight-to-midnight periods and incorporates a nonlinear biological response function. Detailed comparison of results from the Hypoxia Index and RIDEM metrics, applied to the same measurement records, revealed that they lead to qualitatively similar findings (Codiga et al. 2009). However, it should be emphasized that the Hypoxia Index is not a regulatory metric and, while useful to characterize hypoxic conditions, should not be used to assess compliance of Narragansett Bay waters with dissolved oxygen criteria. Massachusetts does not have an equivalent regulatory metric to RIDEM.

The Estuary Program computed multi-site average annual Hypoxia Index results, using the fixed sites grouped by geographic location throughout Narragansett Bay (Table 1; Figure 1):

- Providence River and Upper Bay group (PRUB)
- Upper West Passage group (UWP)
- Upper East Passage group (UEP)
- Greenwich Bay group (GRBY)
- Mount Hope group (MH; one site).

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 threshold) that occur there during the mid-May to mid-October period (Figure 2). Periods of missing observations (gaps), 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 in a given year at a given site (Table 2). Due to these gaps, the moving window trigger algorithm gives a lower bound for the seasonal Hypoxia Index. The gap contribution, and thus an upper bound for the Hypoxia Index, is estimated (Codiga 2016) using the time period(s) of the gap(s), together with event statistics (specifically, the probability and severity of events, for the time of year of the gap and the particular site) from all other years at the site. The seasonal Hypoxia Index is the mean of the upper and lower bounds and its uncertainty due to gaps is half the difference between the upper and lower bound. The multi-site Hypoxia Index is computed for groups of sites as the mean of the Hypoxia Index results of individual sites in the group; they are presented with uncertainties that are the mean, of the sites in the group, of the gap-based uncertainties for individual sites.

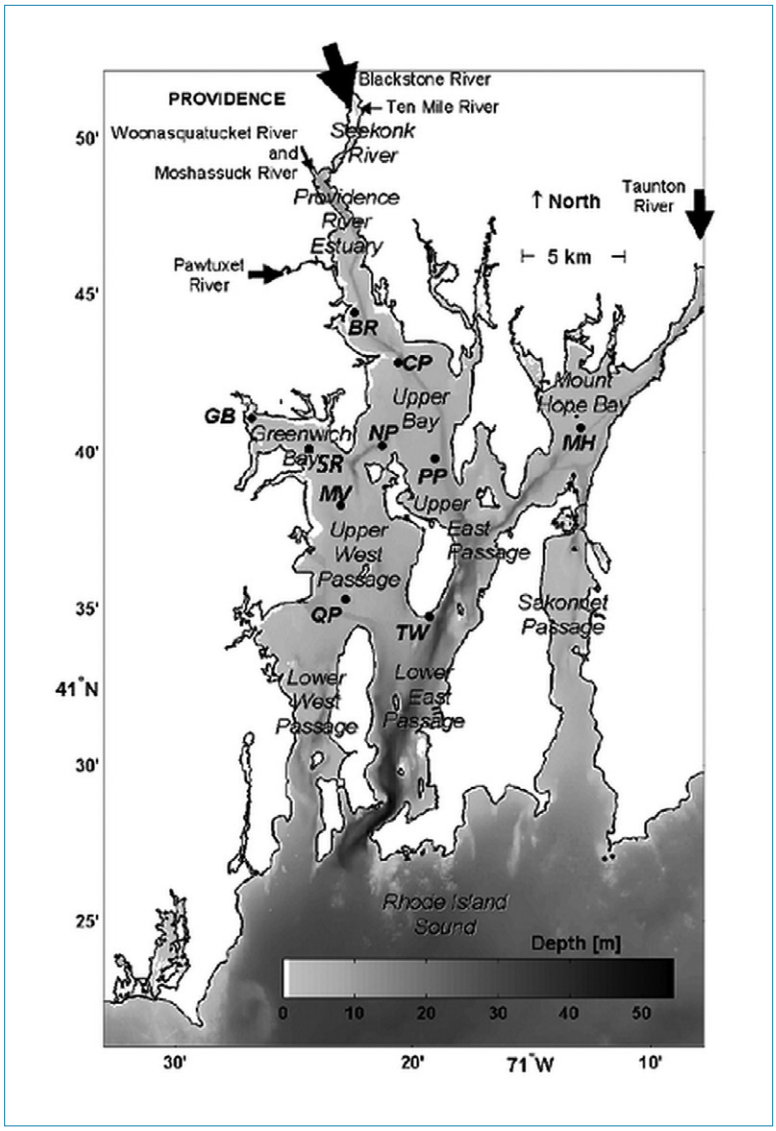


Figure 1. Site locations for the Hypoxia Index. Arrows indicate river discharge to the Bay, with size of the arrow representing relative discharge volume (from Codiga 2016).

SPATIAL SURVEYS

The Spatial Surveys used in this analysis were initiated in 2005 using Sea-Bird 19 Plus SEACAT profilers. Three boat groups sampled 77 sites covering 150 square kilometers (58 square miles) in the Providence River Estuary, Greenwich Bay, and the East and West Passages of Narragansett Bay (Figure 3). The surveys focused on the warm summer months in the morning hours irrespective of tidal phase. Tidal excursions in Narragansett Bay are small compared to the scale of the surveys, so no attempts were made to correct for tidal phase. The data were calibrated and organized to produce an internally consistent and documented, interpolated (0.5 meter) dataset of temperature,

Table 2. Percent of time during mid-May to mid-October analysis period with valid near-bottom dissolved oxygen values at each of the ten sites in each of the fifteen 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.

	BR	CP	NP	MV	QP	PP	TW	GB	SR	MH
2001	100		62							
2002	75		81							
2003	79	65	73				80	63		
2004	86		82	65		64	88	99		
2005	89	76	91	66	*	*	90	83		60
2006	79	79	72	94	78	98	89	98		98
2007	66	94	78	93	55	93	92	93		93
2008	96	96	89	93	97	92	86	88	96	83
2009	100	100	80	83	80	87	88	96	81	87
2010	85	77	78	82	88	82	97	96	83	84
2011	85	90	90	91	85	83	72	100	91	73
2012	98	87	96	96	74	96	100	99	94	96
2013	99	91	98	80	90	92	98	92	93	100
2014	94	96	93	92	96	85	100	100	96	96
2015	77	81	86	91	82	91	100	100	79	86

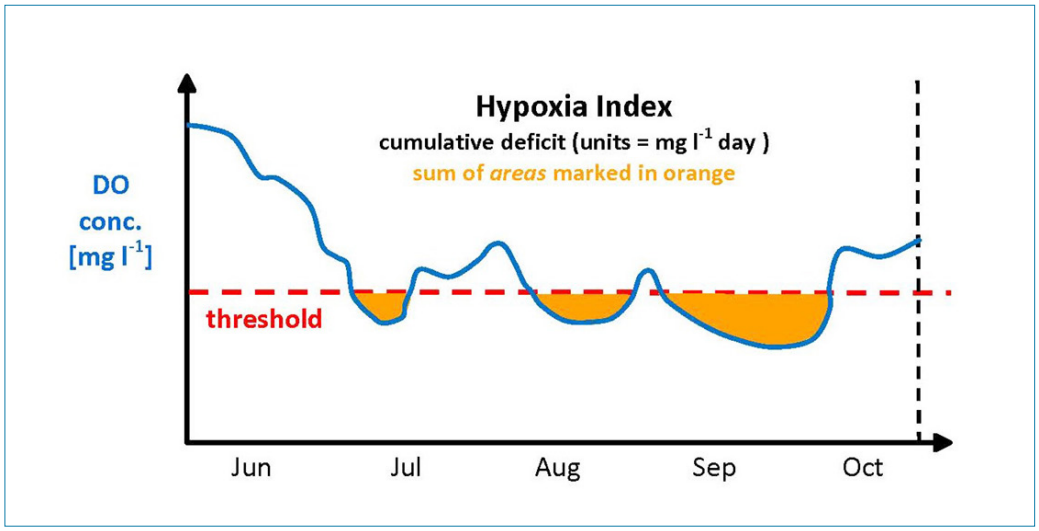
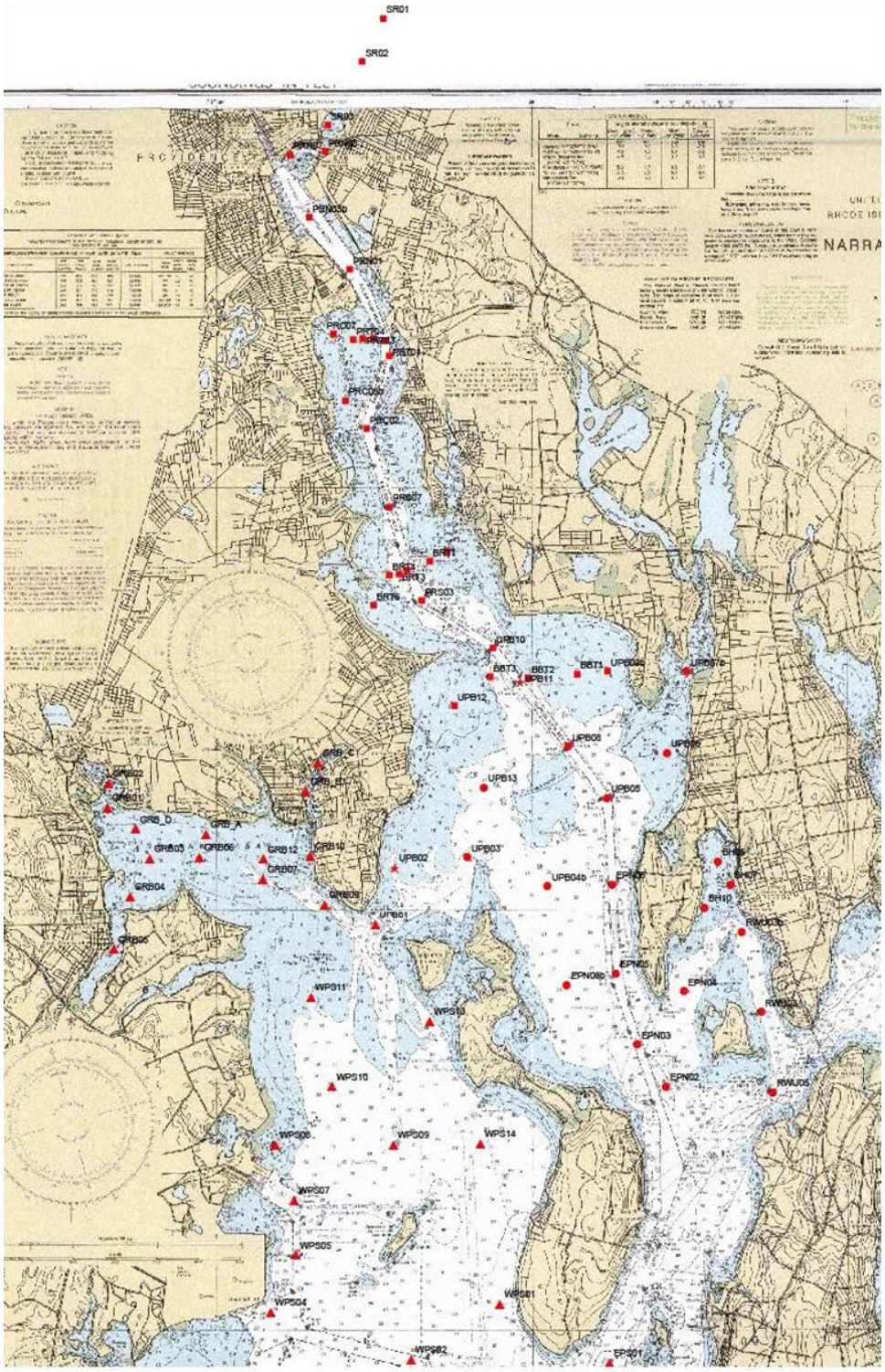


Figure 2. Schematic showing computation of the Hypoxia Index, relative to a given threshold (red dashed horizontal line), from the time series of near-bottom dissolved oxygen measurements (blue line) at a single mooring site. The index is the total area beneath the threshold level. It is the season-cumulative deficit-duration of all individual hypoxic events (this schematic shows three events) during the mid-May to mid-October analysis period.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salinity, dissolved oxygen, density, and chlorophyll (see "Chlorophyll" chapter). The dataset has 58 surveys at 77 sites over eleven years (2005 to 2015) and contains 4,154 individual profiles. Results were interpolated using GIS to determine percentage of the survey area that had bottom water dissolved oxygen concentrations below the thresholds (Prell et al. 2015, 2016).

Determination of Wet and Dry Years

Interannual variations in oxygen concentrations are correlated with freshwater runoff into Narragansett Bay more strongly than other factors (Codiga et al. 2009). Accordingly, the Estuary Program examined differences in dissolved oxygen concentrations and the Hypoxia Index between dry years (low river flow and low precipitation) and wet years (high river flow and high precipitation) to assess the impact of freshwater flux and its associated nutrient flux. The impact of freshwater runoff was assessed using the daily discharge from the Blackstone, Pawtuxet, and Taunton Rivers (as measured by United States Geological Survey gages) for 2005 to 2015 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). The long-term median from 2005 to 2015 was calculated and compared with median flow for individual years. When individual medians were greater than the dataset median (2000 to 2015) they were considered wet years. Dry years were those with individual medians less than the dataset median (Table 3; Prell et al. 2016).

Status and Trends

HYPOXIA INDEX

The Estuary Program reports the status of hypoxia in Narragansett Bay based on conditions in the most recent years (2013 to 2015) using Hypoxia Index results from individual sites (Figure 4) and multi-site average Hypoxia Index results (Figure 5). Trends are analyzed using the entire dataset from 2001 to 2015.

The individual site results from 2013 to 2015 reveal two dominant aspects that are generally applicable to other years. The first aspect is pronounced interannual variability. The Hypoxia Index was higher in 2013 than in 2014 or 2015 at all sites, and substantially so at most sites (Figure 4) indicating lower overall dissolved oxygen concentrations in 2013 than in 2014 or 2015. This interannual variability is notably far larger than uncertainties in the Index values due to sampling gaps. The higher 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. Precipitation is a major factor responsible for this variability, as hypoxia was more severe in 2013, which had wet spring and summer conditions, compared to the drier years of 2014 and 2015 (Table 3).

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 was more pronounced in wet

Table 3. River flux departure during June, July, August, and September. Dry years occur when the annual summer departure is less than the long-term median; wet years occur when the departure is greater than the long-term median. Wet years are shaded, and "wet" is bold text.

YEAR	River Flux Departure m^3/s JJAS	Wet/Dry Designation
2005	-10	DRY
2006	26	**WET**
2007	-13	DRY
2008	-4	DRY
2009	44	**WET**
2010	-17	DRY
2011	25	**WET**
2012	-5	DRY
2013	23	**WET**
2014	-17	DRY
2015	-8	DRY

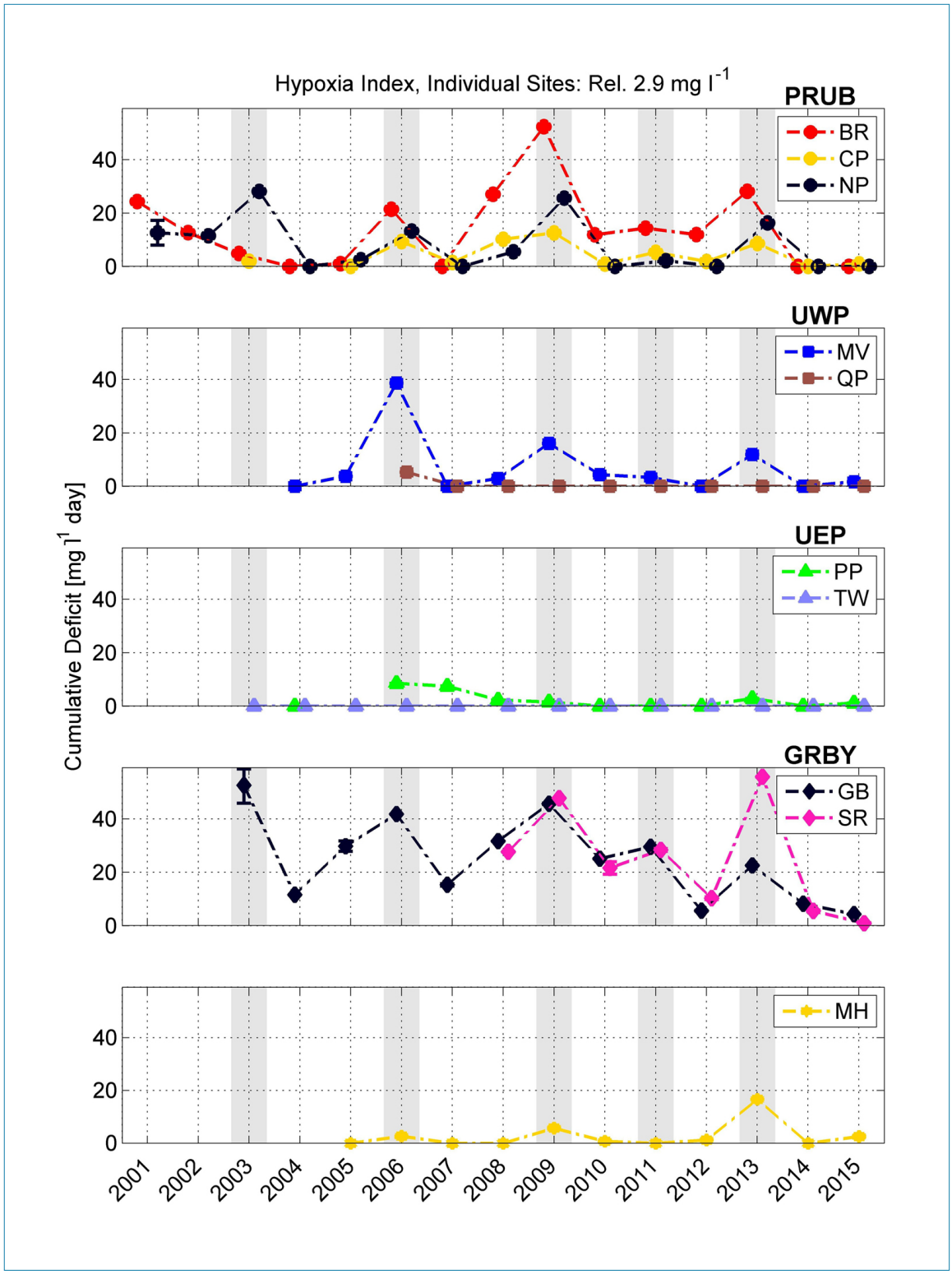

Figure 4. Hypoxia Index for individual sites within each site group, relative to the 2.9 mg/l threshold. Years with higher than typical river runoff during June to September (wet years; Table 3) are marked by gray vertical bars. To improve clarity by reducing overlap of lines and symbols, symbols from each site are systematically offset a small distance horizontally relative to those of other sites in the frame. In most cases the symbols are larger than the error bars, which indicate uncertainties due to gaps in the time series because of sensor malfunction or data not meeting quality standards.

years. The Hypoxia Index decreased from north to south from the Providence River (PRUB) down through the Upper West Passage (UWP) (Figures 4 and 5). Bottom water dissolved oxygen increased with distance from Providence.

Using 2.9 mg/l as a dissolved oxygen threshold, the cumulative deficit results for the Hypoxia Index were typically less than 30 mg/l day with a maximum of about 60 mg/l day (Figure 4). During the drier years of 2014 and 2015, the Index was effectively zero everywhere except in Greenwich Bay (GRBY). During the wet year of 2013, the Index included elevated results for GRBY, PRUB, Mount Hope Bay (MH), and the Mount View site (MV) in UWP, while the Index at other sites in the Bay was zero or very near to zero (oxygen concentrations remained above the 2.9 mg/l threshold).

To detect longer-term trends, the Estuary Program analyzed the results from all years (2001 to 2015), using the multi-site mean Hypoxia Index values for the 2.9 mg/l threshold. However, trends extending over multiple years were difficult to discern due to the relatively large interannual variability. This fundamental characteristic of the dataset sharply limited the confidence that can be placed in conclusions regarding trends (Figure 5).

This trend assessment confirmed 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. However, there was no strong evidence for a long-term temporal trend over the fifteen-year period, due to the interannual variability. This was true whether examining all years together, wet years alone, or dry years alone.

SPATIAL SURVEYS

The Spatial Surveys 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, 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

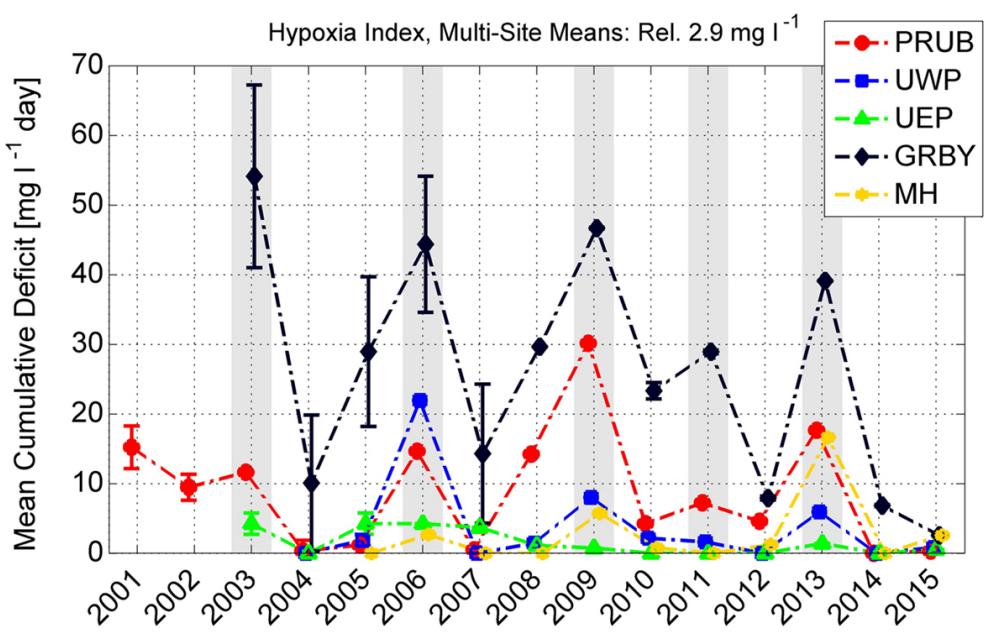

Figure 5. Hypoxia Index averaged over all sites within each site group, relative to threshold 24-hour 2.9 mg/l day. Error bars indicate the mean uncertainty, among the stations in the group, due to gaps in the time series.

Bay, expanding to the Upper and Middle West Passage during more extreme wet-weather events. These maps are useful for showing spatial trends in dissolved oxygen concentrations, but it should be noted that these maps represent a single-day survey event and do not depict the duration of the hypoxic event; duration is an important component for defining a hypoxic event.

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 four to six meters (thirteen 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 intervals of infrequent hypoxia, 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 Estuary north of Conimicut Point, where a number of shallow sites did not change from bottom to minimum maps (Figures 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).

Table 4. 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.

Year	Seekonk and Providence Rivers		Upper Bay		Greenwich Bay		Lower Bay	
	Average	Min.	Average	Min.	Average	Min.	Average	Min.
2015	3.6	2.1	4.5	3.0	4.0	2.5	5.0	3.5
Long-term Average (2005–2015)	3.4	0.9	4.1	1.3	3.9	0.5	4.8	2.5

Table 5. Summary statistics for all summer (June, July, August, September: JJAS) surveys during each survey year. Wet years, based on river flux (m^3/s; see Methods), are shaded. DO is dissolved oxygen.

Year	River Flux Departure m^3/s JJAS	Average Surface Salinity $^0/_{00}$	Average Surface Temp. ^0C	% Area with Bottom DO < 2.9 mg/l JJAS	Average % DO Surface Saturation
2005	-10	28.0	23.2	5.3	101
2006	26	23.7	22.0	27.1	96
2007	-13	27.7	21.1	2.9	91
2008	-4	26.5	23.1	17.6	91
2009	44	24.3	21.6	29.8	101
2010	-17	27.6	24.2	17.4	105
2011	25	25.3	23.6	13.7	107
2012	-5	27.6	23.7	12.2	97
2013	23	23.9	23.0	18.0	107
2014	-17	27.9	23.6	3.7	101
2015	-8	28.4	23.4	5.6	88

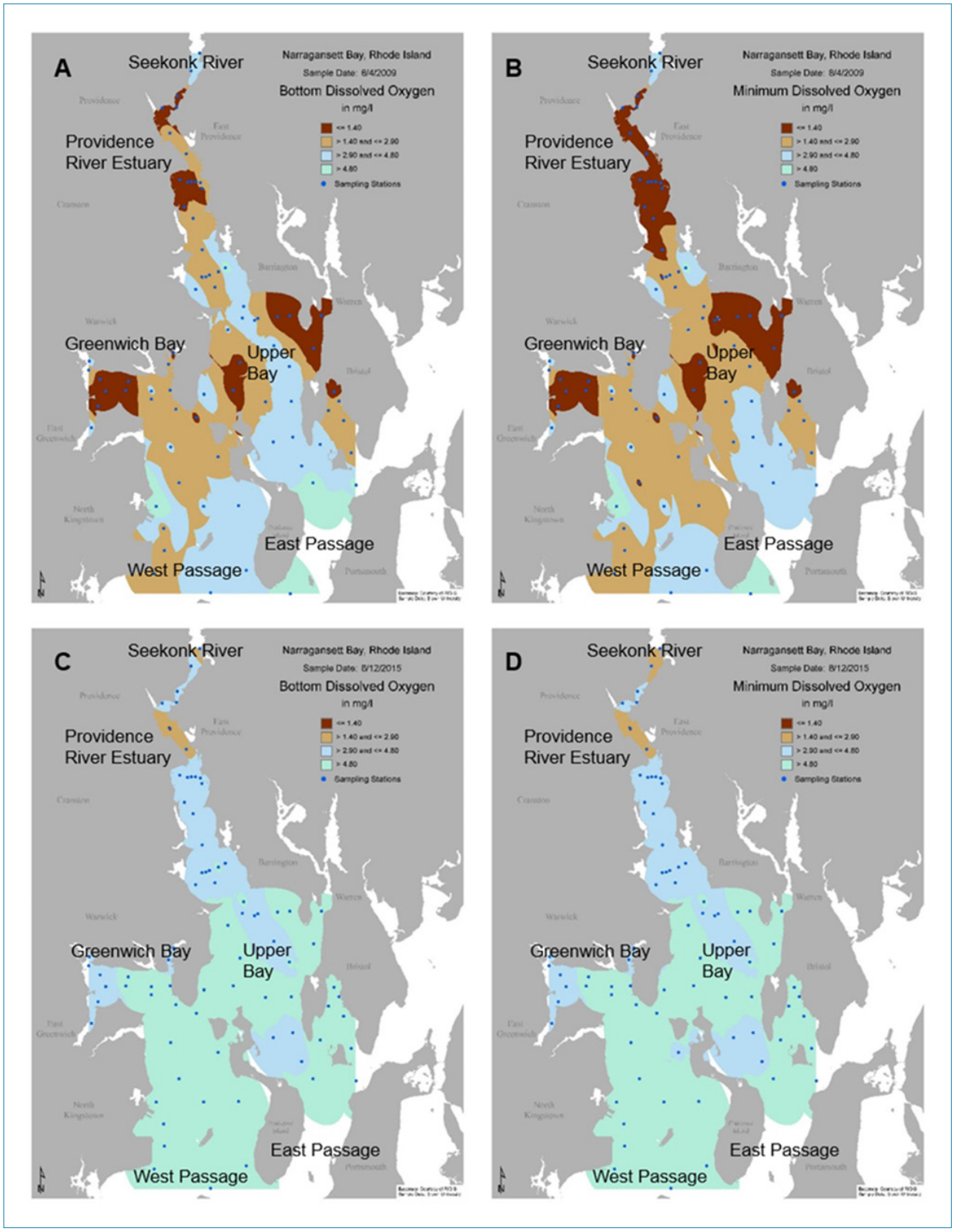

Figure 6. The spatial extent of bottom water dissolved oxygen (left column: 6a, 6c) and minimum dissolved oxygen (right column: 6b, 6d), comparing a highly hypoxic survey (top row: 6a, 6b; August 4, 2009) and a minimally hypoxic survey (bottom row: 6c, 6d; August 12, 2015). Dissolved oxygen categories correspond to the three thresholds (4.8, 2.9, and 1.4 mg/l) used by RIDEM to identify chronic and acute hypoxia.

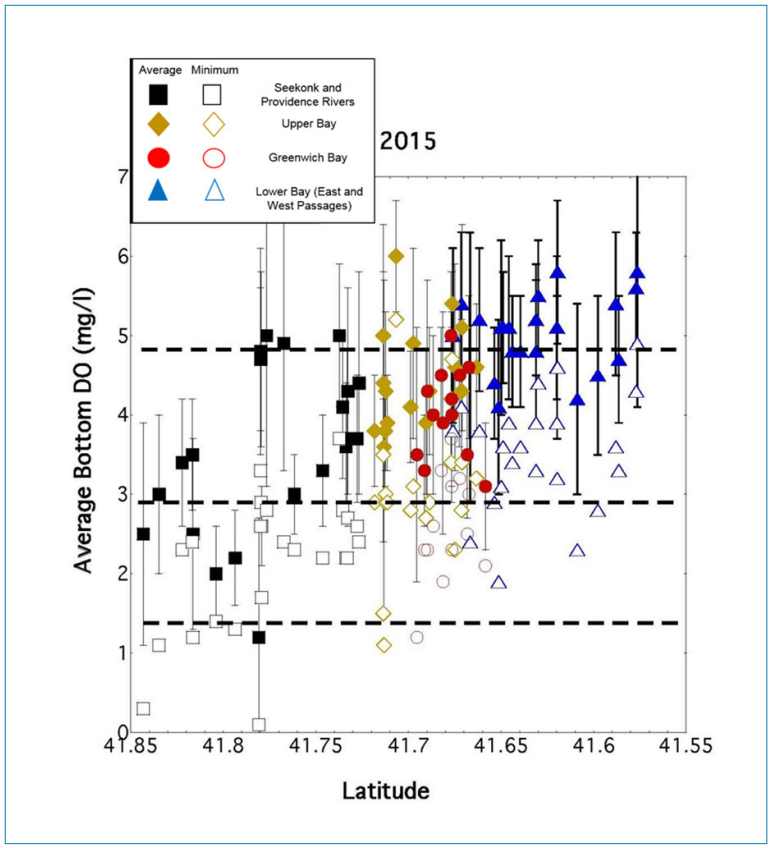

Figure 7. The distribution of average (solid symbols) and minimum (open symbols) dissolved oxygen concentrations in bottom water for sites in each region of Narragansett Bay in 2015 surveys. Sites are shown in the graph from north (left) to south (right). The irregular north-to-south gradient in dissolved 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 for waters below a pycnocline. However, EPA and RIDEM have established different allowable exposure periods associated with each DO threshold, while the spatial surveys results are instantaneous measurements. Bars indicate standard deviation for mean dissolved oxygen.

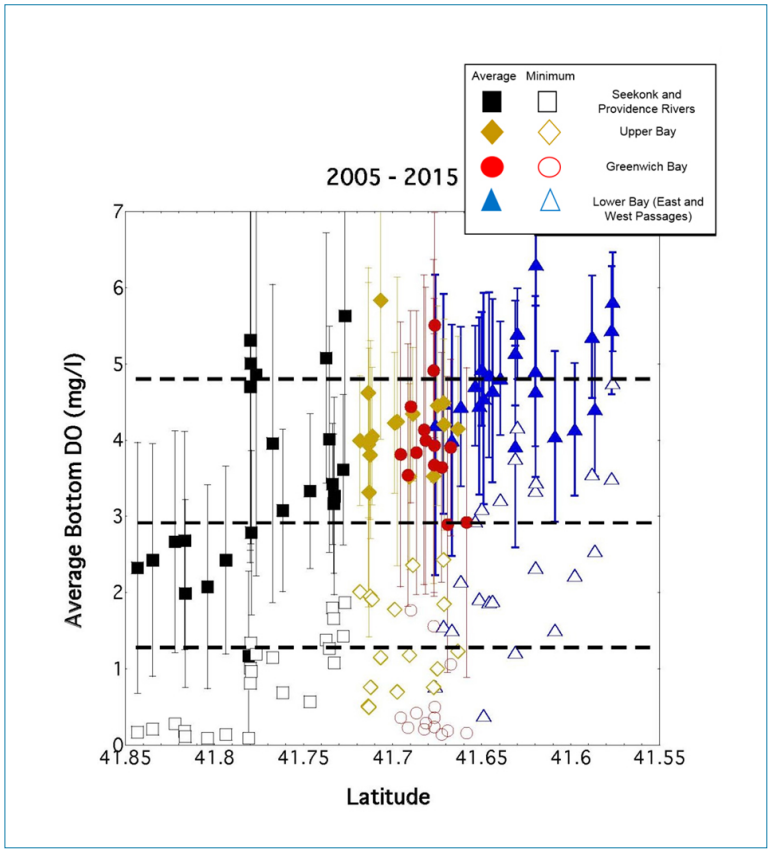

Figure 8. The distribution of average (solid symbols) and minimum (open symbols) dissolved oxygen concentrations in bottom water for sites in each region of Narragansett Bay averaged over all surveys (2005 to 2015). Shown as in Figure 7.

The average bottom dissolved oxygen for different parts of the Bay in 2015 was slightly higher (about 0.2 mg/l) than the 2005 to 2015 average (Table 4; Figures 7 and 8), 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 (Table 5; Figure 9).

The minimum bottom water dissolved oxygen observed at each site and the mean bottom water dissolved oxygen values for each site and its standard deviation over all surveys revealed bottom conditions throughout the Bay (Figure 8). Of the 77 sites, eleven sites (14 percent) had mean bottom water dissolved oxygen of less than 2.9 mg/l, and 67 sites (87 percent) had a minimum observed dissolved oxygen of less than 2.9 mg/l.

Although the average dissolved oxygen values (Figures 7 and 8) show large-scale spatial gradients in the Bay, they do not capture the temporal variability. To document these patterns, the Estuary Program mapped the dissolved oxygen in bottom waters and calculated the area of each dissolved oxygen class (Figure 9). The percent area of hypoxic bottom water (less than 2.9 mg/l) during the summer (JAS) exhibited significant intra- and interannual

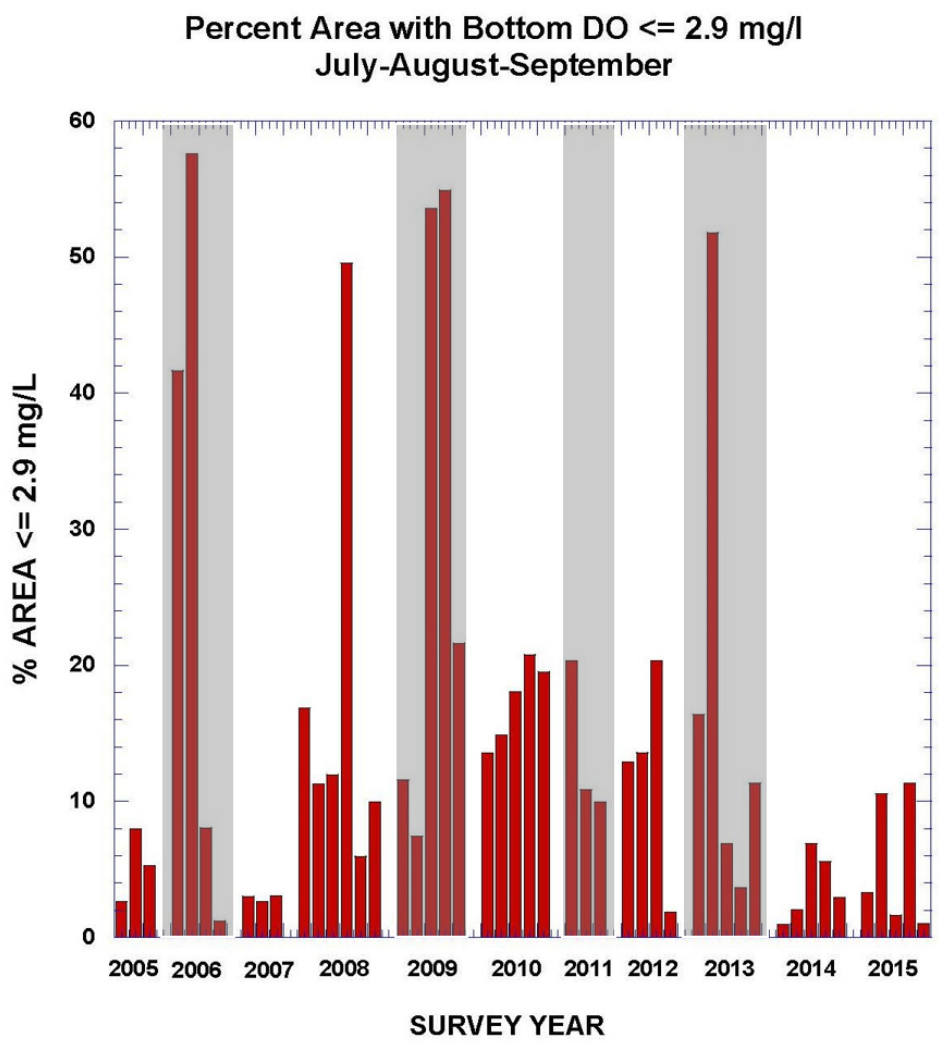

Figure 9. Percent of the survey area (150 square kilometers; 58 square miles) considered hypoxic (dissolved oxygen less than 2.9 mg/l) from 2005 to 2015. Each bar represents a survey. Only July, August, and September (JAS) surveys are shown.

variability. Typically, less impairment occurred in June (not shown), which tended to have lower water temperatures. The area of hypoxic bottom waters ranged from only a few percent to over 40 percent in sporadic extremes in 2006, 2008, 2009, and 2013, all wet years except for 2008.

Discussion

COMPARISON OF METHODS

The Hypoxia Index and the Spatial Surveys are different but complementary methods, using different data and different temporal scales. The Hypoxia Index uses an array of temporal data collected every fifteen minutes from May to October, but it does not have high spatial resolution, given that there are just ten fixed sites used by the Index. Conversely, the Spatial Surveys have more spatial resolution (both horizontally and vertically) with 77 sites, but it focuses on only five or six survey days each summer with a single dissolved oxygen profile measure at each station, providing low temporal resolution. The Estuary Program conducted an initial analysis comparing these methods in the Providence River Estuary. The Hypoxia Index results for two sites (Bullocks Reach, BR; Conimicut Point, CP) had a strong correlation to the spatial extent of hypoxia in the entire survey area covered by the Spatial Surveys (Figure 10). These results suggest that bottom water DO concentrations at the BR station is a good predictor of the extent of hypoxia in the entire Upper Bay. There is a need to expand this analysis and complete correlations for other sites in the Bay to assess whether similar correlations exist for stations that experience less frequent hypoxia, and to assess the strength of correlations in a manner that captures interannual variability.

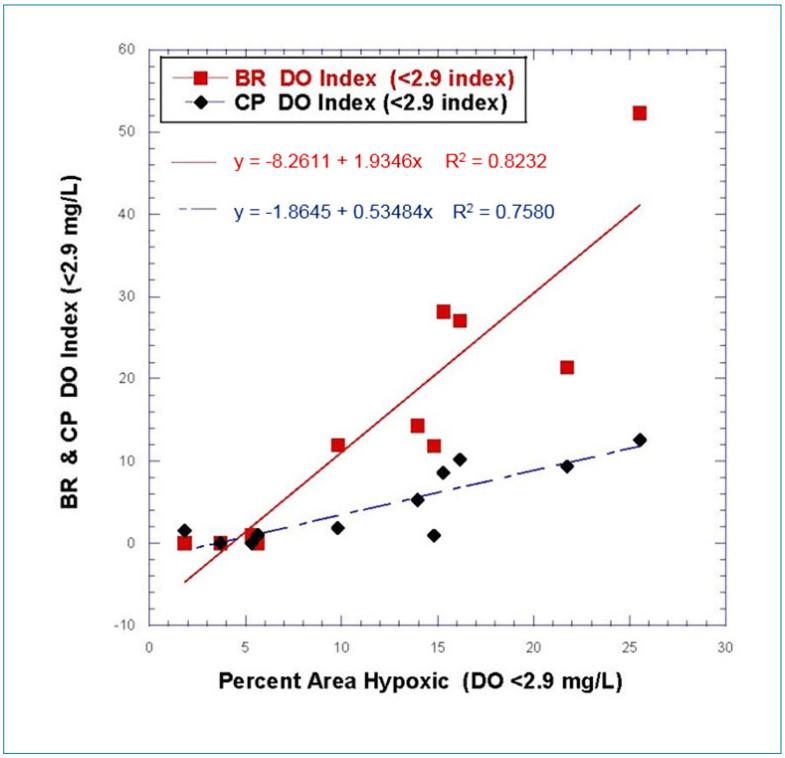

Figure 10. Correlation of Hypoxia Index (DO Index) for Bullock's Reach (BR; red squares and lines) and Conimicut Point (CP; black diamonds and blue line) with spatial survey (percent area hypoxic) at the 2.9 mg/l threshold for 2005 to 2015.

The Hypoxia Index and the Spatial Surveys reveal areas where low levels of dissolved oxygen in bottom water tends to be a problem, including the Providence-Seekonk River Estuary, Upper Bay, and Greenwich Bay, with sporadic events in the 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). These data also show that the Providence River Estuary periodically suffers from hypoxic episodes where dissolved oxygen concentrations fell below the 2.9 mg/l threshold, 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). The most current year (2015) shows increased bottom water dissolved oxygen over the long-term averages for the Spatial Surveys (Table 4), and the Hypoxia Index was similar to other dry years (e.g. 2004, 2007, and 2012) (Figure 5).

The analyses presented in this chapter confirmed the north-to-south, down-Bay gradient in pollution established in prior research (Pilson and Hunt 1989, Doering et al. 1990, Bergondo et al. 2005, Deacutis et al. 2006, Melrose et al. 2007). With the exception of certain embayments (e.g., Greenwich Bay and Mount Hope Bay), there is a down-Bay increase in dissolved oxygen concentration or decrease in the Hypoxic Index starting in the Providence River Estuary and the Seekonk River (Figures 4, 5, and 6). Similarly, the Spatial Surveys showed a down-Bay gradient in which the long-term mean bottom water dissolved oxygen concentration ranged from 1.2 mg/l in the Providence River Estuary to 6.3 mg/l in the shallow West Passage (Figure 8). The decrease of bottom water hypoxia with distance down the Bay follows the gradient of anthropogenic inputs to Narragansett Bay (Oviatt et al. 2002, Murray et al. 2007, Oviatt 2008).

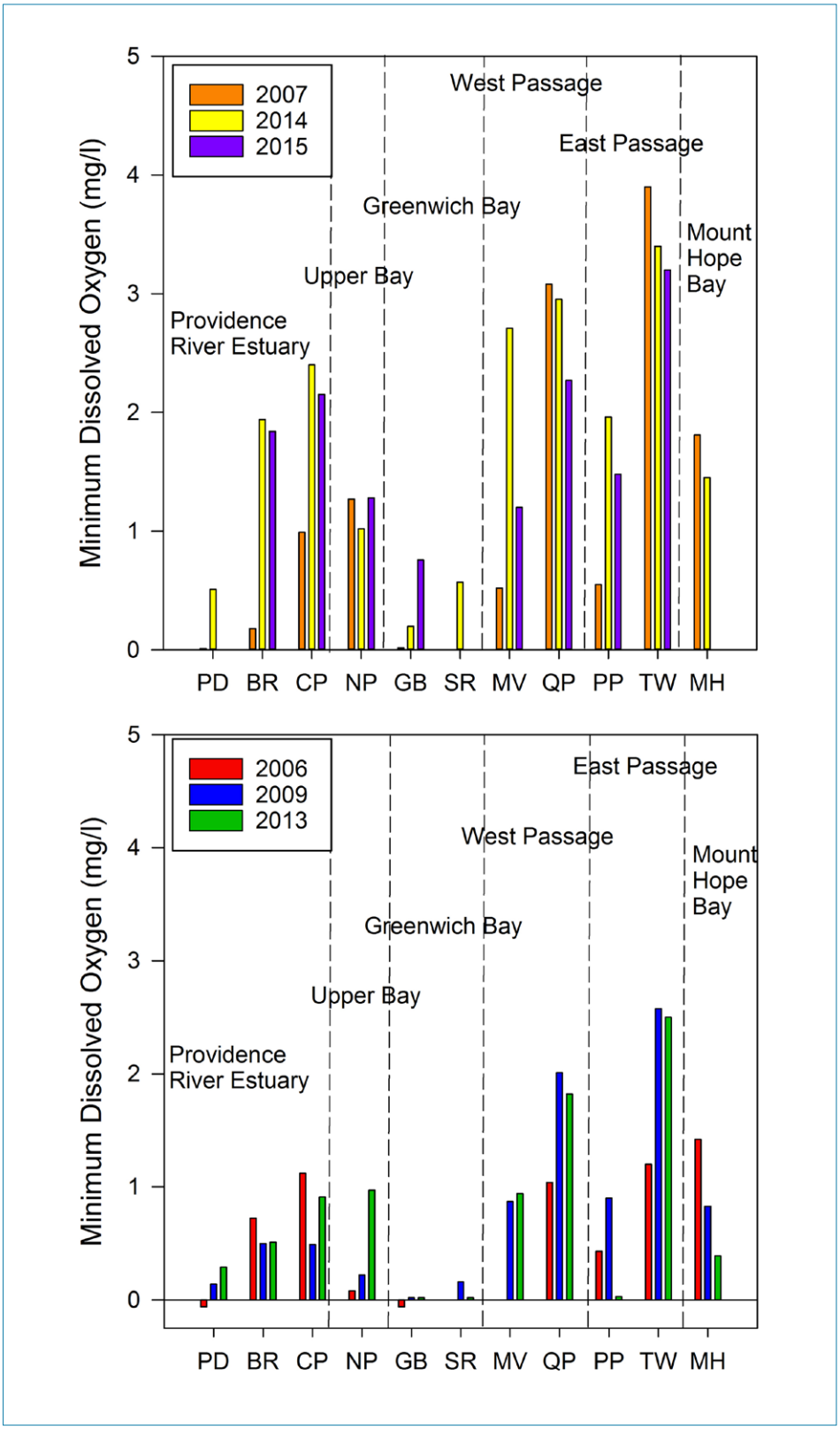

Figure 11. Minimum bottom water dissolved oxygen values for all Narragansett Bay Fixed Site Monitoring Network sites for the dry years of 2007, 2014, and 2015 (top) and for the wet years of 2006, 2009, and 2013 (bottom). See Table 1 for acronyms. PD is Phillipsdale Dock in the Seekonk River. Wet and dry year determination included in Methods section (Table 3). The sites are presented by Narragansett Bay sections.

HYPOXIA IN DRY YEARS VS. WET YEARS

Both the Hypoxia Index and the Spatial Surveys showed high interannual variability (Figures 4 and 9), which appears to be linked with the amount of precipitation in any given summer (June through September; Tables 3 and 5). Freshwater flux was quantitatively defined (see Methods) and wet (2006, 2009, 2011, 2013) and dry (2005, 2007, 2008, 2010, 2012, 2014, 2015) years established (Tables 3 and 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). Hypoxia during dry years may also occur in smaller embayments not included in this analysis, such as the Seekonk River, north of the Providence River Estuary (PD in Figure 11). These areas tend to be tidally restricted and shallower, which could encourage more hypoxia to develop.

The area of hypoxic bottom waters in the Spatial Surveys also appeared to track with the freshwater flux with wet years having a higher area of hypoxic waters (Table 5; Figure 9). The greater area of hypoxic waters in 2010 was likely related to higher nutrient loading from the failed Pawtuxet River wastewater treatment facilities (due to catastrophic April 2010 flooding event), while the cause of the higher area of hypoxic waters in 2008 was unclear (Table 5). 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 5).

An additional comparison analyzed the minimum bottom water dissolved oxygen in wet years (2006, 2009, and 2013) and dry years (2007, 2014, and 2015) (Figure 11). The minimum dissolved oxygen value for each NBFSMN site was the lowest single fifteen-minute value for the entire season. Overall, minimums generally follow a north-south gradient, with higher minimums in the southern sections of the Bay (TW). Minimum DO concentrations were generally higher in drier years. Finally, the minimum DO concentrations for each station do fall below the 2.9 mg/l threshold, indicating some degree of low oxygen during the summer season.

The mechanism by which wetter conditions make hypoxia more severe is not fully understood. Higher-than-average runoff does contribute to stronger stratification, which can enhance hypoxia by impeding re-aeration through reduced vertical mixing (Codiga 2012). Wet years are also thought to increase nutrient loads (see "Precipitation" chapter) and chlorophyll concentrations (see "Chlorophyll" chapter) that drive hypoxia. The relative importance of these processes, and possible influence of differing rates or patterns of circulation during wet and dry years, is a topic that requires additional research.

HYPOXIA AND WASTEWATER TREATMENT FACILITY NUTRIENT REDUCTIONS

An important context for examining trends in hypoxia is that wastewater treatment facilities have been upgrading over the past fifteen years to reduce nutrient pollutant loadings, with a 50 percent reduction in nitrogen loadings (relative to 1995/96 loadings) achieved in the summer of 2012 (see "Nutrient Loading" chapter). Indirectly, these reductions are intended to decrease the amount of hypoxia experienced in the Providence River Estuary and Upper Bay. However, given the multiple factors influencing formation of hypoxia and high interannual variability in the monitoring data, it is too soon to determine how the Bay is responding to the reductions. The Estuary Program is encouraged that the recent results of the Hypoxia Index and Spatial Surveys reflect weakening hypoxia, as results for 2014 and 2015 were the lowest on record. However, those were dry years, and earlier dry years (2004 and 2007; Figures 4, 5 and 9) were comparable to 2014 and 2015. Significant time lags may occur between nitrogen reduction and the biological response of the ecosystem (e.g., organic matter production, decomposition, and oxygen depletion). Additional monitoring is necessary before the response of Bay hypoxia to nutrient reductions can be determined. In particular, much will be learned from future years that are wetter than average. Wet years will best reveal any changes brought by wastewater treatment facility upgrades, which included extensive combined sewer overflow (CSO) abatement efforts (NBC 2017; see "Precipitation" chapter).

HYPOXIA AND CLIMATE CHANGE

Dissolved oxygen levels in Narragansett Bay will be influenced by a changing climate. Warming temperatures are an expected consequence of climate change (see "Temperature" chapter) and are expected to result in higher rates of primary production and respiration. Warmer temperatures also contribute to the stratification of the water column, which prevents mixing of bottom water with the surface (USEPA 2016). Biochemical reactions and respiration in the water column and sediments would continue to decrease the dissolved oxygen concentrations in bottom water, and less vertical mixing

could exacerbate hypoxic conditions. This would increase the consumption of dissolved oxygen and reduce dissolved oxygen concentrations towards hypoxic conditions. Additionally, water temperature dictates how much oxygen is available, with warmer water holding less dissolved oxygen than cooler water. As temperatures rise, DO concentrations will be affected regardless of the impacts of temperature on primary production and stratification although at the projected summer temperatures, the change in DO concentration will be very small compared to biological processes (USEPA 2016).

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).

River runoff in late spring/early summer sets up the severity of hypoxia for the remainder of the summer in Narragansett Bay (Codiga 2012). If river runoff pulses occur in late spring/early summer, hypoxic events could increase throughout the summer, even if no further pulses occur. This type of situation occurred in 2013, when June was very wet and the remainder of the summer was very dry, but summer bottom water dissolved oxygen concentrations were very low. This same phenomena may have also happened during years with higher than average river flow and higher than average stratification, such as 2003 (year of the Greenwich Bay fish kill), 2006, and 2009 (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. The higher runoff may also reduce the flushing time, decreasing the time nutrients stay in the system. Further investigation into these processes is needed.

SUMMARY

The Hypoxia Index and Spatial Surveys show that hypoxia was low for 2014 to 2015. A down-Bay increase was evident in bottom water dissolved oxygen concentrations, with the lowest concentrations occurring in the Providence-Seekonk River Estuaries and the highest at the southern end of Narragansett Bay. The down-Bay gradient is a persistent annual feature, regardless of the hypoxia levels in any given year. Both methods show a strong pattern of interannual variability in dissolved oxygen dynamics that likely stems from the amount of freshwater delivery to the Bay. Therefore, in dry years like 2014 and 2015, bottom water dissolved oxygen concentrations would be higher than in wet years like 2013, resulting in more severe hypoxia in wet years. The Hypoxia Index and Spatial Surveys complement each other, even though the approaches have different data, resolution, and timescales. The wet/dry analysis conducted with both approaches is probably the most important step to learn how dissolved oxygen concentrations are responding to changes in weather/climate. The findings offer hints at how dissolved oxygen is responding to management actions, such as nutrient reductions.

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. Additionally, gaps in the NBFSMN for dissolved oxygen exist for portions of Mount Hope Bay, the Sakonnet River, and the Lower East Passage where there are no monitoring stations.
- High interannual variability limits the discernment of temporal trends in available datasets. Additional data synthesis studies or longer-term monitoring are needed to further explore the different temporal and spatial scales of dissolved oxygen variability and their relationships to other forcing factors (e.g., seasonal rainfall or temperature) and the physical structure of the water column.
- The Phillipsdale site, which has unique circulation patterns and is proximal to a major freshwater source (the Blackstone River), was not analyzed for the Hypoxia Index or the Chlorophyll Bloom Index (see "Chlorophyll" chapter). In light of nutrient reductions and changes to the dissolved oxygen and chlorophyll concentrations in other sections of the Bay, the Phillipsdale data need to be analyzed to see how this upper section of the Seekonk River is changing.
- The combination of dissolved oxygen data and hydrodynamic modeling efforts can 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. Models should be used to better understand the connection between benthic conditions and overlying dissolved oxygen conditions.

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