## 2. Water Quality




Figure VI-1. Estuarine water quality monitoring station locations in the Plymouth Bay estuary system. Station labels correspond to those provided in Table VI-1.

## 2.1 Introduction

Duxbury Bay, located along the Massachusetts coast, supports a diverse array of ecological habitats and provides valuable services to the surrounding community, including shellfish aquaculture, boating, and recreation. Like many estuarine systems, the bay is sensitive to nutrient enrichment, warming temperatures, and changing land use patterns in its watershed. Regular monitoring of environmental indicators is essential to track these changes and guide effective stewardship.

This report presents a synthesis of available water quality data to evaluate the current state of Duxbury Bay and assess trends in ecological condition. The analysis focuses on five core environmental indicators: nutrients, phytoplankton, dissolved oxygen, turbidity, and water temperature. These indicators were selected based on their relevance to estuarine health, data availability, and their use in regional coastal assessments.

Data Sources and Scope of Analysis

The findings in this report are based on data collected by three monitoring programs: the Center for Coastal Studies (CCS), the Cape Cod Cooperative Extension (CCCE), and the Massachusetts Bays National Estuary Partnership (MassBays). Together, these programs have compiled over two decades of monitoring data within Duxbury Bay and its tributaries. However, only the CCS and CCCE datasets met the quality standards for inclusion in this report. These data were selected for their consistency, methodological rigor, and temporal coverage.
The CCS dataset spans from 2006 to 2023 and includes monthly measurements of nutrients, chlorophyll-a, dissolved oxygen, and turbidity from three long-term stations in Duxbury Bay: Harbormaster Dock, Power Point Bridge, and Bluefish River Bridge. Additional CCS monitoring stations are in Kingston Bay (Jones River Estuary), Plymouth Harbor, and adjacent Cape Cod Bay locations (see Appendix X for summary information from these stations). The CCCE data supplement this with high-frequency measurements of water temperature and dissolved oxygen recorded at 15-minute intervals during the growing season (May–October) over the last decade.

MassBays data from 2023 and 2024 were reviewed but excluded from this version of the report due to the monitoring locations and period of record. While these data may prove useful in future assessments, they were not deemed appropriate for trend analysis or condition evaluation at this time.

Although the Massachusetts Estuaries Project (MEP) did not provide raw monitoring data for use in this report, it remains a foundational source. The MEP conducted a comprehensive assessment of nitrogen loading and ecological health in the Plymouth-Kingston-Duxbury (PKD) embayment system, including modeled watershed nitrogen inputs, analysis of eelgrass habitat loss, benthic community condition, and development of nitrogen thresholds to protect estuarine habitat. These thresholds (e.g., 0.331–0.335 mg/L for total nitrogen to protect eelgrass) serve as important reference points throughout this report and are cited where appropriate in discussions of nutrient trends and management implications.

| Parameter | CCS (2006–2023) | CCCE (2006–2023) | MassBays (2023–2024) | Used in Report? |
|---|---|---|---|---|
| Total Nitrogen | ✓ | ✓ | ✓ | ✓ |
| Ammonium | ✓ | ✓ | ✓ | ✓ |
| Nitrate + Nitrite | ✓ | ✓ | ✓ | ✓ |
| Total Phosphorus | ✓ | ✗ | ✓ | ✓ |
| Orthophosphate ($PO_4$) | ✓ | ✗ | ✓ | ✓ |
| Chlorophyll-a | ✓ | ✓ | ✓ | ✓ |
| Dissolved Oxygen | ✓ | ✓ | ✓ | ✓ |
| Turbidity | ✓ | ✓ | ✓ | ✓ |
| Water Temperature | ✓ | ✓ | ✓ | ✓ |
| Quality Rating | High | High | Moderate/Variable | — |
| Used in This Report | ✓ | ✓ | ✗ | — |

***Table 2.*** *Water Quality Monitoring Data Used in This Report*

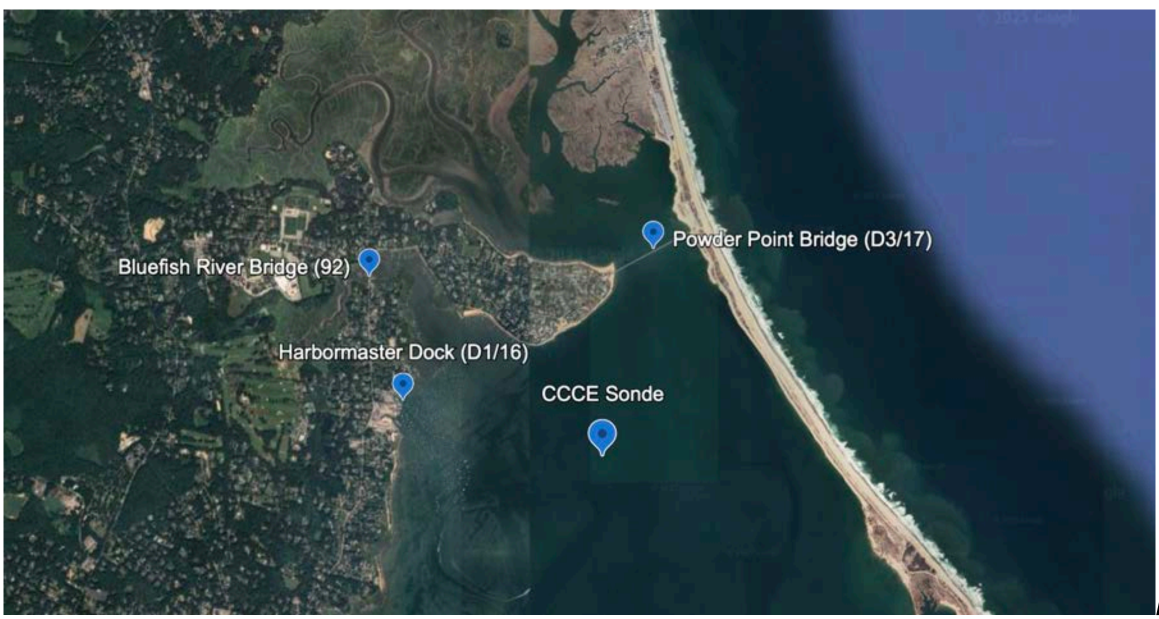



***Figure 1.*** *Locations of long-term water quality monitoring stations in Duxbury Bay. The Center for Coastal Studies (CCS) maintains stations at Bluefish River Bridge (Station 92), Harbormaster Dock (D1/16), and Powder Point Bridge (D3/17). The Cape Cod Cooperative Extension (CCCE) operates a high-frequency monitoring sonde at a mid-bay location.*

| Station Name | Station ID | Latitude | Longitude |
|---|---|---|---|
| Bluefish Creek | 92 | 42.050 | -70.670 |
| Powder Point | 71 | 41.965 | -70.670 |
| Harbormaster Dock | 16 (D1) | 42.040 | -70.670 |
| CCCE Sonde | — | 42.035 | -70.652 |
| | | | |

***Table 3.*** *Geographic coordinates of the four primary water quality monitoring stations evaluated in this report, including three Center for Coastal Studies (CCS) stations (Bluefish Creek, Powder Point, and Harbormaster Dock) and the CCCE continuous monitoring sonde location in central Duxbury Bay.*

Understanding the condition of Duxbury Bay requires a consistent and long-term assessment of the environmental factors that influence water quality, habitat health, and biological productivity. This section summarizes trends and patterns for six key indicators: nutrients, phytoplankton (as measured by chlorophyll-a), blue-green algae (BGA), dissolved oxygen, turbidity, and water temperature. These indicators were selected based on their ecological importance, their role in estuarine function, and the availability of high-quality data across multiple monitoring programs.

For each indicator, we assess both spatial and temporal patterns using data collected by the Center for Coastal Studies (CCS) and Cape Cod Cooperative Extension (CCCE). Analyses include median value ranges, statistically significant trends over time, and exceedances of scientifically recognized thresholds. Each subsection integrates figures and tables to support interpretation and identify areas of concern, particularly during the growing season (May through October), when biological activity is highest and estuarine systems are most vulnerable to stress.
Taken together, these indicators provide a foundation for understanding the ecological health of Duxbury Bay. They also help identify where management actions may be needed to protect or restore critical habitats, reduce nutrient loads, and improve resilience to climate change.

## 2.2 Nutrients

<u>Why We Track This Indicator</u>

Nitrogen and phosphorus are essential nutrients that support primary production in estuarine systems. However, when present in excess—often due to human activities—these nutrients fuel algal blooms, deplete dissolved oxygen, and degrade sensitive habitats like eelgrass beds.

Tracking nutrient concentrations provides a direct measure of the amount of biologically available nutrients in the water column at the time of sampling. These measurements complement estimates of nutrient loading by showing how inputs translate to actual environmental conditions that affect estuarine organisms.

### 2.2.1 Total Nitrogen (TN)

<u>Why We Track This Indicator</u>

Nitrogen is a critical nutrient for primary production in estuarine ecosystems, but when present in excess, it can contribute to eutrophication—fueling algal blooms, reducing water clarity, and accelerating oxygen depletion. Total Nitrogen (TN)is a composite measure that includes both *inorganic forms* (nitrate, nitrite, and ammonium) and *organic forms* (dissolved and particulate organic nitrogen). This comprehensive measure is used to evaluate overall nutrient loading and its potential to drive ecological change.

Although Duxbury Bay is relatively well-flushed compared to many other New England estuaries, the upper reaches, particularly near the Bluefish River and inner embayment, experience longer residence times that allow for nutrient accumulation and biological response. Monitoring TN concentrations helps assess the cumulative impact of watershed inputs—such as wastewater, septic systems, stormwater, and agricultural runoff—on water quality.

Tracking this indicator is vital for understanding long-term trends, evaluating ecological thresholds such as those defined by the Massachusetts Estuaries Project (MEP), and supporting nutrient management strategies. It also helps identify areas at risk of organic enrichment, eelgrass loss, and hypoxia, especially under changing climate and land use conditions.

<u>Monitoring Results</u>

**Historical Monitoring (2003–2007: MEP)**
The Massachusetts Estuaries Project (MEP) identified moderate impairment in the upper

reaches of Duxbury Bay due to nitrogen enrichment and oxygen stress. Elevated nutrient levels in the Bluefish River were linked to organic matter accumulation and eelgrass loss.

**Recent Monitoring (2006–2023: Center for Coastal Studies)**
Total nitrogen (TN) concentrations have been monitored in Duxbury Bay since 2006 by the Center for Coastal Studies (CCS) at three long-term locations: Harbormaster Dock, Powder Point Bridge, and Bluefish River Bridge. Earlier studies by the Massachusetts Estuaries Project (MEP) from 2003 to 2007 established a nitrogen threshold of 0.331–0.335 mg/L (23.6–23.9 µM) to support healthy eelgrass habitat. This threshold remains a valuable benchmark for assessing nitrogen-related stress in the estuary.

Spatial and Temporal Trends

The Bluefish River Bridge station consistently reports the highest TN concentrations, with annual median values ranging from 56.5 to 71.6 µM, well above the MEP threshold. This area is also characterized by a lack of eelgrass and some degree of benthic community degradation, indicating nutrient-related impacts. It should be noted that this site is adjacent to a saltmarsh and mudflat environment and these typically do have elevated TN signatures compared to well-mixed open bays.

At Powder Point Bridge and Harbormaster Dock, TN concentrations have shown statistically significant increasing trends over the monitoring period (2007–2023), with median values ranging from 16.5 to 40.4 µM. These concentrations generally fall within the moderate concern range according to the U.S. EPA National Coastal Condition Assessment, with some years reaching into the high range (above 0.48 mg/L or ~34 µM).

Ecological Significance

Elevated TN fuels phytoplankton growth and organic matter accumulation, which can lead to hypoxia and habitat degradation through enhanced microbial respiration. The consistently high concentrations in the upper estuary—especially at Bluefish River—suggest localized nutrient loading and poor flushing conditions. Increasing trends at the other stations indicate a widening footprint of eutrophication stress, reinforcing the need for watershed-based nutrient management strategies.

| Source | TN Threshold (mg/L) | TN Threshold (µM) | Ecological Interpretation |
|---|---|---|---|
| MEP (Duxbury Bay Target) | 0.331–0.335 | 23.6–23.9 | Supports eelgrass growth; exceeds threshold may impair habitat |
| NCCA (EPA) – Low | <0.34 | <24.3 | Considered healthy |
| NCCA (EPA) – Moderate | 0.34–0.48 | 24.3–34.3 | Increasing risk of eutrophication |

| | | | |
|---|---|---|---|
| NCCA (EPA) – High | >0.48 | >34.3 | Often associated with eutrophic conditions |

***Table 4.*** *Ecological threshold ranges for total nitrogen (TN) concentrations in estuarine waters based on guidance from the Massachusetts Estuaries Project (MEP) and the U.S. EPA National Coastal Condition Assessment (NCCA). Thresholds represent concentrations above which negative impacts on eelgrass, benthic fauna, and water quality are likely to occur.*

Continued exceedance of the MEP threshold and upward trends at multiple locations suggest that total nitrogen reductions are warranted, particularly in tributary inputs to the upper bay, to support long-term eelgrass restoration and estuarine health.

| Location | Monitoring Period | Significant Change | Range of Median Values |
|---|---|---|---|
| Harbormaster Dock | 2007–2023 | Yes (↑) | 9.6–24.0 µM |
| Power Point Bridge | 2007–2023 | Yes (↑) | 16.5–40.4 µM |
| Bluefish River Bridge | 2016–2023 | No | 56.5–71.6 µM |

***Table 5.*** *Summary of annual median total nitrogen (TN) concentrations at three long-term monitoring stations in Duxbury Bay. The table shows the monitoring period, presence of statistically significant trends, and the range of annual median values (in micromolar, µM) at each site. Notably, TN concentrations are highest and most persistent at the Bluefish River Bridge, while significant increasing trends were observed at the Harbormaster Dock and Power Point Bridge.*

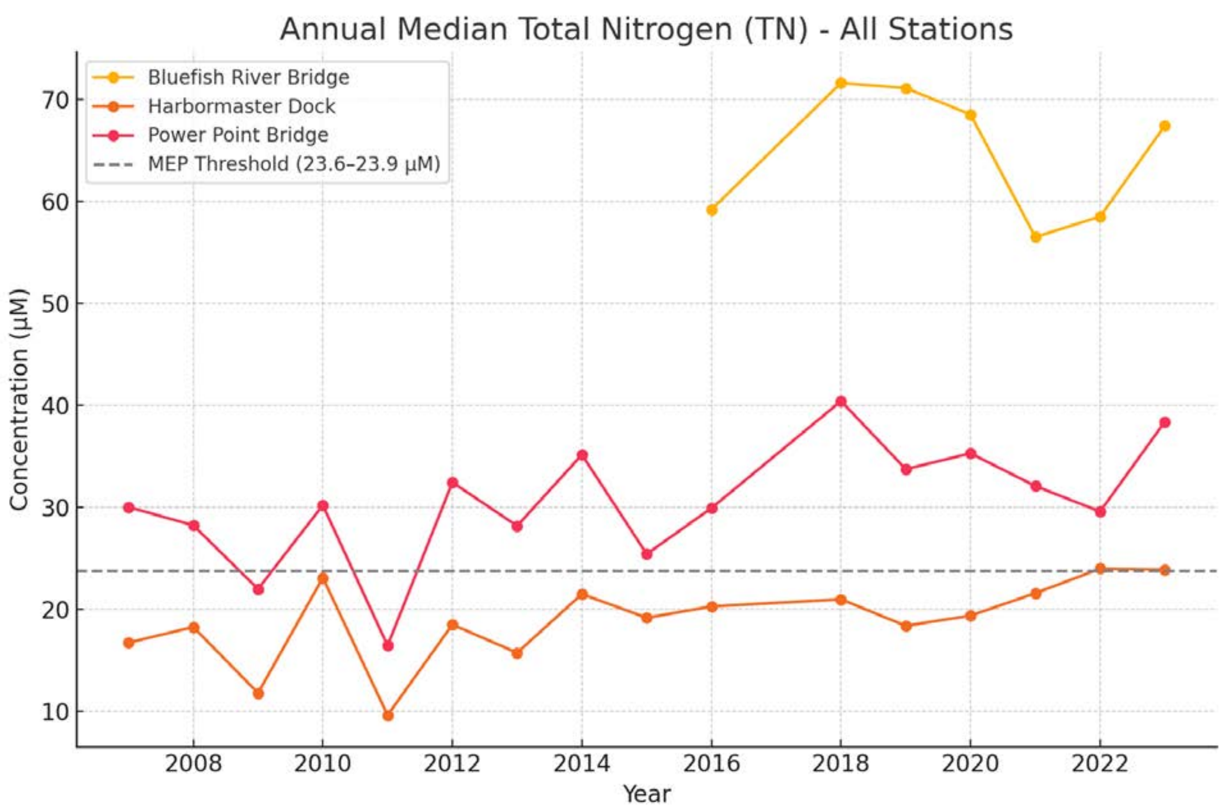



***Figure 1:*** *Annual Median Total Nitrogen (TN) at All Monitoring Stations (2007–2023).*

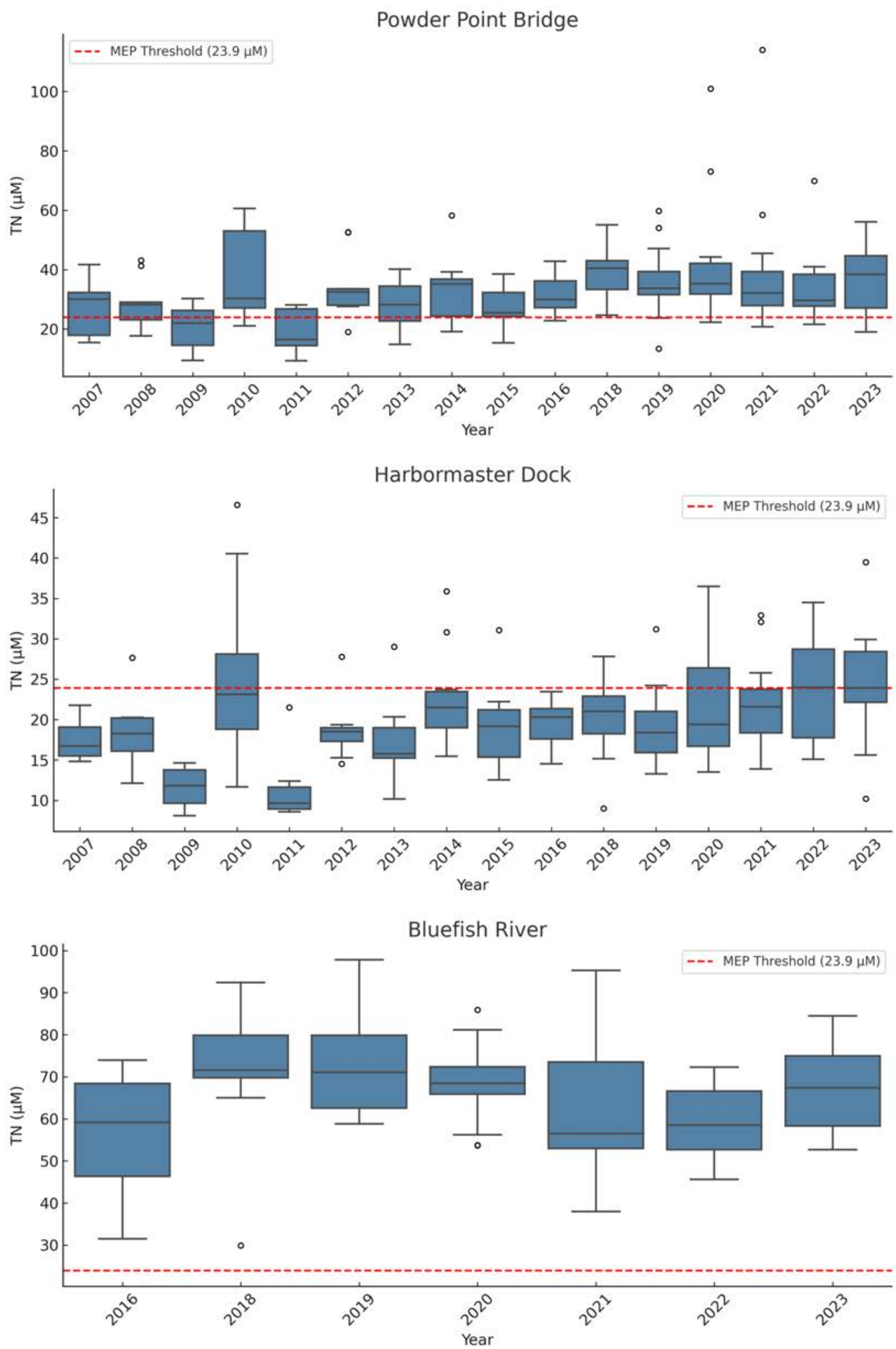



***Figure 2.*** *Annual box plots of total nitrogen (TN) concentrations. In each box plot, the horizontal line indicates the median; the box represents the interquartile range (IQR); the whiskers extend to 1.5 times the IQR; and individual points beyond this range are plotted as outliers.*

## 2.2.2 Dissolved Inorganic Nitrogen (DIN)

Why We Track This Indicator

Dissolved Inorganic Nitrogen (DIN)—composed of nitrate ($NO_3^-$), nitrite ($NO_2^-$), and ammonium ($NH_4^+$)—is a highly bioavailable form of nitrogen that directly fuels phytoplankton growth in estuarine systems. Unlike total nitrogen, which includes both organic and inorganic fractions, DIN reflects the immediate nutrient pool available for primary production. This makes it a sensitive and timely indicator of eutrophication potential, especially during the growing season when nutrient uptake by algae is most intense.

Monitoring DIN is critical because its concentrations fluctuate more rapidly than total nitrogen in response to changes in watershed inputs, sediment fluxes, and biological uptake. High DIN levels, particularly when coupled with warm, stratified conditions, can trigger algal blooms, promote hypoxia through microbial respiration, and destabilize benthic habitats. Tracking seasonal and spatial patterns of DIN helps identify areas of nutrient enrichment, assess the effectiveness of management actions, and inform future efforts to reduce nitrogen loads in Duxbury Bay—a relatively well-flushed estuary that is nonetheless vulnerable to eutrophication in its upper reaches.

Monitoring Results

**Historical Monitoring (2003–2007: MEP)**
The Massachusetts Estuaries Project (MEP) report for the Plymouth-Duxbury-Kingston (PDK) embayment system does not specifically reference Dissolved Inorganic Nitrogen (DIN) concentrations—i.e., the combined concentrations of nitrate, nitrite, and ammonium—as a primary focus of its analysis.

Instead, the MEP emphasizes Total Nitrogen (TN) concentrations and nitrogen loading rates (in kg/day) to the estuary from watershed sources. Their analysis centers on watershed-based nitrogen inputs, in situ total nitrogen levels in water column samples, sediment regeneration, and habitat thresholds (particularly for eelgrass). While ammonium is sometimes measured in sediment flux studies, there is no consistent presentation of DIN in the water column, either in terms of spatial distribution or concentration ranges.

“The MEP report focused on total nitrogen concentrations and loading rates as key indicators of nutrient impairment in Duxbury Bay. While dissolved inorganic nitrogen (DIN) concentrations were not explicitly reported, sediment flux studies included measurements of ammonium release, suggesting a role for regenerated DIN in sustaining algal productivity during the summer season.” (p. 216-217)

**Recent Monitoring (2006–2023: Center for Coastal Studies)**

Dissolved Inorganic Nitrogen (DIN), composed of nitrate, nitrite, and ammonium, is the key group of nutrients influencing phytoplankton growth and estuarine productivity. The Center for Coastal Studies (CCS) has monitored DIN at Harbormaster Dock, Powder Point Bridge, and Bluefish River Bridge from 2006 to 2023. DIN provides a consistent indicator of biologically available nitrogen from watershed sources and internal recycling of organic matter.

Spatial and Temporal Trends

DIN concentrations vary by location and year, reflecting differences in nutrient loading, water circulation, and the recycling of organic matter (via decomposition). The Bluefish River Bridge consistently exhibits the highest DIN concentrations, with annual medians between 24.0 and 39.8 µM. These elevated values align with observed eutrophic conditions and impaired eelgrass habitat in this part of the estuary.

DIN levels at the Harbormaster Dock and Powder Point Bridge are substantially lower, with medians ranging from 0.5 to 7.1 µM. Despite previous findings of increasing nitrate concentrations at these sites, no statistically significant trend in total DIN was detected at any of the three stations, likely due to variability in ammonium concentrations over time.

Ecological Significance

DIN serves as a critical source of nitrogen for phytoplankton, macroalgae, eelgrass, and saltmarsh vegetation. Elevated concentrations, particularly in the upper estuary, can promote algal blooms, increase organic loading, and contribute to oxygen depletion through microbial respiration. The consistently high DIN at Bluefish River indicates persistent nutrient enrichment. Meanwhile, the lack of trends at other sites, despite increasing nitrate, suggests that changes in ammonium dynamics play a moderating role.

Management efforts should continue to target nutrient reductions in the upper estuary and improve understanding of the sources and seasonal behavior of ammonium, which may mask or offset overall changes in DIN trends.

| Location | Monitoring Period | Significant Change | Range of Median Values |
|---|---|---|---|
| Harbormaster Dock | 2009–2023 | No | 0.5–4.0 µM |
| Power Point Bridge | 2009–2023 | No | 0.5–7.1 µM |
| Bluefish River Bridge | 2016–2023 | No | 24.0–39.8 µM |

***Table 6.*** *Summary of Dissolved Inorganic Nitrogen (DIN) Concentrations at Long-Term Monitoring Stations in Duxbury Bay. Median annual DIN concentrations from three stations between 2009 and 2023 indicate generally low levels at Harbormaster Dock and Power Point Bridge, with no statistically significant trends*

*detected. In contrast, Bluefish River Bridge consistently exhibits elevated DIN concentrations, reflecting localized nutrient inputs in the upper estuary. Median ranges are based on monthly samples collected during the May–October monitoring season.*

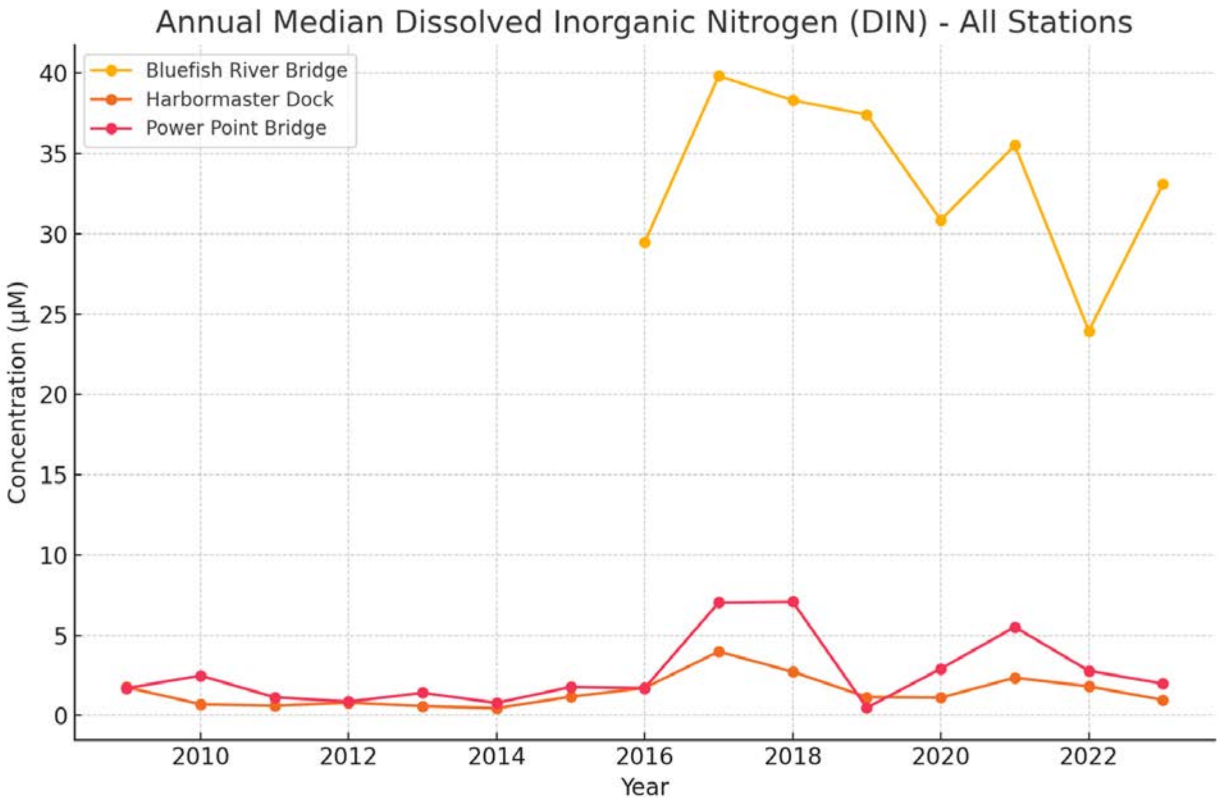



***Figure 3.*** *Annual median concentrations of dissolved inorganic nitrogen (DIN) at three long-term monitoring stations in Duxbury Bay from 2009 to 2023. DIN concentrations remain low at Harbormaster Dock and Power Point Bridge, with no statistically significant trends. In contrast, Bluefish River Bridge exhibits persistently elevated DIN levels, with annual medians ranging from 24 to nearly 40 µM, suggesting localized nutrient enrichment in the upper estuary.*

## 2.2.3 Phosphorus

Why We Track This Indicator

While nitrogen is generally the limiting nutrient in most temperate estuarine and coastal systems, including Duxbury Bay, phosphorus remains an important indicator of eutrophication risk and nutrient imbalance. Total phosphorus (TP)includes all forms of phosphorus—both organic and inorganic, particulate and dissolved— while orthophosphate ($PO_4^{3-}$) represents the immediately bioavailable fraction that phytoplankton can readily assimilate. Elevated phosphorus levels, especially when paired with high nitrogen concentrations, can exacerbate algal blooms, shift phytoplankton community structure, and contribute to oxygen depletion in bottom waters.

Tracking TP and orthophosphate provides insight into watershed sources such as agricultural runoff, stormwater inputs, and septic leachate. These indicators also reflect internal loading from sediment release, particularly under low-oxygen conditions when phosphorus can be regenerated from organic-rich sediments. Although Duxbury Bay is relatively well-flushed and not phosphorus-limited under most conditions, localized phosphorus enrichment may still affect ecological processes, especially in upper estuarine zones with reduced mixing and longer residence times. Continued monitoring of phosphorus alongside nitrogen supports a more complete understanding of nutrient dynamics and potential shifts in limiting conditions under climate change or altered land use.

<u>Monitoring Results</u>

**Historical Monitoring (2003–2007: MEP)**
From the MEP report: "The MEP did not report estuarine phosphorus concentrations or establish phosphorus thresholds for Duxbury Bay. While phosphorus was considered in watershed loading models, the study emphasized nitrogen as the limiting nutrient driving eutrophication in the embayment system. As a result, phosphorus was not a focal point of the water quality monitoring or habitat assessment efforts."

**Recent Monitoring (2006–2023: Center for Coastal Studies)**
The Center for Coastal Studies (CCS) has monitored both total phosphorus (TP) and orthophosphate concentrations in Duxbury Bay since 2006 at three long-term stations: Harbormaster Dock, Powder Point Bridge, and Bluefish River Bridge. Total phosphorus includes all forms of phosphorus—dissolved and particulate—while orthophosphate represents the immediately bioavailable form. These metrics are essential for understanding nutrient dynamics that drive phytoplankton productivity and eutrophication risk in estuarine waters.

<u>Spatial and Temporal Trends</u>

The highest TP and orthophosphate concentrations were consistently observed at Bluefish River Bridge, with annual median TP ranging from 2.22 to 3.60 µM and orthophosphate from 1.12 to 1.99 µM. These elevated values reflect greater nutrient loading and lower flushing in the upper estuary. Powder Point Bridge exhibited intermediate concentrations, while Harbormaster Dock had the lowest phosphorus levels.

Despite spatial differences in concentration, no statistically significant trends were detected in TP or orthophosphate over the monitoring period at any of the three stations. This suggests that phosphorus inputs have remained relatively stable over the past decade, even as nitrogen trends increased at some locations.

<u>Ecological Significance</u>

Phosphorus, along with nitrogen, fuels primary production in estuarine systems. When present in excess, it can promote harmful algal blooms and decrease water clarity, which in turn impacts eelgrass health and benthic habitats. Although no long-term changes in phosphorus levels have been detected, the persistently high concentrations in the upper estuary—particularly at Bluefish River Bridge—indicate localized sources that may warrant targeted management attention, particularly in areas with ongoing ecological impairment.

| Location | Monitoring Period | Significant Change | Range of Median Values |
|---|---|---|---|
| Harbormaster Dock | 2007–2023 | No | 0.9–1.95 µM |
| Power Point Bridge | 2007–2023 | No | 1.7–3.38 µM |
| Bluefish River Bridge | 2016–2023 | No | 2.22–3.6 µM |

*Table 7. Summary of total phosphorus concentrations (µM) at three Center for Coastal Studies monitoring locations in Duxbury Bay. The table includes the monitoring period, whether a statistically significant long-term trend was detected, and the observed range of annual median values at each site.*

| Location | Monitoring Period | Significant Change | Range of Median Values |
|---|---|---|---|
| Harbormaster Dock | 2007–2023 | No | 0.24–0.74 µM |
| Power Point Bridge | 2007–2023 | No | 0.24–1.52 µM |
| Bluefish River Bridge | 2016–2023 | No | 0.64–1.2 µM |

***Table 8.*** *Summary of orthophosphate concentrations (µM) at three Center for Coastal Studies monitoring locations in Duxbury Bay. The table presents the monitoring period, whether a statistically significant long-term trend was detected, and the observed range of annual median values at each site.*

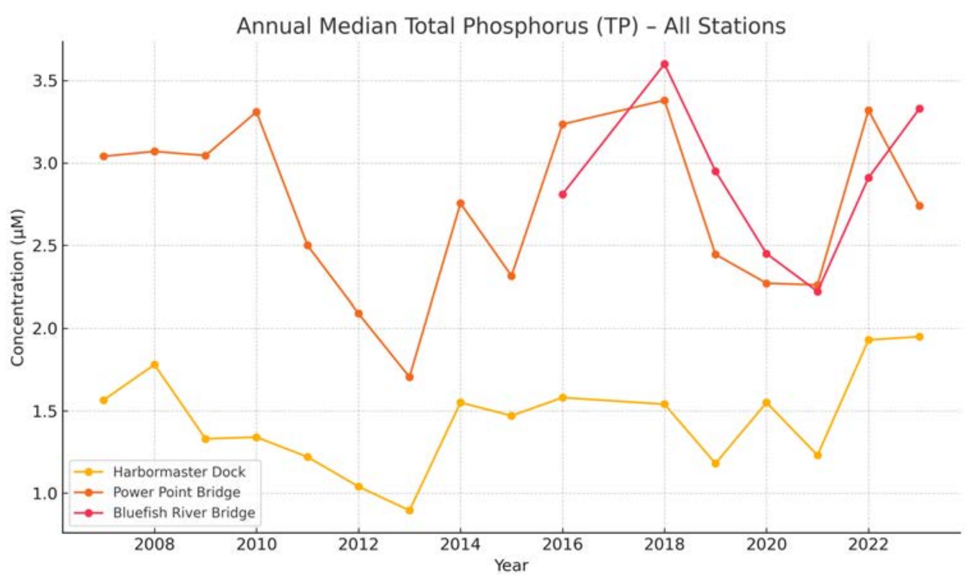



***Figure 4.*** *Annual median concentrations of total phosphorus (TP) at three long-term monitoring stations in Duxbury Bay from 2007 to 2023. TP concentrations remain relatively low at Harbormaster Dock and Power Point Bridge, while Bluefish River Bridge exhibits persistently elevated levels. These patterns suggest localized*

*phosphorus enrichment in the upper estuary. Data represent growing season (May–October) samples collected by the Center for Coastal Studies (CCS).*

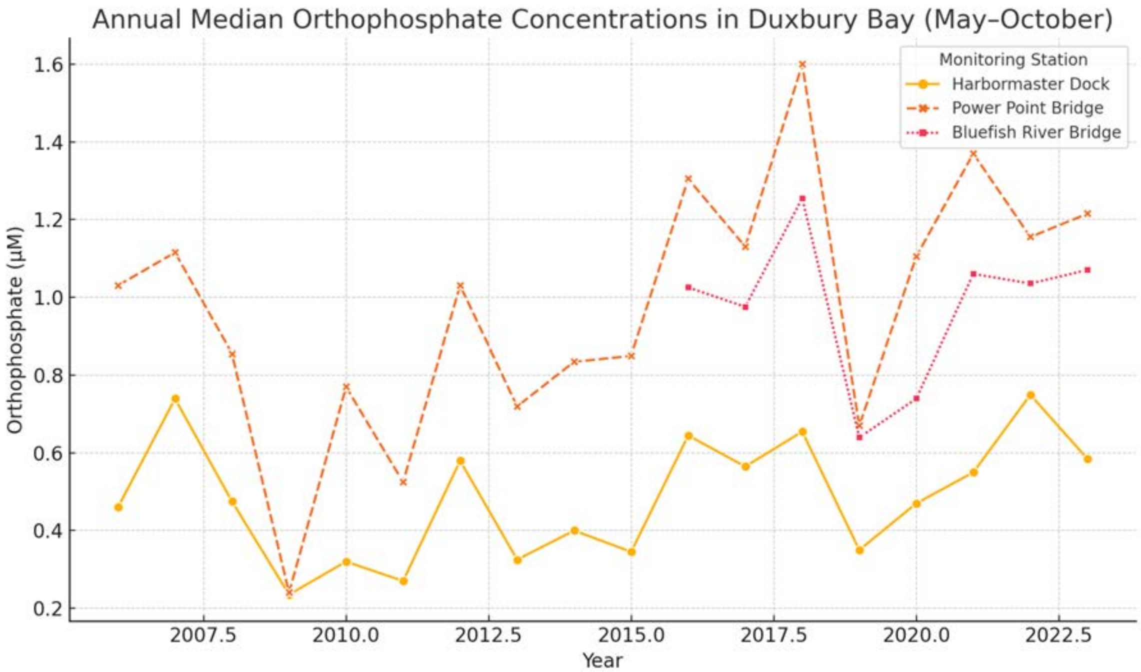



***Figure 5.*** *Annual median orthophosphate ($PO_4^{3-}$) concentrations (µM) during the growing season (May–October) at three long-term monitoring stations in Duxbury Bay from 2006 to 2023. Values are based on monthly grab samples collected by the Center for Coastal Studies. This indicator represents the bioavailable fraction of total phosphorus and is important for assessing potential contributions to algal productivity. Variation among sites and years reflects differences in watershed inputs, estuarine flushing, and internal nutrient cycling.*

| Parameter | Low (Background) | Moderate | High (Ecologically Concerning) | Bluefish River Bridge Median |
|---|---|---|---|---|
| Total Phosphorus (TP) | < 0.5 µM | 0.5–1.6 µM | > 1.6 µM | 2.22–3.60 µM |
| Orthophosphate ($PO_4$) | < 0.3 µM | 0.3–0.5 µM | > 0.5–1.0+ µM | 0.64–1.20 µM |

***Table 9.*** *Summary of ecological thresholds for total phosphorus and orthophosphate in estuarine waters, based on EPA guidance and literature benchmarks. Values observed at Bluefish River Bridge fall within the high/ecologically concerning range for both parameters.*

### 2.2.4 Phytoplankton

Why We Track This Indicator

Phytoplankton are the foundational primary producers in estuarine ecosystems, forming the base of the aquatic food web and supporting a wide array of consumers, from zooplankton to commercially important shellfish and finfish. The abundance, composition, and seasonal dynamics of phytoplankton communities influence food availability, energy transfer efficiency, and overall ecosystem productivity. Shifts in phytoplankton biomass or species dominance can cascade through the food chain, altering trophic interactions and impacting ecosystem services such as fisheries yield and water quality.

In nutrient-enriched systems, excessive phytoplankton growth can lead to harmful algal blooms (HABs), reduced water clarity, and hypoxic conditions—especially when bloom decay depletes oxygen in bottom waters. These stressors threaten eelgrass beds, benthic invertebrate communities, and the resilience of estuarine habitats to climate change.

Because phytoplankton are microscopic and taxonomically complex, long-term trend detection typically relies on the measurement of chlorophyll-a, a light-harvesting pigment common to all photosynthetic algae. Chlorophyll-a is widely used as a proxy for phytoplankton biomass and offers an efficient, cost-effective way to assess trends in productivity and eutrophication. While chlorophyll-a measurements do not reveal species composition or bloom toxicity, they remain a core environmental indicator in estuarine monitoring due to their consistency, ease of interpretation, and linkage to broader ecological processes.

In Duxbury Bay, tracking chlorophyll-a concentrations allows managers to detect productivity changes over time, identify potential eutrophication hotspots, and evaluate the effectiveness of nutrient management strategies. Continued monitoring of this indicator is essential for understanding phytoplankton dynamics and maintaining estuarine health.

Monitoring Results

**Historical Monitoring (2003–2007: MEP)**
The Massachusetts Estuaries Project (MEP) did not directly monitor phytoplankton community composition in Duxbury Bay. Instead, the MEP assessed estuarine productivity and eutrophication risk using chlorophyll-a concentrations as a proxy for algal biomass. These measurements, alongside dissolved oxygen profiles and sediment nutrient flux studies, provided evidence of elevated biological activity in the upper bay and estuarine tributaries. The MEP identified the Bluefish River area as exhibiting signs of organic enrichment and declining habitat quality, likely linked to high nutrient loads fueling phytoplankton growth. While taxonomic or toxin-related assessments were not included, the MEP results support the interpretation that nutrient-fueled phytoplankton production contributes to ecological stress in the upper estuary.

**Recent Monitoring (2006–2023: Center for Coastal Studies)**

Long-term chlorophyll-a data collected by the Center for Coastal Studies from 2006 to 2023 show spatial and temporal variability in phytoplankton biomass across Duxbury Bay. Power Point Bridge frequently exhibits the highest peak chlorophyll-a concentrations among the three sites, with annual median values reaching up to 12.9 µg/L, occasionally exceeding thresholds of ecological concern during the growing season. Harbormaster Dock exhibits more moderate chlorophyll-a levels, with annual medians ranging from 3.3 to 8.5 µg/L, while Bluefish River Bridge shows a slightly narrower range of 4.8 to 8.0 µg/L.

These concentrations generally fall within the moderate concern range for estuarine waters, indicating elevated but not extreme levels of primary productivity. Spatial gradients are evident, with Power Point Bridge representing a transition zone between the more nutrient-influenced upper estuary and the better-flushed lower estuary.

A statistically significant upward trend in chlorophyll-a concentrations was observed only at Harbormaster Dock, suggesting a possible increase in phytoplankton biomass over time in this mid-bay region. No consistent long-term trend was detected at either Power Point Bridge or Bluefish River Bridge, though both experienced episodic high values, particularly during late summer. These patterns may reflect localized variation in nutrient inputs, circulation, and temperature, underscoring the need for site-specific monitoring to detect and manage emerging eutrophication risks.

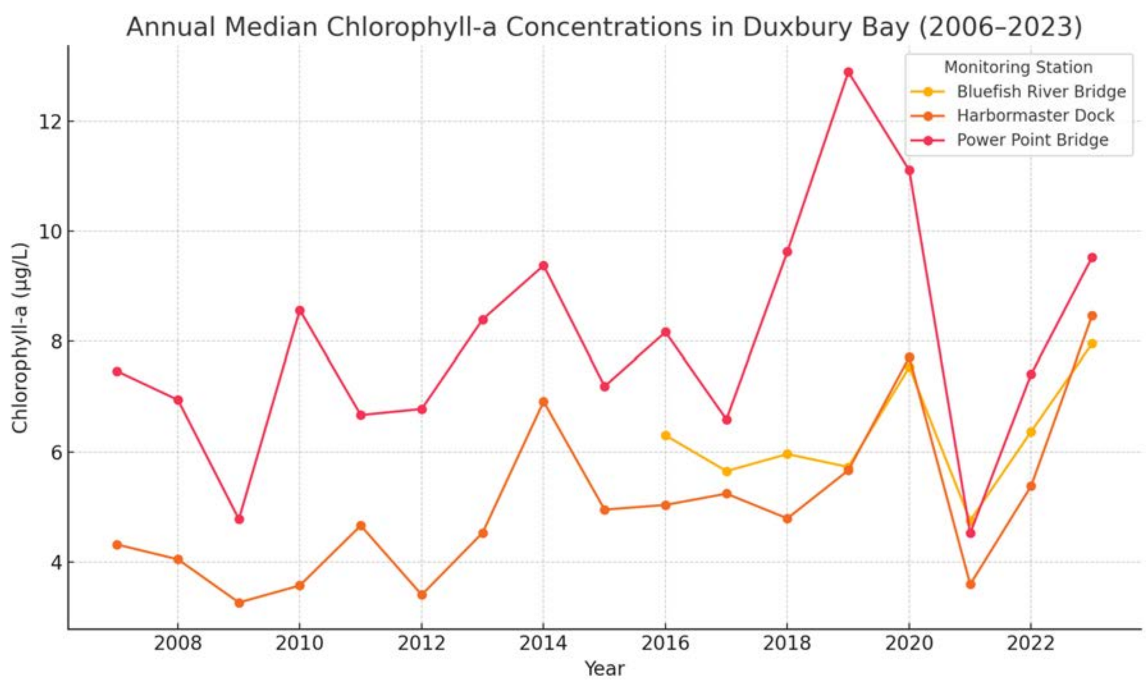



***Figure 6.*** *Annual median chlorophyll-a concentrations at three long-term monitoring stations in Duxbury Bay from 2006 to 2023. Chlorophyll-a serves as a proxy for phytoplankton biomass. Variability among stations reflects spatial differences in productivity, nutrient inputs, and hydrodynamic conditions.*

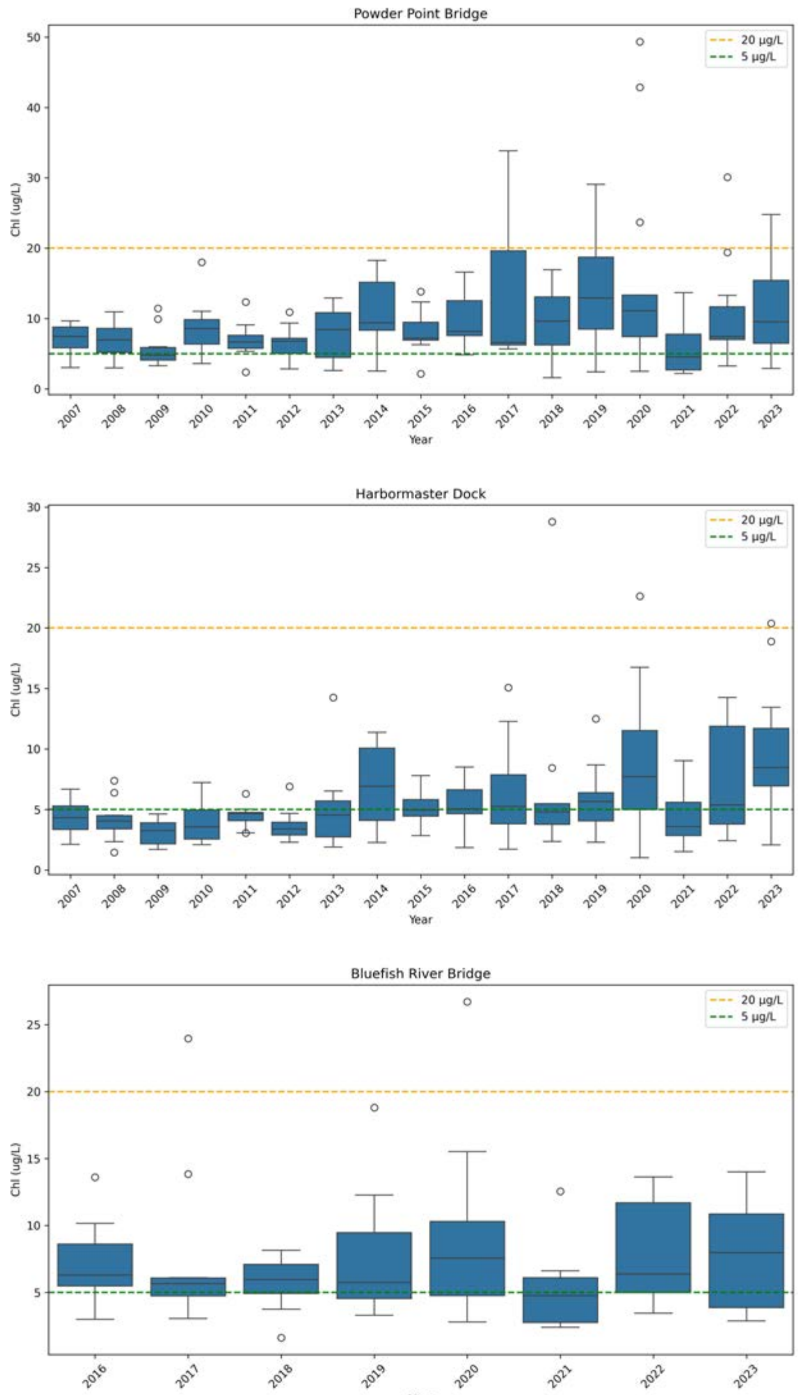



***Figure 7.*** *Annual box plots of chlorophyll-a concentrations showing upper and lower thresholds. In each box plot, the horizontal line indicates the median; the box represents the interquartile range (IQR); the whiskers extend to 1.5 times the IQR; and individual points beyond this range are plotted as outliers.*

Ecological Significance

Elevated chlorophyll-a concentrations are indicative of increased phytoplankton biomass and can initiate a series of ecological responses that impair estuarine health. One of the primary consequences is reduced light penetration through the water column, which can limit photosynthesis and hinder the growth and survival of submerged aquatic vegetation such as eelgrass. Eelgrass beds are foundational habitats in shallow estuaries, supporting biodiversity and stabilizing sediments; thus, their decline can have far-reaching ecosystem impacts.

Another consequence of excessive phytoplankton is the accumulation of organic matter in the water and sediments, which fuels microbial respiration during decomposition. This process consumes dissolved oxygen, particularly at night or during periods of water column stratification and can lead to hypoxic conditions that stress or exclude oxygen-sensitive species such as benthic invertebrates and juvenile fish.

Additionally, high nutrient availability combined with elevated chlorophyll-a concentrations can create favorable conditions for harmful or nuisance algal blooms, including cyanobacteria. These blooms can outcompete more beneficial phytoplankton species, reduce water quality, and in some cases, release toxins harmful to aquatic life and human health.

The chlorophyll-a data presented in this report suggest that the mid- to upper reaches of the estuary—particularly at the Harbormaster Dock and Power Point Bridge stations—are experiencing heightened eutrophication stress. These areas show both higher concentrations and upward trends over time, reinforcing the need for continued nutrient monitoring, targeted source reduction efforts, and adaptive management strategies to protect water quality and ecosystem function.

| Chlorophyll-a (µg/L) | Condition |
|---|---|
| < 5 | Low – Oligotrophic |
| 5 – 20 | Moderate – Mesotrophic |
| > 20 | High – Eutrophic |

*Table 10. General classification thresholds for chlorophyll-a concentrations in estuarine waters. These thresholds reflect trophic status and potential eutrophication risk, with higher concentrations indicating increased algal biomass and productivity.*

| Station | Median Chlorophyll-a Range (µg/L) |
|---|---|
| Harbormaster Dock (16) | 3.3–8.5 |
| Power Point Bridge (17) | 4.5–12.9 |
| Bluefish River Bridge (92) | 4.8–8.0 |

***Table 11.*** *Range of annual median chlorophyll-a concentrations (2006–2023) at three long-term monitoring stations in Duxbury Bay. These values reflect spatial variability in phytoplankton biomass, with the highest concentrations consistently observed at Power Point Bridge.*

## 2.2.5 Harmful Algal Blooms (HABs)

Why We Track This Indicator

Phytoplankton are microscopic algae that form the foundation of the estuarine food web. While most species are ecologically beneficial, some—particularly blue-green algae (BGA), or cyanobacteria—can form harmful algal blooms (HABs) under favorable environmental conditions. These blooms may reduce light availability, lower dissolved oxygen levels, and produce toxins that impair the growth and reproduction of filter-feeding shellfish such as oysters. In estuarine environments, HABs are commonly linked to excess nutrient inputs, elevated water temperatures, poor flushing, and reduced water clarity.

**Monitoring Results (2014–2024: CCCE)**

Since 2014, the Cape Cod Cooperative Extension (CCCE) has conducted high-frequency monitoring of BGA in Duxbury Bay using in situ sondes deployed at one fixed location. Continuous data were recorded between April and November each year, but data from May through October were analyzed for the purpose of consistency (there were different start and end dates each year). These 15-minute interval data capture peak biological activity and bloom development windows.

BGA concentrations consistently increase in late summer, coinciding with warm, stratified, and low-oxygen conditions. Elevated BGA levels have been detected most frequently at the Harbormaster Dock and Bluefish River Bridge during August and September. Sustained elevated concentrations during some years have raised concern about the presence of potentially toxin-producing genera such as Microcystis and Anabaena.

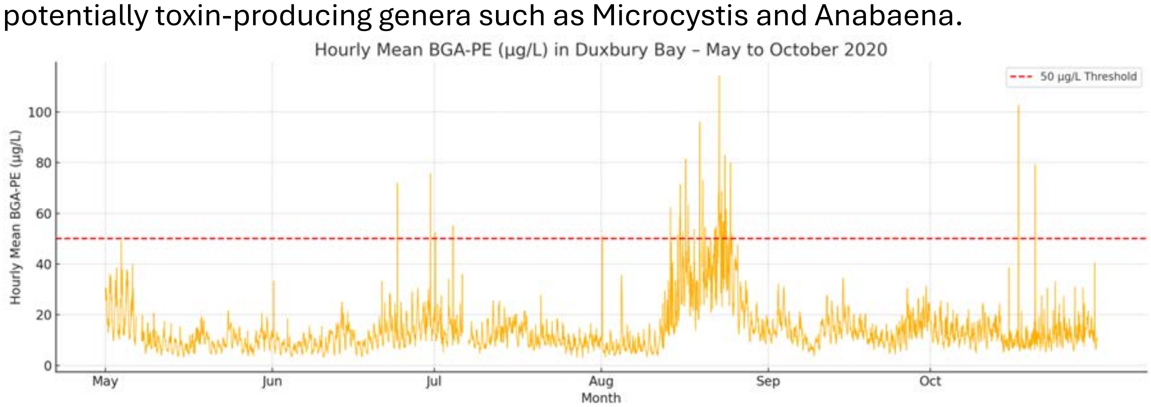



*Figure 8. Hourly mean concentrations of phycocyanin-based blue-green algae (BGA-PE) in Duxbury Bay from May to October 2020. A red dashed line marks the 50 µg/L threshold for elevated BGA-PE levels, indicating periods of potential concern for water quality and harmful algal blooms.*

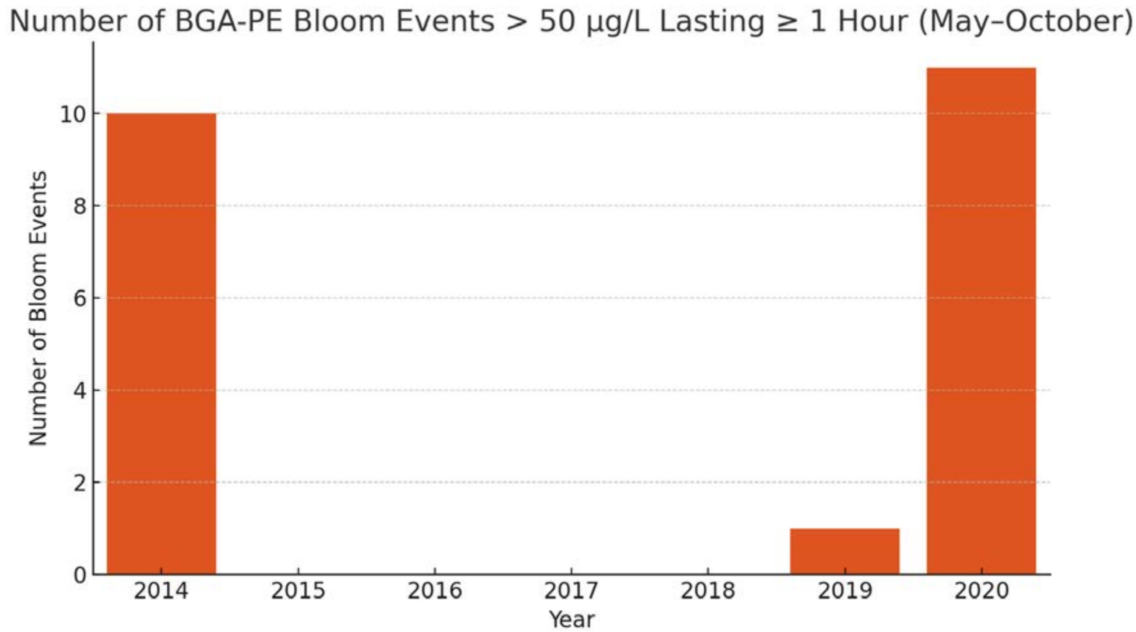



***Figure 9.*** *Number of blue-green algae (BGA-PE) bloom events in Duxbury Bay exceeding 50 µg/L and lasting at least one hour, based on CCCE high-frequency sonde monitoring from May through October. Notable bloom activity occurred in 2014 and 2020, with smaller events recorded in 2019. No qualifying bloom events were observed in other years.*

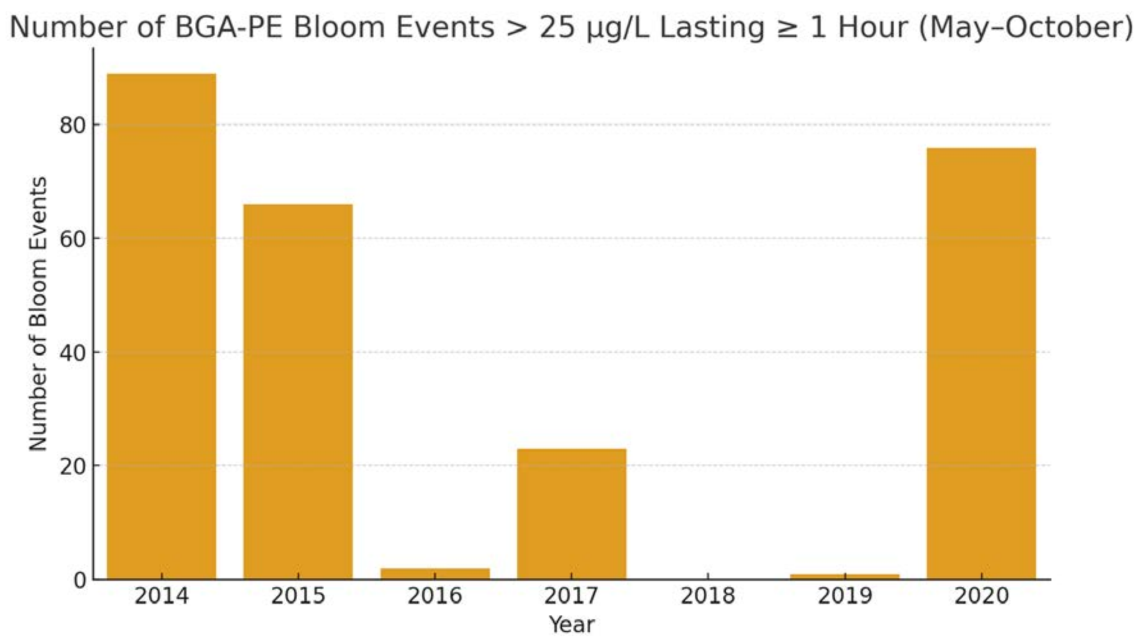



***Figure 10.*** *Number of blue-green algae (BGA-PE) bloom events in Duxbury Bay exceeding 25 µg/L and lasting at least one hour from May through October. Elevated bloom activity was observed in 2014, 2015, and 2020, with lower but notable levels in 2017. Minimal or no events were detected in other years. These results highlight interannual variability in bloom frequency and underscore the importance of continuous monitoring to capture episodic cyanobacterial events linked to environmental drivers.*

<u>Drivers of BGA and HABs in Duxbury Bay</u>

Cyanobacterial blooms in Duxbury Bay are influenced by a combination of environmental drivers. Elevated concentrations of nitrogen and phosphorus—particularly nitrate and orthophosphate—provide the nutrients necessary for growth. During the summer months, thermal conditions exceeding 25°C, coupled with calm weather and low turbidity, create stable, well-lit conditions that favor bloom persistence and potential dominance by harmful taxa. These findings are consistent with regional studies which link climate-driven warming and altered circulation (in Cape Cod Bay and the Gulf of Maine) to increased HAB frequency and intensity.

Implications for Oyster Aquaculture and Estuarine Health

Duxbury Bay supports one of the largest oyster aquaculture operations in Massachusetts. Harmful algal blooms can pose multiple risks to this industry. Cyanobacteria may produce toxins such as microcystins, which could accumulate in shellfish tissues. In addition, certain BGA taxa interfere with feeding by clogging gills or being rejected by oysters. A shift in phytoplankton community composition toward smaller, less nutritious, or potentially toxic species may reduce food quality and compromise shellfish growth and health.

| Category | Characteristic |
|---|---|
| Organism Type | Cyanobacteria (photosynthetic bacteria) |
| Size Range | 1–100 µm, including picocyanobacteria |
| Bloom Conditions | Warm, stratified, nutrient-rich, calm waters |
| Risks to Shellfish | Toxin accumulation, gill clogging, reduced feeding |
| Known Genera | Microcystis, Anabaena, Dolichospermum |

***Table 12.*** *Summary of key characteristics and potential risks associated with cyanobacteria observed in Duxbury Bay. These photosynthetic bacteria can form harmful algal blooms (HABs) under warm, nutrient-rich, and low-flow conditions. Such blooms may interfere with shellfish aquaculture by reducing feeding efficiency, clogging gills, and introducing toxins.*

## 2.2.6 Dissolved Oxygen

Why We Track This Indicator

Dissolved oxygen (DO) is a fundamental measure of estuarine health. It supports the survival of fish, shellfish, and benthic invertebrates, and plays a critical role in nutrient cycling and the breakdown of organic matter. Healthy estuarine ecosystems typically maintain DO concentrations above 6 mg/L, while values below 2 mg/L—a condition known as hypoxia—can lead to fish kills, mortality of bottom-dwelling organisms, and a reduction in biodiversity.

In Duxbury Bay, DO concentrations are influenced by a complex interplay of physical, chemical, and biological processes, many of which vary on a diel (24-hour) timescale. These short-term fluctuations are particularly evident during the summer growing season and are shaped by the following factors:

Photosynthesis and Respiration: During daylight hours, phytoplankton and submerged vegetation produce oxygen through photosynthesis, increasing DO levels in surface waters. At night, photosynthesis ceases but respiration by plants, animals, and microbes continues, consuming oxygen and causing DO to decline—often sharply before dawn.

Temperature: Warmer water holds less dissolved oxygen and can also accelerate microbial respiration. This is particularly important in shallow estuarine systems like Duxbury Bay, where summer water temperatures frequently exceed 25°C, intensifying nighttime oxygen depletion.

Stratification and Mixing: In calm conditions, temperature or salinity gradients can create vertical stratification in the water column, isolating bottom waters from surface reoxygenation. This can lead to hypoxic conditions even if surface DO remains adequate. Wind-driven mixing can break down stratification, redistributing oxygen but also resuspending nutrients and organic matter that contribute to oxygen demand.

Organic Loading and Decomposition: Elevated inputs of nutrients (nitrogen and phosphorus) stimulate phytoplankton blooms, which eventually die off and sink. The microbial decomposition of this organic matter consumes large amounts of oxygen, especially in poorly mixed areas with high residence times, such as tidal creeks and upper embayment zones.

High-frequency monitoring in Duxbury Bay, such as that conducted by CCCE, has captured these diel DO patterns clearly showing midday peaks followed by early morning lows. These fluctuations offer important insight into ecosystem metabolism and stress and can help identify areas most vulnerable to eutrophication and hypoxia.

Monitoring Results

**Historical Monitoring (2003–2007: MEP)**

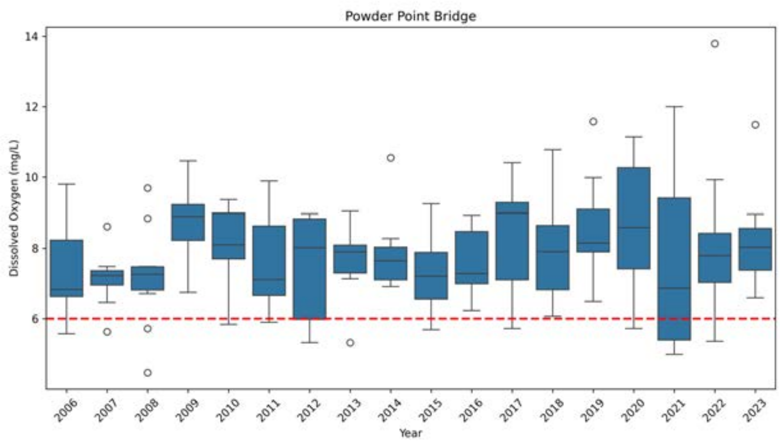
The Massachusetts Estuaries Project (MEP) concluded that Duxbury Bay exhibited moderate impairment in its upper reaches, with signs of organic enrichment and declining eelgrass habitats associated with elevated nitrogen and oxygen demand near the Bluefish River. The MEP deployed four DO sensors in Duxbury Bay for a short period in 2013 as part of their system metabolism study. Their sediment flux and nutrient data suggested DO cycling stress during summer.

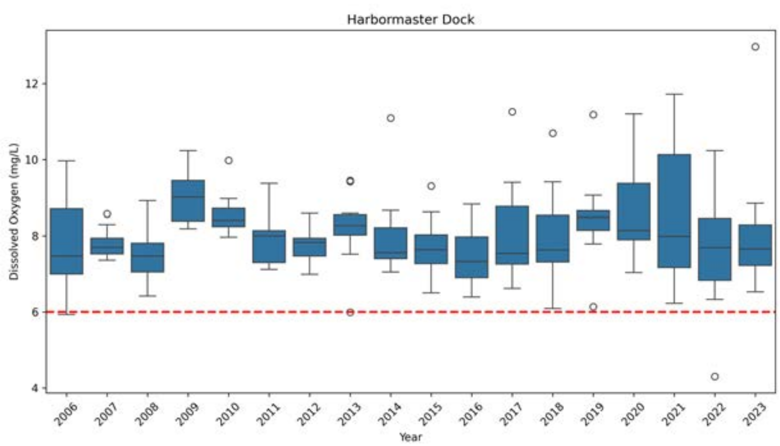
**Recent Monitoring (2006–2023: Center for Coastal Studies)**

The Center for Coastal Studies (CCS) has conducted monthly spot measurements of dissolved oxygen (DO) at three long-term monitoring sites in Duxbury Bay: Powder Point Bridge, Harbormaster Dock, and Bluefish River Bridge. Among these, Bluefish River Bridge consistently exhibits the lowest DO concentrations, with values frequently approaching or dipping below 4 mg/L during late summer. Harbormaster Dock has shown a gradual decline in DO over time, particularly during the August–September period when some measurements have fallen below the 4 mg/L stress threshold. While Powder Point Bridge generally maintains healthier oxygen levels, this site is not immune to episodic declines, especially under warm, calm conditions.

**Continuous Monitoring (2014–2024: CCCE 15-Minute Intervals)**
The Cape Cod Cooperative Extension (CCCE) has supplemented CCS's long-term dataset with high-frequency DO monitoring, using in situ loggers deployed at 15-minute intervals

from May through October each year. These data offer a detailed view of diel DO cycling and acute hypoxic events that may be missed by monthly sampling. Frequent pre-dawn lows have been recorded in the upper estuary, particularly at Bluefish River Bridge, where DO concentrations often fall below 4 mg/L—even when daily averages remain above 6 mg/L. Hypoxic events, defined as DO dropping below 2 mg/L for at least one hour, have been detected in multiple years at both Bluefish River Bridge and Harbormaster Dock. These episodes typically occur in August and early September, coinciding with peak water temperatures, high phytoplankton biomass, and minimal wind-driven mixing, all of which contribute to oxygen depletion in bottom waters.



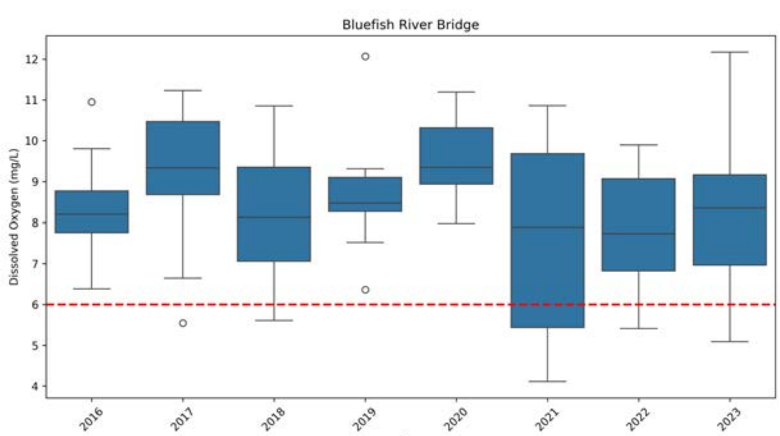



***Figure 11***. *Annual box plots of dissolved oxygen concentrations at the CCS Duxbury Bay monitoring stations. In each plot, the horizontal line represents the median, the box spans the interquartile range (IQR), the whiskers extend to 1.5 times the IQR, and individual points beyond this range are shown as outliers. The 6 mg/L threshold, commonly used as a minimum concentration to support healthy estuarine aquatic life.*

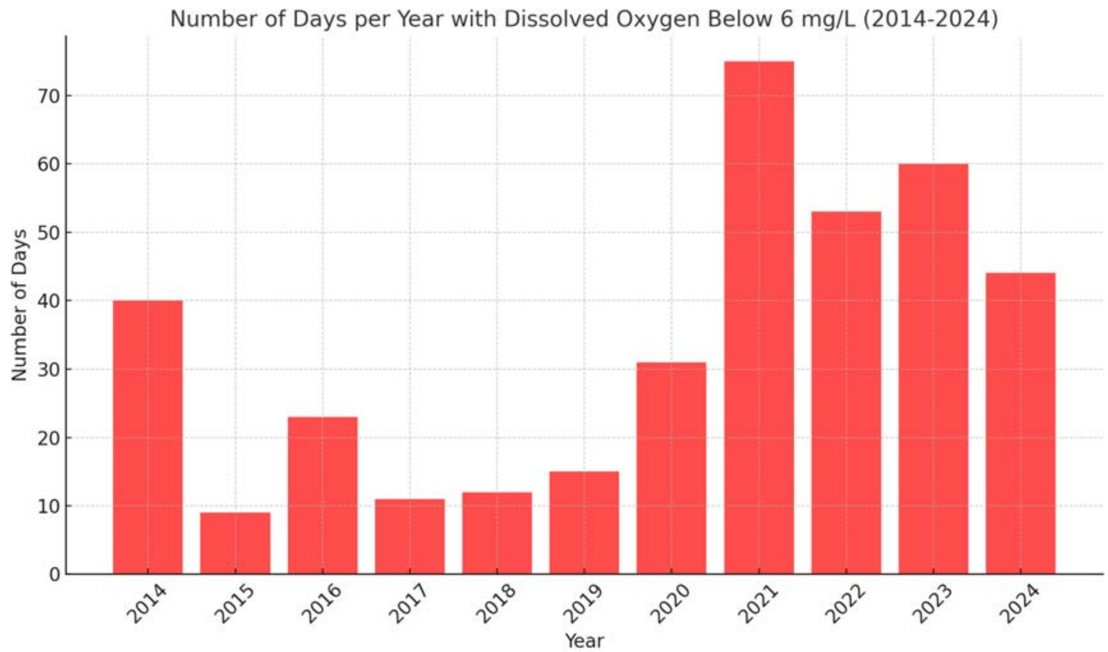



*Figure 12. Number of days per year with at least one dissolved oxygen measurement below 6 mg/L in Duxbury Bay, based on CCCE high-frequency sonde data collected from 2014 to 2024. The 6 mg/L threshold is a common ecological benchmark for maintaining suitable conditions for estuarine aquatic life.*

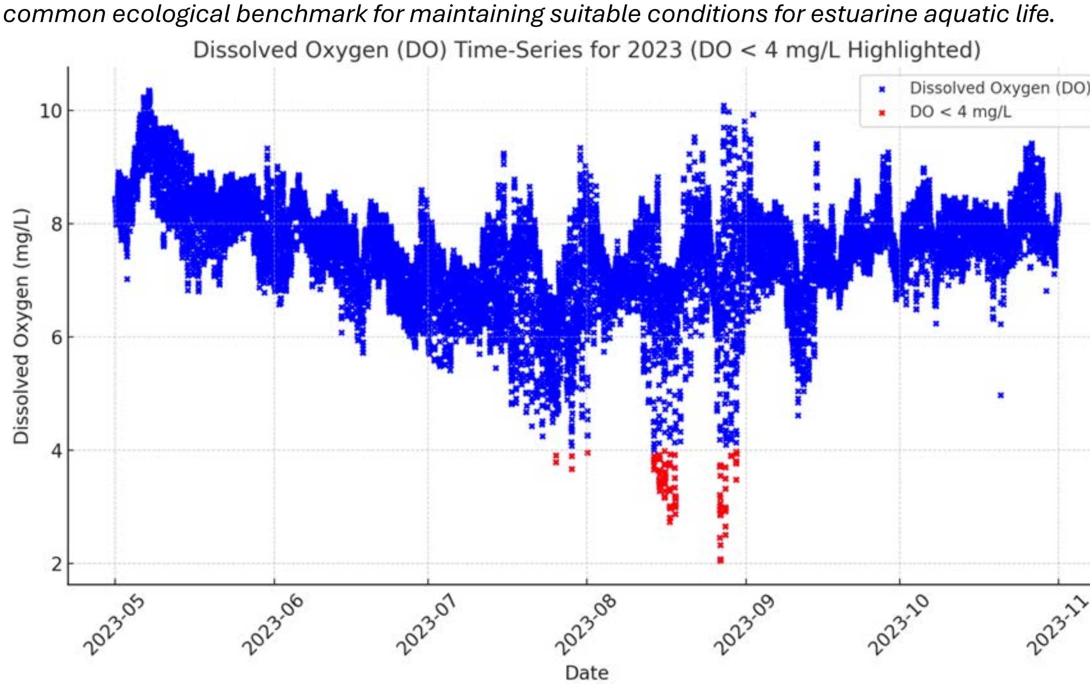



***Figure 13.*** *Dissolved oxygen (DO) time-series in Duxbury Bay from May through October 2023, based on CCCE high-frequency (15-minute interval) monitoring. Each blue point represents an individual DO measurement; red points highlight measurements below 4 mg/L, a commonly used stress threshold for aquatic life. Periodic low-oxygen events are most pronounced in August and early September, aligning with peak summer temperatures.*

Ecological Significance

Oxygen stress in Duxbury Bay is episodic but appears to be increasing in frequency and severity, particularly in nutrient-impacted and poorly flushed areas such as the upper estuary and the Bluefish River system. Several interacting factors contribute to these low-oxygen events. Elevated nitrogen and phosphorus levels support dense phytoplankton blooms, which upon senescence and decay, drive down oxygen levels through microbial respiration. This process is exacerbated by warm summer temperatures and water column stratification, which limit vertical mixing and oxygen replenishment. Additionally, oxygen demand from organic-rich sediments further intensifies DO depletion near the bottom, placing stress on benthic habitats.

These conditions threaten the long-term stability of the estuarine ecosystem. Prolonged or repeated exposure to low DO reduces eelgrass resilience, weakens benthic invertebrate communities, and disrupts nitrogen cycling processes, including coupled nitrification–denitrification, which is essential for mitigating nutrient buildup.

Powder Point Bridge continues to serve as a useful reference site, generally maintaining healthier DO levels. However, episodic drops in oxygen have also been observed at this station, particularly during calm, warm periods. These emerging trends across the estuary emphasize the need for a multi-pronged response: reducing nutrient inputs at the watershed scale, restoring hydrologic connectivity and mixing in impaired tributaries, and maintaining high-frequency monitoring efforts to better capture the timing and extent of stress events.

| Condition | DO Concentration | Implications |
|---|---|---|
| Healthy | > 6 mg/L | Optimal for most aquatic life |
| Moderate Stress | 4–6 mg/L | Sensitive species begin to exhibit stress responses |
| Episodic Hypoxia | 2–4 mg/L | Metabolic stress, disrupted behavior |
| Severe Hypoxia | < 2 mg/L | Mortality risk, especially for infauna and shellfish |
| Anoxia | 0 mg/L | Catastrophic losses; no oxygen available |

***Table 13.*** *Dissolved oxygen (DO) condition categories and their ecological implications for estuarine environments such as Duxbury Bay. These thresholds reflect the range of DO concentrations observed in monitoring data and help interpret potential stress levels for aquatic organisms, particularly during warm, stratified periods when oxygen depletion is most likely.*

## 2.2.7 Turbidity

Why We Track This Indicator

Turbidity is a measure of water clarity and reflects the concentration of suspended particles such as sediment, algae, and detritus. It is reported in Nephelometric Turbidity Units (NTU) and is influenced by stormwater runoff, wind-driven resuspension, dredging, algal blooms, and boat traffic.

Elevated turbidity reduces light penetration, impairing photosynthesis in submerged aquatic vegetation like eelgrass. It can also disrupt habitat conditions for fish and invertebrates, increase contaminant transport, and contribute to oxygen depletion when organic particles decompose.

| Turbidity Range (NTU) | Ecological Interpretation |
|---|---|
| Low (1–5 NTU) | Clear, generally healthy |
| Moderate (5–10 NTU) | Can begin to impact benthic habitat and light availability |
| High (10–50 NTU) | Harmful to submerged vegetation and filter feeders |
| > Very High (>50 NTU) | Often signals sediment stress or eutrophic bloom conditions |

***Table 14.*** *General guidance for interpreting turbidity levels in estuarine systems. These ranges reflect typical ecological responses to increasing turbidity, from clear and healthy conditions to levels that may indicate sediment resuspension, nutrient-driven algal blooms, or other forms of ecosystem stress.*

Monitoring Results

**Historical Monitoring (2003–2007: Massachusetts Estuaries Project)**
The Massachusetts Estuaries Project (MEP) did not include turbidity as a directly measured parameter in their assessment of Duxbury Bay. However, water clarity was addressed indirectly through evaluations of eelgrass distribution and habitat quality. The MEP emphasized that reduced light availability—due to factors such as suspended sediments and phytoplankton biomass—can impair eelgrass growth, particularly in nutrient-enriched or poorly flushed areas. While no long-term turbidity data were reported, the importance of maintaining high water clarity to support submerged aquatic vegetation was highlighted as a key management concern.

**Recent Monitoring (2006–2023: Center for Coastal Studies)**
Turbidity has been monitored by the Center for Coastal Studies at three long-term stations in Duxbury Bay: Powder Point Bridge, Bluefish River Bridge, and Harbormaster Dock. These stations reveal distinct spatial and seasonal patterns in turbidity levels across the estuary. Powder Point Bridge exhibits a long-term decreasing trend in turbidity, suggesting an improvement in water clarity over time. In contrast, Bluefish River Bridge tends to maintain

moderate turbidity values throughout the monitoring period. This pattern likely reflects limited flushing, continued inputs from the surrounding watershed, and frequent sediment resuspension. Harbormaster Dock shows greater seasonal variability, with elevated turbidity readings during the summer months and following storm events, which are known to stir sediments and increase runoff.

Box plots and time series analyses indicate that turbidity across most of the estuary generally falls within the “low” to “moderate” range according to estuarine health guidelines. However, localized high-turbidity events are occasionally observed, particularly near shoreline discharge points or in areas subject to wind-driven mixing and recreational boating activity.

**Continuous Monitoring (2014–2024: CCCE 15-Minute Intervals)**
The Cape Cod Cooperative Extension (CCCE) has operated a single mid-bay monitoring station equipped with a data sonde that records turbidity at 15-minute intervals during the growing season (May through October). This high-frequency dataset captures short-term variability in water clarity and identifies episodic events—such as spikes in turbidity following storms or boating activity—that are often missed by monthly monitoring. Although turbidity at this site typically falls within the “low” to “moderate” range (1–10 NTU), occasional excursions into higher ranges have been recorded, especially following wind-driven resuspension or runoff events. These episodic increases can reduce light availability, posing risks to submerged aquatic vegetation such as eelgrass. CCCE’s continuous monitoring has proven valuable in detecting these dynamics and adds important context to long-term trends observed at other stations in the bay.

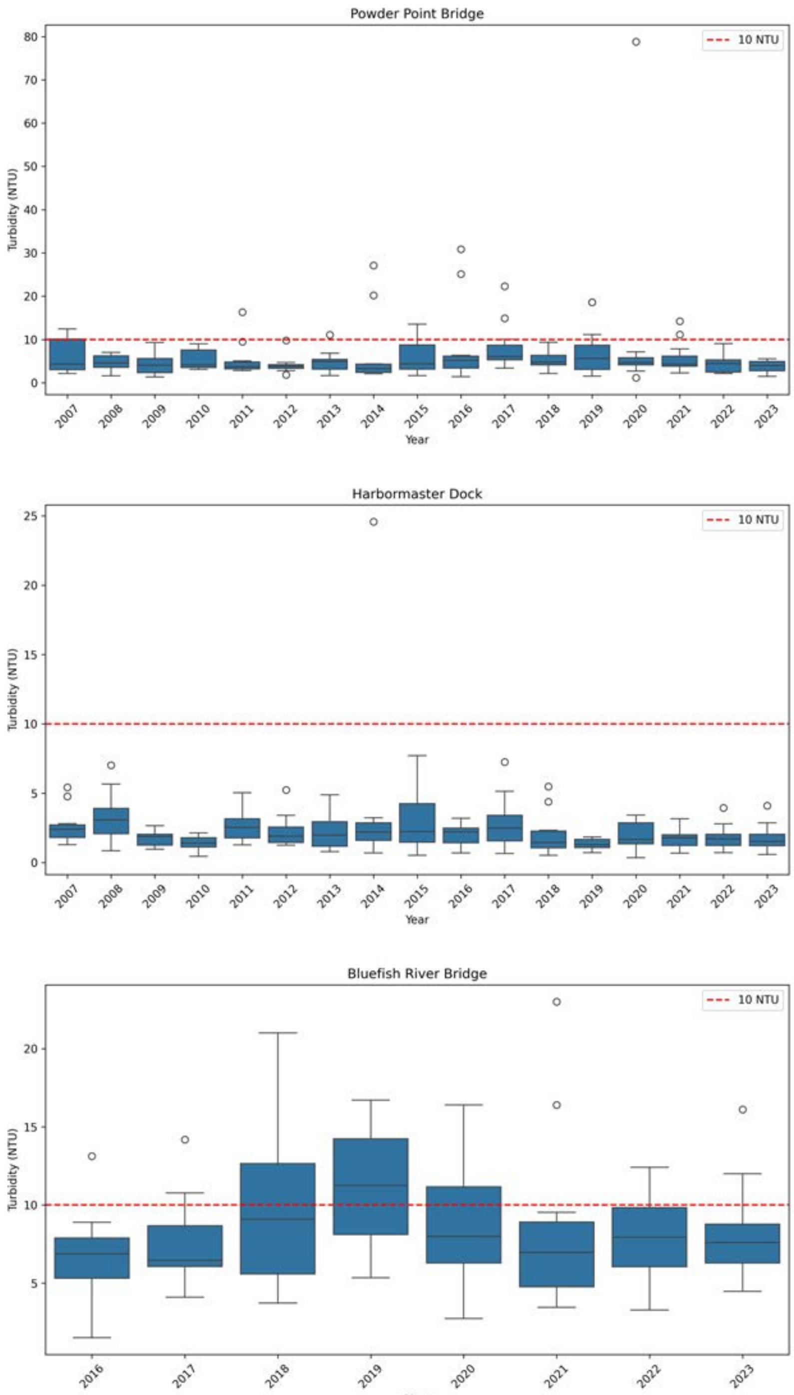



***Figure 14.*** *Annual box plots of turbidity measurements at the CCS Duxbury Bay monitoring stations. Each box represents the interquartile range (IQR), the horizontal line indicates the median, whiskers extend to 1.5 times the IQR, and points beyond that range are shown as outliers. The red dashed line marks the 10 NTU threshold, often used to indicate conditions that may begin to limit light availability for submerged aquatic vegetation.*

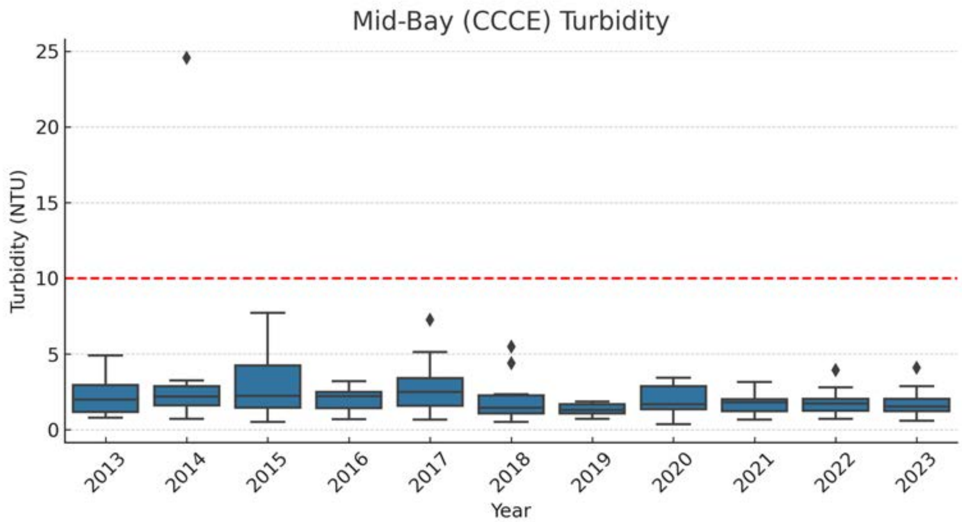



***Figure 15.*** *Annual distribution of turbidity (NTU) at the mid-bay CCCE monitoring station in Duxbury Bay. Each box represents the interquartile range of 15-minute turbidity observations during the growing season (May–October), with the red dashed line indicating the 10 NTU threshold commonly associated with potential impacts on water clarity, eelgrass, and filter-feeding organisms. Outliers are shown as individual points.*

Ecological Significance

Water clarity, as measured by turbidity, plays a vital role in maintaining healthy estuarine ecosystems. In Duxbury Bay, overall water clarity is generally good, with long-term data from Powder Point Bridge showing a declining turbidity trend. This improvement suggests that watershed management efforts—such as erosion control, stormwater mitigation, and nutrient reduction—may be contributing to reduced sediment and organic matter inputs in this area.

In contrast, the upper estuary near Bluefish River Bridge consistently exhibits moderate turbidity levels. These elevated values can limit the penetration of sunlight into the water column, reducing the availability of light necessary for photosynthesis. This condition may inhibit the growth and survival of submerged aquatic vegetation, such as eelgrass (*Zostera marina*), which requires clear, well-lit conditions to thrive. Eelgrass provides critical habitat for finfish and invertebrates and supports biogeochemical functions like nutrient cycling and sediment stabilization.

Seasonal and episodic increases in turbidity—often associated with storm events, wind-driven resuspension, and boating activity—can further impair water clarity in nearshore and shallow regions. While brief turbidity spikes may be tolerated by established plant beds, persistent or repeated events can reduce eelgrass resilience and hinder restoration efforts, especially in areas already constrained by suboptimal light conditions.

Continued high-resolution monitoring is essential to track these patterns and detect shifts that could threaten the bay's ecological balance. Protecting and enhancing water clarity should remain a key focus of bay-wide management, particularly in support of eelgrass recovery and long-term estuarine health.

## 2.3 Water Temperature

Why We Track This Indicator

Water temperature regulates nearly all biological and chemical processes in estuarine ecosystems. It affects dissolved oxygen solubility, metabolic and growth rates, reproductive timing, and the spatial distribution of aquatic species. In shallow embayments like Duxbury Bay, temperatures can increase rapidly in response to warm, sunny weather—particularly during the summer months—creating stressful conditions for sensitive organisms such as eelgrass, shellfish, and juvenile fish.

Estuarine systems are experiencing long-term warming trends due to climate change. These shifts are not only extending the duration of the growing season but also intensifying the frequency and severity of short-term thermal stress events. Elevated water temperatures can reduce oxygen availability, disrupt life cycles, and exacerbate the effects of nutrient loading and algal blooms.

Although Duxbury Bay is relatively well-mixed and flushed compared to other embayments, it remains vulnerable to rapid warming, especially in upper, more sheltered regions. Complicating these dynamics, the broader oceanographic setting of Cape Cod Bay influences local temperature regimes. Wind-driven upwelling events, common just outside the mouth of the Kingston-Plymouth-Duxbury (KPD) embayment system, can intermittently bring colder, nutrient-rich bottom waters to the surface. These upwelling pulses may temporarily moderate nearshore temperatures but can also interact with estuarine circulation patterns in complex ways that influence stratification, productivity, and oxygen dynamics.

Tracking water temperature at high resolution is essential to detect these fluctuations, assess ecosystem responses, and inform resource management in the face of continued climatic and oceanographic change.

Monitoring Results

**Historical Monitoring (2003–2007: MEP)**
The Massachusetts Estuaries Project (MEP) did not explicitly include water temperature as a core indicator in its assessment of Duxbury Bay. While temperature plays a central role in regulating estuarine processes—such as dissolved oxygen solubility, nutrient cycling, and species physiology—it was not a primary focus of the MEP's long-term monitoring strategy. Nonetheless, temperature likely influenced many of the project's findings related to oxygen stress and eelgrass loss. Subsequent monitoring efforts have recognized the need to track

water temperature directly, especially given the increasing influence of climate-driven warming in shallow coastal systems.

**Recent Monitoring (2006–2023: Center for Coastal Studies)**

The Center for Coastal Studies (CCS) recorded water temperature during its monthly water quality sampling at long-term monitoring sites throughout Duxbury Bay. While these discrete observations provide useful context on seasonal temperature conditions, their limited temporal resolution does not capture the rapid fluctuations or short-term extremes that can strongly influence estuarine health. As such, this report relies primarily on the high-frequency data collected by the Cape Cod Cooperative Extension (CCCE), which offer a more detailed and continuous record of thermal variability. These finer-scale data are better suited to assess ecological thresholds, detect extreme events, and track long-term trends associated with climate warming.

**Continuous Monitoring (2014–2024: CCCE 15-Minute Intervals)**

High-frequency data collected by the Cape Cod Cooperative Extension (CCCE) from 2014 to 2024 offer a detailed view of temperature dynamics in the bay. Measurements were recorded every 15 minutes from May through October were analyzed for the purpose of interannual consistency. This period is the primary growing season for eelgrass and the period of peak biological activity.

Over the past decade, growing season temperatures have gradually increased, particularly in July and August. Several recent years—including 2020, 2022, and 2023—recorded extended periods above 25°C, with 2023 showing the longest total duration of heat exposure.

Short-term heat stress events, defined as hourly water temperatures above 25°C, have become more frequent and persistent. These events often occur in late summer when solar heating and low wind conditions reduce mixing. The number of thermal stress days has increased over time, contributing to cumulative heat exposure during critical periods for estuarine life.

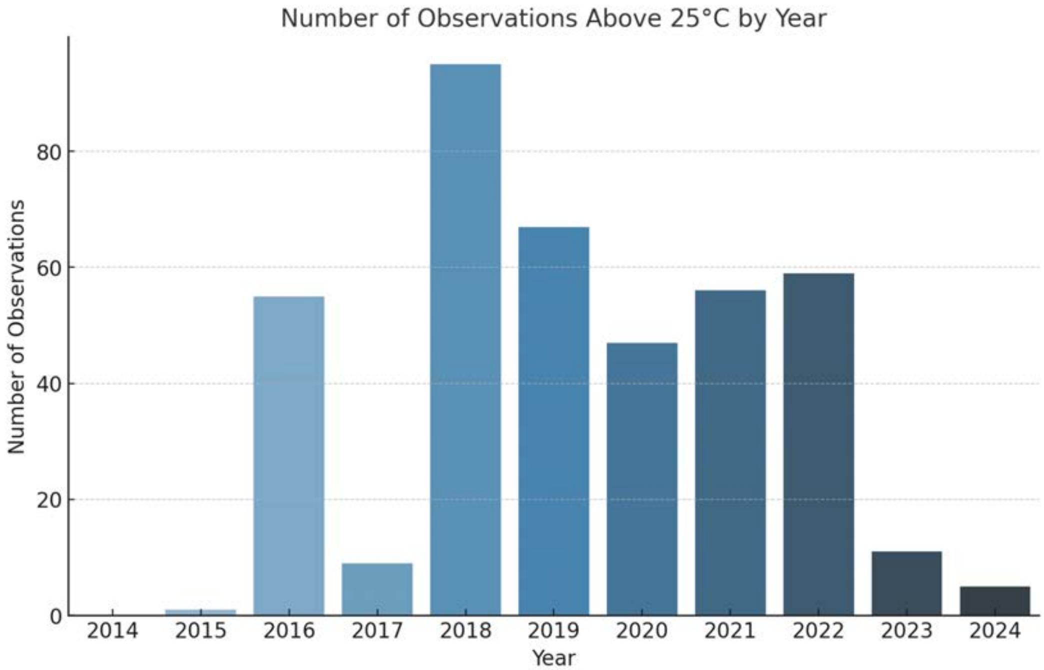



***Figure 16.*** *Number of 15-minute observations per year with water temperature exceeding 25°C in Duxbury Bay, based on CCCE high-frequency sonde monitoring from 2014 to 2024. The threshold of 25°C is commonly used to indicate thermal conditions that may stress estuarine organisms or intensify eutrophication-related processes.*

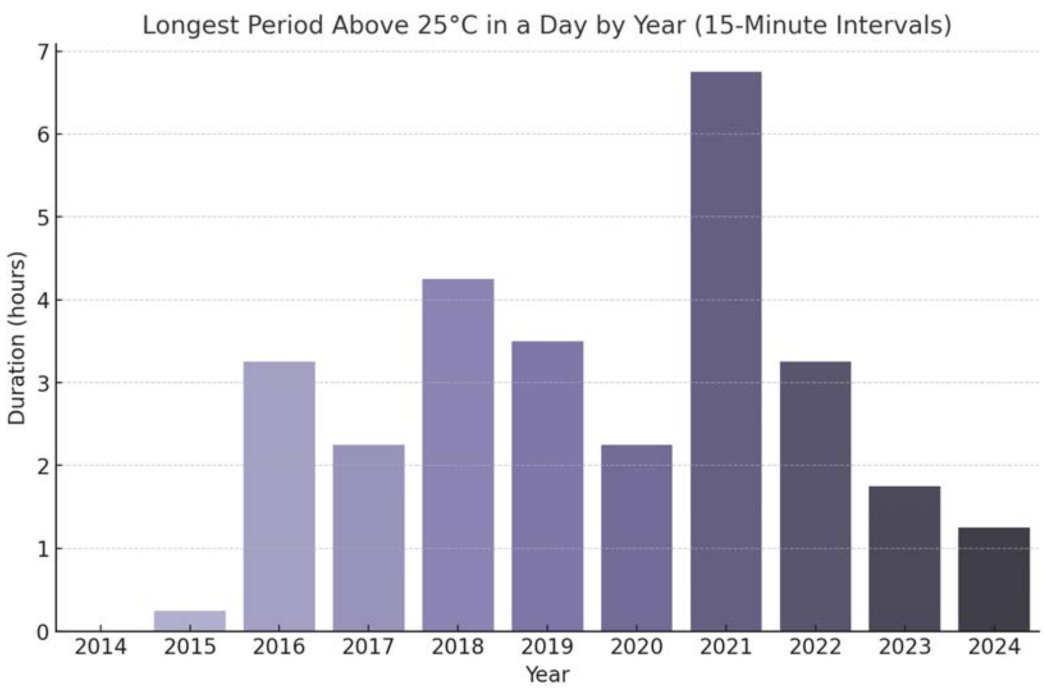



***Figure 17.*** *Longest daily duration of water temperature exceeding 25°C in Duxbury Bay by year, based on CCCE high-frequency (15-minute interval) monitoring from 2014 to 2024. Bars represent the maximum number of consecutive hours above the 25°C threshold observed on any single day each year.*

Ecological Implications

Prolonged temperatures above 25°C are known to impair eelgrass (*Zostera marina*) by reducing photosynthetic efficiency, shoot density, and habitat stability. These impacts are particularly concerning when combined with poor water clarity or excess nutrients, both of which affect Duxbury Bay's upper regions.

Estuarine benthic invertebrates, such as polychaetes and bivalves, also experience stress under elevated temperatures. Short-term temperature spikes during larval stages can reduce survival and alter reproductive success, potentially shifting community composition toward more opportunistic species.

Higher temperatures also stimulate phytoplankton—including cyanobacteria—and accelerate microbial processes like decomposition. These changes increase biological oxygen demand, contributing to hypoxia and feedback loops that exacerbate eutrophication symptoms.

Together, these patterns underscore the importance of maintaining nutrient control, habitat resilience, and water clarity to buffer against future warming.

Temperature Thresholds and Ecological Stress

Water temperatures below 20°C are generally within the optimal range for most estuarine species. Temperatures between 20°C and 25°C may begin to induce physiological stress, especially when combined with low oxygen or high nutrient conditions. Temperatures above 25°C are associated with eelgrass stress and may alter invertebrate reproduction, while temperatures exceeding 28°C pose a risk of ecosystem-level disruption.

| Temperature Range (°C) | Ecological Interpretation |
|---|---|
| < 20 | Optimal for most estuarine species |
| 20 – 25 | Physiological stress possible, especially under low DO or high nutrients |
| 25 – 28 | Eelgrass stress and reproductive disruption in invertebrates |
| > 28 | High risk of ecosystem-level disruption |

***Table 15.*** *Temperature Thresholds and Associated Ecological Stress in Estuarine Systems. This table outlines general temperature ranges and their potential biological impacts on estuarine organisms. As temperatures increase, risks to eelgrass, invertebrates, and ecosystem stability also rise, particularly when combined with other stressors such as low oxygen or nutrient enrichment.*

## 2.4. Water Quality / Management Implications

Recent monitoring results highlight several areas of concern for the ecological condition of Duxbury Bay, particularly regarding nutrient enrichment, phytoplankton productivity, and thermal stress. These findings closely align with the 2007 Massachusetts Estuaries Project (MEP), which established nitrogen thresholds to protect eelgrass habitats and recommended targeted load reductions within the watershed. Revisiting and reinforcing these strategies is essential to restoring and protecting the bay's ecological health.

Elevated nutrient concentrations, especially total nitrogen (TN) and dissolved inorganic nitrogen (DIN), persist in the upper bay, with the Bluefish River Bridge consistently exhibiting values above MEP thresholds. These levels are associated with historic and ongoing eelgrass decline and organic enrichment. The MEP report emphasized that the greatest nitrogen load reductions should be achieved in the Bluefish River sub-watershed, which contributes approximately 24% of the total watershed load despite occupying only 8% of the watershed area. Secondary priorities include the Island Creek watershed and sub-areas surrounding the Powder Point Bridge and Kingston/Duxbury interface. Management actions in these areas should include continued improvement of stormwater treatment, upgrades or removal of septic systems, and land-use zoning to limit future nutrient contributions.

The patterns in phytoplankton indicators, including elevated chlorophyll-a and increasing cyanobacteria prevalence, are consistent with excess nitrogen loading and suggest that the bay remains vulnerable to harmful algal blooms. Nutrient reduction measures described in the MEP remain relevant and critical to mitigating bloom formation and maintaining a stable phytoplankton community.

Dissolved oxygen conditions generally meet ecological criteria in surface waters, but episodic nighttime hypoxia during summer months—especially in the upper estuary—may stress benthic organisms and compromise habitat quality. These observations reinforce the need to reduce organic inputs and maintain strong tidal flushing, particularly in shallow and enclosed embayments such as the Bluefish River and Island Creek.

While turbidity generally falls within acceptable ranges, episodic increases, likely from storm-driven runoff or sediment resuspension, can limit light availability and delay eelgrass recovery. These conditions typically call for targeted efforts to stabilize shorelines, limit construction-related sediment inputs, and manage boat traffic in sensitive areas.

Warming trends in water temperature have already resulted in multiple thermal stress events (>25°C) across recent growing seasons. These events increase the risk of low oxygen conditions and may further suppress eelgrass productivity. While temperature itself cannot be directly managed, maintaining good water quality and reducing other stressors—particularly nitrogen—will enhance the resilience of Duxbury Bay's habitats to a warming climate.

**In summary, the findings of this report reinforce the nitrogen management priorities first established by the MEP. Achieving meaningful reductions in nitrogen loading—particularly in the Bluefish River, Island Creek, and surrounding sub-watersheds—will be necessary to reverse eutrophication trends, restore eelgrass beds, and safeguard long-term ecosystem functions. These efforts must be accompanied by continued monitoring, community engagement, and coordination among local and regional management agencies.**

## 2.5. Recommendations and Research Priorities

<u>Management Recommendations</u>

**1. Reinforce Nitrogen Load Reductions**

Nutrient enrichment, particularly from nitrogen, remains the dominant stressor in Duxbury Bay. The most recent data and the Massachusetts Estuaries Project (MEP) both identify the Bluefish River as the sub-watershed with the greatest need for nitrogen load reductions due to its disproportionately high contribution relative to its size. Targeted actions should include upgrading or replacing aging septic systems, expanding sewer service in high-load neighborhoods, reducing fertilizer use, retrofitting stormwater infrastructure to include green practices (e.g., bioretention, permeable pavement), and preserving or restoring riparian buffers. Success in these areas will help reduce algal blooms, improve oxygen dynamics, and enhance habitat for eelgrass and shellfish. Targeted nutrient source tracking by applying microbial or isotopic techniques to better identify nitrogen and phosphorus sources (e.g., wastewater vs. fertilizer vs. atmospheric deposition) can inform management strategies and allocate responsibility appropriately

**2. Eelgrass Restoration and Habitat Protection**

Eelgrass beds provide essential ecosystem services such as sediment stabilization, carbon sequestration, and habitat for finfish and shellfish. Historic declines in eelgrass acreage within the bay are closely tied to water clarity and nutrient conditions. Protection of remaining eelgrass through anchoring restrictions and vessel management, combined with strategic restoration efforts where water quality has improved, should be prioritized. Successful restoration depends on light availability, sediment quality, and appropriate hydrodynamic conditions, all of which must be evaluated at candidate sites.

**3. Integrated Monitoring and Public Access to Data**

A comprehensive monitoring program is needed to track the bay's response to management actions and to detect emerging stressors. Expansion of monitoring frequency and spatial coverage, particularly in the upper bay and tributaries, will improve trend detection. Real-time sensors can provide critical information on temperature, oxygen, and turbidity dynamics. Making these data available through public dashboards or open-access repositories will increase transparency, support academic collaboration, and engage the community in stewardship.

4. **Augment Shellfish Propagation for Nitrogen Removal**

Explore the expansion of shellfish propagation—especially oysters, clams, or mussels—in upper estuary areas such as the Bluefish and Back Rivers. Research from other Massachusetts estuaries (e.g., Waquoit Bay and the Three Bays system) shows that municipal shellfish propagation programs can provide measurable nitrogen removal benefits through both bio assimilation and sequestration of particulate organic matter in shell and tissue. While Duxbury Bay already supports large commercial shellfish farms, targeted municipal propagation in nutrient-impaired areas could provide supplemental nutrient control. The Massachusetts Shellfish Initiative and EPA's National Estuary Program have both highlighted shellfish as nature-based tools for nitrogen management.

5. **Limit Fertilizer Use in Contributing Watersheds**

Evaluate the feasibility of seasonal or year-round bans on lawn and turf fertilizer use within the watershed, particularly for non-agricultural properties. Several Cape Cod towns—including Falmouth and Orleans—have adopted fertilizer control bylaws to reduce nitrogen runoff into sensitive estuarine systems. Education campaigns and municipal ordinances can help reduce unnecessary nutrient inputs, especially during the spring and summer growing seasons when estuaries are most vulnerable to eutrophication.

6. **Strengthen Public Outreach and Citizen Engagement**

Build public understanding of estuarine health through targeted outreach. Promote best practices in landscaping, septic system maintenance, and stormwater management. Encourage public involvement in monitoring efforts and stewardship programs.

<u>Research Priorities</u>

**1. Phytoplankton Composition and Bloom Risk**

Recent increases in chlorophyll-a concentrations and the detection of cyanobacteria in Duxbury Bay suggest that phytoplankton communities are undergoing shifts potentially linked to warming waters, nutrient enrichment, and changing stratification patterns. However, current monitoring programs rely on bulk chlorophyll-a measurements and optical fluorescence sensors, which provide little taxonomic resolution and cannot distinguish between benign and harmful taxa.

To better understand bloom dynamics and potential ecological or public health risks, expanded research should include taxonomic identification and functional group characterization of the phytoplankton community. For example, Sharpe et al. (2023)[1] identified critical gaps in our understanding of estuarine phytoplankton ecology, particularly the need for more detailed, seasonal, and spatially resolved data that link species composition to environmental drivers. They advocate for a multifaceted approach incorporating microscopy, pigment profiling (e.g., HPLC), and molecular tools such as 18S and 16S rRNA gene sequencing to distinguish phytoplankton taxa and monitor shifts in dominance—especially among bloom-forming or toxin-producing species.

Applying these methods in Duxbury Bay would improve our ability to detect harmful algal bloom (HAB) precursors, understand competitive interactions within mixed phytoplankton assemblages, and assess how nutrient ratios and temperature fluctuations shape community structure. This research would also inform risk assessments for aquaculture and recreational uses, guide targeted nutrient reduction strategies, and serve as an early warning system for emerging bloom threats.

**2. Diurnal and Tidal Variability in Oxygen and Temperature**
Many low oxygen events in estuaries occur at night and may not be captured in monthly grab samples. High-frequency measurements—at intervals of 15 minutes or less—are needed to characterize diurnal oxygen depletion and its coupling with temperature, biological oxygen demand, and tidal flushing. Smith et al. (2024)[2] demonstrate how diel oxygen stress can shape benthic community composition and limit recovery from eutrophication. Deploying sensors at key locations such as the Bluefish River and Harbormaster Dock would provide critical insight into when and where hypoxia occurs.

**3. Trophic Interactions and Benthic-Pelagic Coupling**
Phytoplankton blooms, suspended sediments, and low oxygen events all affect benthic habitat quality, yet the connections between pelagic processes and benthic community dynamics remain understudied. Research that combines water column data with benthic infaunal surveys can reveal how changes in the upper bay affect shellfish and infaunal biodiversity. The study in Frontiers in Marine Science (2024)[3] highlights how eutrophication can decouple benthic-pelagic interactions, reducing food quality and oxygen availability for bottom-dwelling species.

**4. Climate Change Stressor Interactions**
Temperature extremes, sea level rise, and altered precipitation patterns interact with existing stressors to amplify ecological risks. Climate modeling studies suggest that warming will expand the duration and intensity of algal blooms and hypoxia. Scenario-

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[1] Sharpe, A. E., Francis, C. A., & Kudela, R. M. (2023). Linking phytoplankton community structure with environmental drivers in a California estuary. *PLOS ONE, 18*(2), e0313271. https://doi.org/10.1371/journal.pone.0313271

[2] Smith, A. D., Dykman, D., Hall, E. K., & Giblin, A. E. (2024). Diel oxygen stress structures benthic communities and hinders recovery in eutrophic estuaries. *Frontiers in Marine Science, 11*, 1448718. https://doi.org/10.3389/fmars.2024.1448718

[3] Francis, C. A., Sharpe, A. E., & Kudela, R. M. (2024). Eutrophication weakens benthic-pelagic coupling and reduces resource quality in a temperate estuary. *Frontiers in Marine Science, 11*, 1448718. https://doi.org/10.3389/fmars.2024.1448718

based simulations, coupled with empirical field studies, can help project the impacts of different management strategies under future climate conditions. Long-term planning must account for these interactions to ensure adaptive and resilient decision-making.

**5. Ecosystem Services Valuation**
Ecosystem services provided by Duxbury Bay—such as water filtration, recreational use, and support for fisheries—can be economically quantified to support cost-benefit analyses of management actions. Valuation studies that estimate the economic returns of eelgrass restoration, improved water quality, and shellfish harvests can help prioritize investments and engage diverse stakeholders, including local residents, resource managers, and funding agencies.

## 2.6. Conclusion

This updated State of Duxbury Bay report on water quality and temperature is based on the review, analysis, and synthesis of over a decade of environmental monitoring data and other sources information. Specifically, this report provides revised and expanded assessments of nutrient concentrations, phytoplankton indicators, dissolved oxygen dynamics, turbidity, and water temperature across key locations in the bay. The data were sourced from the Center for Coastal Studies, Cape Cod Cooperative Extension, and other regional partners, and were analyzed in the context of ecological thresholds, seasonal dynamics, and long-term trends.

Key findings highlight the ongoing impact of nutrient enrichment in the upper estuary, particularly in the Bluefish River, where nitrogen concentrations routinely exceed thresholds identified in the Massachusetts Estuaries Project. Patterns in chlorophyll-a, cyanobacteria presence, and episodic hypoxia further underscore the bay's sensitivity to eutrophication and the need for continued nutrient management. At the same time, warming trends in summer water temperatures and short-lived but ecologically significant oxygen sags suggest that climate-related stressors are compounding existing challenges.

The revised environmental indicator sections incorporate recent high-frequency sensor data, interannual monitoring trends, and comparisons to historical MEP findings. Each section has been updated to reflect current conditions, identify emerging stressors, and contextualize trends within the broader ecological framework of the estuary. Data visualizations and summary tables support interpretation of these trends and provide clear communication tools for stakeholders.

In addition to revising existing content, this report expands the original format by including management implications, targeted recommendations, and a forward-looking research agenda. These additions address the secondary objective of enhancing the report with new content related to benthic conditions, nitrogen loading, and future monitoring priorities. The findings and recommendations herein offer actionable insights for decision-makers, nonprofit partners, and the community as they work to restore and protect Duxbury Bay's ecological integrity.