1. **Introductory comments**

This final report is intended to serve as a source of content to be used in the Status and Trends report. It has been written in order to provide raw material that can be drawn from, and inserted in to, the various sections of the “chapter template” for the Status and Trends report, as provided to me by Courtney Schmidt of NBEP.

I have provided here material to address two main aspects of the template, based on my understanding of Courtney’s instructions. The first aspect is methods. This is material that could go in to Section 6 (“Expanded methods section”) of the template, and could be summarized, and/or excerpted from, for Section 3A (“Development of the indicator / Developing status and trends”) of the template. If this material is too long to be included in Section 6, then it could be adapted to a separate report and omitted from the Status and Trends report, but cited by it.

The second portion covers interpretations. It is material suitable for Section 3B (“Development of the indicator / Status, trends, and discussion”) and possibly Section 3C (“Next steps to consider / Data gaps, Future needs”).

In the template some of the sections are broken out by region, for three regions (Narragansett Bay, Little Narragansett Bay, and Southwest Coastal Ponds). This analysis treats only Narragansett Bay, so no such divisions of the material are made.

I anticipate the need for the material provided here to be redrafted and/or restructured, in order to most effectively help generate the Status and Trends report. For example, an extensive set of detailed figures could have been included in the methods section, but has deliberately been omitted, under the expectation that they are not as germane as the balance of the material, and could later be added. Also, because the methods for the oxygen and chlorophyll analyses are so similar I have combined them; they may need to be treated separately in the Status and Trends report, which will require dividing the material for those two sections accordingly. Finally, I recognize that there are non-time series measurements of oxygen and chlorophyll being analyzed and reported on by others, and the material here may need to be integrated with those. Although this is my final report I am ready to carry out such efforts for redrafting, restructuring, and integrating as requested by NBEP, and consider such efforts to be part of my contract responsibilities.

2. **“Expanded methods section”**

   a. **Overview**
Time series observations of near-bottom dissolved oxygen concentration and near-surface chlorophyll concentration from May to October at ten sites are used to characterize conditions for hypoxia (low oxygen) and phytoplankton blooms (high chlorophyll). The metrics for hypoxia and blooms are event-based, where events are typically up to several days long and defined as deviations of concentrations relative to constant thresholds. Indices useful for evaluating status and trends are then computed for individual sites as season-cumulative event-based results and by combining those results from multiple sites. Careful attention is given to accounting of uncertainties due to sampling gaps in each given year, and for multi-site indices during years when not all sites were sampled, in order to yield the longest record for analysis and make possible quantitative comparisons of site to site and year to year variations.

b. Records treated

The analysis is based on measurements from in situ sensors on an array of moorings, the Narragansett Bay Fixed Site Monitoring Network (NBFSMN). Information about the network, including partners collaboratively maintaining it as coordinated by the Rhode Island Department of Environmental Management (RIDEM), and site locations and seafloor depths is available online (e.g., NBFSMN, 2007). The quality control and quality assurance protocols used are described in Quality Assurance Project Plans (e.g., RIDEM, 2007).

Sensors located 0.5 or 1 m above the seafloor collected the dissolved oxygen records, in units of mg l⁻¹ oxygen concentration. Fluorometers located 1 m deep collected the chlorophyll records, in units of µg l⁻¹ concentration of chlorophyll a.

Ten mooring sites are treated (Figure 1). Most are in relatively deeper locations nearly centrally located between coastlines on either side of passages. Three are in the southern Providence River estuary and Upper Bay: Bullocks Reach (BR), Conimicut Point (CP), and North Prudence Island (NP). Three are in the upper West Passage: Sally Rock (SR), Mount View (MW), and Quonset Point (QP). Two are in the East Passage: Poppasquash Point (PP) and the Prudence Island T-Wharf (TW). One is in Mount Hope Bay (MH), a substantially separate waterbody connected to the East Passage, which in contrast to all other stations is strongly influenced by the Taunton River. Finally, the Greenwich Bay marina (GB) site is shallower, more protected, and less influenced by river runoff as compared to the other sites.

Data from 2001 through 2015 are used. From 2001 to 2005 a relatively small number of sites was sampled, mostly in the Providence River estuary and Upper Bay. From 2006 to 2015 most or all of the 10 sites were sampled (Table 1).

The temporal resolution is \( \Delta t = 15 \) minutes and the period from May 15 through Oct 14 is treated, for a total of 153 days possible sampling. In this description, \( C_{ij}(t) \) denotes the time series observations for oxygen or chlorophyll concentration at site \( i \) (\( i = 1 \) to 10) during year \( j \) (\( j = 1 \) to 15), where \( t \) is the time of year, relative to May 15.

At a given site in a given year, good data were typically collected between 60 and 90% of that time, reduced from 100% by operational constraints such as deployment scheduling, sensor malfunction, and/or biofouling. The sampling gaps are characterized by the function \( u_{ij}(t) \), which
is the unitless quantity 1 during a gap and 0 otherwise, used below in the uncertainty analysis. Records with less than 55% good data were omitted (oxygen at QP and PP in 2005; chlorophyll at QP in 2005). In total, 120 season-long oxygen records and 116 season-long chlorophyll records were treated.

c. Event identification

To identify and quantify hypoxic events and chlorophyll blooms the moving window trigger algorithm is used, with 9 hour trigger duration and 24-hour minimum event duration (Codiga, 2008, Codiga et al. 2009). For hypoxia, the metric for individual events is the deficit-duration (units: mg l\(^{-1}\) day). This is the area swept out, during the event, by the concentration time series curve relative to the horizontal line that corresponds to the fixed threshold value. Higher deficit-duration results from oxygen reaching lower values during an event, and/or from an event having a longer duration. Thus, the deficit-duration is a reflection of both the intensity of the event (concentration difference from the threshold, during the event) and its duration. For this reason it is considered a more useful metric than the latter alone.

To assess hypoxic events at a range of different concentrations, three fixed oxygen thresholds are used: 1.4 mg l\(^{-1}\), 2.9 mg l\(^{-1}\), and 4.8 mg l\(^{-1}\). These thresholds and are not site specific, as they are based on responses of aquatic organisms (e.g. Codiga et al., 2009).

For chlorophyll blooms, the metric for individual events is the surplus-duration (units: \(\mu g l^{-1}\) day). This is parallel to the deficit-duration for oxygen, except that events are defined when concentration exceeds the threshold rather than falling below it. The thresholds used for chlorophyll are site-specific and computed as the 80\(^{th}\) percentile of all chlorophyll values recorded, in all sampled years, at a given site (Table 2). Geographic variations in the thresholds reflect the long-term mean chlorophyll concentrations; the highest values occur in Greenwich Bay, the Providence River estuary, and the upper West Passage.

At a given site, in a given year, for a given threshold, \(N_{ij}\) is the number of events that are identified. The deficit-duration, or surplus-duration, of the \(k\)\(^{th}\) event (\(k = 1\) to \(N_{ij}\)) is denoted \(A_{ijk}\), where \(A\) indicates area swept out by the observed concentration curve below the threshold.

d. Season-cumulative results at individual sites, with uncertainties due to sampling gaps

For a given threshold the metric for a season at an individual site is the season-cumulative deficit/surplus-duration, or cumulative sum of the deficit-duration or surplus-duration from all events that year. This quantity (units: mg l\(^{-1}\) day for hypoxia; \(\mu g l^{-1}\) day for chlorophyll blooms) is denoted \(A_{Sij}\), for site \(i\) in year \(j\), where the superscript \(S\) indicates season-cumulative.

Because typically 10-40% of the May 15 and Oct 14 period is not sampled at a given site in a given year, as noted above, there is uncertainty in estimating the season-cumulative deficit/surplus-duration. This uncertainty must be addressed quantitatively, to minimize bias in the estimates, and also make them comparable from year to year and from site to site when considering multi-site metrics as discussed in the next subsection below.
To compute $A_i^S$, the estimated lower $A_i^SL$ and upper $A_i^SU$ bounds are averaged, and the uncertainty in $A_i^S$ is taken to be $U_i^S = (A_i^SU - A_i^SL)/2$. The lower-bound estimate is computed as $\Sigma_k(A_{ijk})$, using all events determined using the sampled portions of the May 15 to Oct 14 period; the moving window trigger algorithm handles sampling gaps in the record in a systematic way, properly identifying and quantifying events in the presence of the gaps, and ignoring periods of missing values.

The upper-bound estimate $A_i^SU$ is higher than $A_i^SL$ by an amount computed using a method that takes into account (a) the lengths and times of year of the gaps at that station in that year, (b) the typical probability of an event at that station during those times of year, and (c) the typical intensity of an event at that station. This approach is taken because more crude ways to estimate the upper bound, for example by simply assuming all unsampled periods occur during events, can generally lead to unrealistically high upper bounds and uncertainties.

The statistics of events at a given station $i$ are presumed stationary and characterized by the probability $e_i(t)$, a unitless quantity between 0 and 1, that an event occurs at time of year $t$. For $e_i(t)=0$ an event never falls at that time, while for $e_i(t)=1$ there is an event every year at that time. The function $e_i(t)$ is computed empirically using all years of observations at that station, as the ratio of the number of years that an event occurred at time $t$ to the total number of years sampled at time $t$. In order to yield a smooth function that is less sensitive to individual events and that is conservatively (that is, as an upper bound) representative of the upper limit of probabilities, a 2-week running mean is applied to this ratio, and the result is scaled up by a multiplicative factor such that its peak value is as large as the maximum prior to application of the running mean. Finally, for each station the statistical-average event-mean difference $<\Delta C>_i$ between the concentration and the threshold during an event is presumed to be a constant, for the purpose of the uncertainty estimation, and is determined conservatively (that is, as an upper bound) as the maximum event-mean difference from among all events in all years at station $i$.

The upper-bound estimate $A_i^SU$ is computed as

$$A_i^SU = A_i^SL + \Sigma_t [ u_{ij}(t) * e_i(t) * <\Delta C>_i * \Delta t ],$$

in which the summation is over all times between May 15 and Oct 14. This formulation has the desired characteristics: if there are no sampling gaps, all $u_{ij}$ are 0 and the upper bound is equal to the lower bound; if sampling gaps occur during a time of year when events are more probable, $e_i(t)$ is higher and the upper bound is higher; and, all other aspects being equal, the upper bound is higher for a station with a higher statistical-average event-mean difference $<\Delta C>_i$ between the concentration and the threshold.

e. Multi-site indices

To develop indices that are suitable for bay-wide conditions, or conditions in a subregion of the bay that contains more than one site, the results from a group of multiple stations are treated together to form an index that characterizes the group. Such an index $A_{ij}^G$ for a given year $j$, where the G superscript indicates a group of $n_G$ stations, is computed as the mean $\Sigma_i A_{ij}^S / n_G$ over all stations $i$ within the group. The uncertainty $U_{ij}^G$ of the group index is the mean $\Sigma_i U_{ij}^S / n_G$ of the uncertainties of all sites $i$ within the group, during that year $j$. 
As demonstrated from the results of individual sites, described below, the following groupings (and shorthand names) of stations are motivated: all 10 sites together (“All”); three sites BR, CP, and NP in the Providence River Estuary and Upper Bay (“PRUB”); the three sites SR, MV, QP in and near the West Passage (“WP”); and the two sites in the East Passage (“EP”); and finally the 8 sites not including GB and MH (“Core”; the groups PRUB, WP, and EP together).

In order to increase the number of years for which a multi-site index can be computed, thus strengthening the ability to assess trends, a method to estimate $A_{ij}^S$ for a missing record (and its uncertainty) for one or more sites in a group from a given year is necessary. As a primary goal for the method is for such estimates to reflect inter-annual differences, which as shown below are the major part of the variability, the following method was applied.

If more than half the sites in the group are not available in a given year, the index is not computed for that year. If half or more of the sites have records, those records are each used to determine their percentile level within the distribution of $A_{ij}^S$ values from that same site in all its other available years. Those percentile levels are averaged. Then the estimate for each site missing a record that year is computed by drawing that average percentile level from the distribution of $A_{ij}^S$ values from all available years at that site. The uncertainty used for the estimated missing record is taken to be the standard deviation of the $A_{ij}^S$ values from that station from all its sampled years, to help properly include the influence of inter-annual variability.

3. “Development of the indicator / Status, trends, and discussion / Next steps to consider / Data gaps, Future needs”

The following material is mainly specific to the time series analysis. Issues that are broader, and applicable to oxygen and chlorophyll as measured by other means in addition to time series methods—such as the history of nutrient loads to the bay and how they have changed, detailed discussions/investigations of the relationships of oxygen and chlorophyll to environmental forcing/processes such as river flow, etc—are taken up only superficially, and mainly through reference to other work. This is based on the understanding that such material in the Status and Trends report will be written in such a way as to lay the foundation for more than solely the time series analysis component of the report—i.e. for multiple sections (including this time series analysis)—and therefore seems unsuitable for the present write-up.

As fundamental context too important to omit, it should however be noted that the most substantial decreases to nutrient loading of the bay, in association with treatment plant upgrades, occurred starting in 2013 (Pers. Comm., C. Oviatt and A. Liberti). As such, under the reasonable presumption that changes to nutrient loads are the most important influences on trends in hypoxia and chlorophyll blooms, a good initial starting point for status and trends interpretation is as follows. The years up to and including 2012 are useful for assessing status, or baseline conditions, prior to reduced nutrient loads. Then the years 2013 to 2015 (the most recent year analyzed) are most useful for detecting trends or changes in response to the reduced nutrient loads.

a. Hypoxia
i. Status

The years prior to 2013 in the superposed time series of season-cumulative deficit duration for all individual stations, shown for the three oxygen concentration thresholds (Figs 2, 3 and 4), make clear many detailed aspects of the status of hypoxia.

Consider first the results for threshold 4.8 mg l\(^{-1}\) (Figure 2). The most dominant characteristic is pronounced inter-annual variability, which far exceeds the uncertainties due to sampling gaps. It has been shown that this inter-annual variability is most closely tied to spring and summer river runoff (e.g. Codiga et al., 2009; Codiga 2012). In wet years, for example 2003, 2006, and 2009, the hypoxia metric is at its highest, and this is true across nearly all sites. In dry years, for example 2004, 2007, 2010, the metric is at its lowest, also the case across nearly all sites. While wet conditions are directly linked to increased density stratification, a system characteristic that is among the most strongly correlated with hypoxia, they are also known to be responsible for increased nutrient loading, from rivers and treatment plants; the relative importance of these two processes in driving hypoxia is not well understood and remains an area of active research.

The geographic structure of hypoxia is also evident in Figure 2: the most hypoxic sites are GB, BR, SR, CP, and NP, all located in the northern and western areas, including the Providence River Estuary, the upper West Passage, or Greenwich Bay. The least hypoxic sites are QP and TW, both farthest south and most distant from river inputs. Intermediate hypoxia occurs at MV and PP, which are slightly further south and east from the most hypoxic northern and western areas, and at MH which is isolated from the other stations in Mount Hope Bay to the east and influenced by different river forcing as noted above. The geographic pattern of most intense hypoxia in northern and western areas of the “core” Narragansett Bay—that is, excluding MH—has been noted to result from the superposed influences of the northern location of the most concentrated nutrient loading (river and treatment plant inputs) that drive hypoxia, and the counterclockwise residual circulation (e.g., Codiga, 2012).

The same general characteristics of inter-annual variability and spatial structure are also apparent, with only relatively minor modifications, in the results for threshold 2.9 mg l\(^{-1}\) (Figure 3). As expected for this lower threshold level, the spatial extent of hypoxia is smaller, and the index is typically zero for a higher number of stations in a given year. For the lowest threshold 1.4 mg l\(^{-1}\) (Figure 4), the spatial extent decreases further and number of stations with zero index increases further, also as expected. Hypoxic events relative to this lowest threshold level only occur at the few stations, in the northern and western sites, where events relative to the higher thresholds are the most common and the most pronounced as noted above.

The record from one station, GB, has notably distinct characteristics compared to all the others. GB is the shallowest site and is located in the least exposed waters, with very weak local riverine influence. Its metric is generally the highest among all stations, and even during low-hypoxia years it typically does not reach values as low as the other stations. Furthermore, there is some visual evidence (Figures 2-4) that its inter-annual variations do not follow those of most other stations as closely as they follow each other. These features lead to the conclusion that this site is subject to influences, such as local winds or local circulation patterns, which are not as important to the rest of the sites (e.g. Codiga et al. 2009).
Indices that combine results from multiple stations reinforce the above conclusions (Figures 5, 6, and 7). For the 4.8 mg l⁻¹ threshold (Figure 5) the PRUB group has the highest values, followed by the WP group, with distinctly lower values for the EP group. The latter is also characterized by inter-annual variations that are weaker and less coherent with that of the other groups. The Core group (which combines the PRUB, WP, and EP groups) shows correspondingly central magnitudes and somewhat weaker inter-annual variations than PRUB and WP, as expected. Finally, results for All (the group including the Core sites plus GB and MH) are very similar to Core but slightly higher, as expected because GB and MH each experience strong hypoxia, as noted above.

For the 2.9 mg l⁻¹ and 1.4 mg l⁻¹ thresholds (Figures 6 and 7) the patterns are similar, but two notable features emerge. First, the nature of the inter-annual variability changes to include numerous low-value years with fewer high-value years, as opposed to comparable numbers of high and low values. Second, at threshold 2.9 mg l⁻¹ the WP group has values comparable to PRUB and at threshold 1.4 mg l⁻¹ it has the highest values.

ii. Trends

With regard to trends extending over multiple years, the first conclusion to be drawn is that, if present, they are weaker than inter-annual variability. There is little to no long term trend apparent in the records prior to 2013 (Figures 2-7). It is instructive to examine the year 2013, because it had high runoff comparable to earlier wet years such as 2006 and 2009; its hypoxia indices are also comparable to those years, indicating that although nutrient load reductions were substantially in effect that year (as noted above), a weakened hypoxia response was not yet observed.

Notably there is visual evidence that 2014 and 2015 are among the least hypoxic years, which supports the conclusion that nutrient load reductions have led to a trend of reduced hypoxia in these years. However it is also true that 2014 and 2015 were years when river runoff was not high, and on comparing their hypoxia indices to those of earlier dry years (2004, 2007, 2010) it is clear that this apparent change is not particularly strong.

An investigation of the river runoff and stratification during 2014 and 2015 compared to prior years would be necessary in order to further assess the extent to which the low hypoxia in 2014 and 2015 was indicative of a change in the system in response to decreased nutrient loads. For example, a strong indication that hypoxic response has changed in recent years would consist of quantitative confirmation that 2014 and 2015 had stronger runoff and stratification as compared to earlier years for which the hypoxia indices were as low as 2014 and 2015. (This type of analysis is beyond the scope of the current contract, as explicitly discussed when it was established, but would be a suitable additional effort if that were to merit consideration.)

More convincing evidence of a long-term trend for reduced hypoxia as a result of the nutrient load reductions since 2013 may be provided in some future year should the spring and summer river runoff be higher than average, and the hypoxia indices remain closer to conditions in earlier dry years than earlier wet years. It is clear that analysis methods such as those used here are
capable of definitively answering this question as long as the present level of time series monitoring is sustained for at least several additional years, in order to detect and confirm any trend as distinct from the larger-amplitude inter-annual variations.

b. Chlorophyll

i. Status

Results for the chlorophyll bloom metrics are based on a single threshold at each station (Table 2), so consist of one set of individual site metrics (Figure 8) and one set of multi-site metrics (Figure 9).

The individual site metrics (Figure 8) reveal pronounced inter-annual and inter-site variability. Focus first on all years except 2001. The sites where the highest values occur most often include BR, GB, CP, and SR. The sites where the lowest values occur more often are NP, QP, and TW. Intermediate values occur most often at sites MV, PP, and MH. However the differences from site to site are not particularly strong, and year to year changes in the rankings of the sites are common. With the exception of NP, higher values generally occur at more northern locations. As compared to the hypoxia results, the geographic patterns in chlorophyll blooms are less pronounced and less consistent from year to year.

The nature of the inter-annual variability has some similarities to that of hypoxia described above, but generally is less coherent among sites. The chlorophyll bloom metric tends to be higher and lower in years when hypoxia metrics were notably higher (e.g., 2006) or lower (e.g., 2007), but this pattern is not strong. For example, hypoxia was relatively severe in 2003 but the chlorophyll bloom metric was not particularly high that year.

The multi-site metrics (Figure 9) since 2008 make clear that blooms were typically most pronounced in PRUB, least pronounced in EP, and intermediate in WP. Prior to 2008 this pattern was not as evident. This pattern is broadly similar to the geographic pattern of the baseline (long-term mean, during all times whether bloom or not) chlorophyll concentrations (Table 2).

ii. Trends

In 2001 only the BR and NP stations were monitored. The BR result is higher than any other station in any other year and the NP result was also among the highest (Figure 8). Correspondingly, the highest value for a multi-site index is at PRUB in 2001 (Figure 9). Because these high values were measured at only two stations during only one year, and it was during the earliest year of the monitoring, they do not seem representative of a trend or long-term change in the system. They do however suggest the possibility that chlorophyll levels were higher prior to 2002 than during the monitoring results since then, which are the focus of this analysis.

The results from 2002 through 2015 do not show a clear long-term trend (Figures 8, 9). There is weak visual evidence that values from the most recent years are slightly lower than the earliest years, and that the range of inter-annual variability has decreased slightly. But these apparent patterns are not prominent amid the geographic and inter-annual variability.
It is illustrative that in 2013, when the most substantive nutrient load reductions were first implemented, chlorophyll bloom index results were relatively high and not distinguishable from earlier years that had higher values (e.g., 2006). This is parallel to the findings for oxygen discussed above, that the system was not responsive to reduced loads in that first year they were substantially implemented.

In contrast to the hypoxia results, in 2014 and 2015 the chlorophyll results are essentially indistinguishable from earlier years. Consequently these time series observations do not suggest that long term change in chlorophyll blooms is occurring. As noted above, these time series measurements are mostly from sites in relatively deeper areas of the bay (Figure 1), relatively far from coastlines, for example near the midpoints between opposite sides of passages. They may thus not necessarily be representative of baywide conditions, to the extent that a large fraction of the total bloom activity may occur in shallower areas nearer to coastlines. This limited representativeness for the existing sites is a more important issue for chlorophyll, because it is concentrated at shallow depths where there is a larger surface area, than it is for hypoxia which is concentrated at depths near the bottom where the total area is reduced.
References


Table 1. Records analyzed. O = Dissolved oxygen. C = Chlorophyll.

<table>
<thead>
<tr>
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<th>QP</th>
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Table 2. Chlorophyll thresholds for each station, computed as the 80th percentile of all data between May 15 and Oct 15 in all years’ records from that station.

<table>
<thead>
<tr>
<th>Station</th>
<th>Threshold [µg l⁻¹]</th>
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<tbody>
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<td>26.1</td>
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<tr>
<td>Conimicut Point</td>
<td>19.6</td>
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<tr>
<td>North Prudence</td>
<td>15.0</td>
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<td>Sally Rock</td>
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<td>Mount View</td>
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<td>Quonset Point</td>
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<td>T-Wharf</td>
<td>5.0</td>
</tr>
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<td>Greenwich Bay</td>
<td>28.7</td>
</tr>
<tr>
<td>Mount Hope</td>
<td>14.6</td>
</tr>
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</table>
Figure 1. Site locations, bathymetry and river sources (arrow sizes proportional to annual mean flow). See text for discussion.
Figure 2. Hypoxic event season-cumulative deficit-duration relative to 4.8 mg l$^{-1}$ threshold, individual stations.
Figure 3. Hypoxic event season-cumulative deficit-duration relative to 2.9 mg l⁻¹ threshold, individual stations.
Figure 4. Hypoxic event season-cumulative deficit-duration relative to 1.4 mg l$^{-1}$ threshold, individual stations.
Figure 5. Hypoxic events, multi-site average season-cumulative deficit-duration relative to 4.8 mg l$^{-1}$ threshold.
Figure 6. Hypoxic events, multi-site average season-cumulative deficit-duration relative to 2.9 mg l⁻¹ threshold.
Figure 7. Hypoxic events, multi-site average season-cumulative deficit-duration relative to 1.4 mg l$^{-1}$ threshold.
Figure 8. Chlophyll bloom events, season-cumulative surplus-duration relative to site-specific 80th percentile thresholds (Table 2).
Figure 9. Chlorophyll bloom events, multi-site average season-cumulative deficit-duration relative to 80th percentile thresholds.