Water Column Monitoring Results for Cape Cod Bay and Stellwagen Bank National Marine Sanctuary 2020-2022

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Executive Summary

This report documents nutrient and plant pigment chemistry, phytoplankton and zooplankton communities, and right whale observation data in Cape Cod Bay (CCB) during 2020 through 2022. The data presented in the report were collected by the Center for Coastal Studies (CCS), to document conditions in the Bay, and to better understand the linkages between nutrient and plankton conditions in the Bay, and whale usage of the Bay. Data presented include data from the three locations in CCB and Stellwagen National Marine Sanctuary (SBNMS) MWRA is required to monitor. It also includes data collected by CCS's right whale aerial and right whale habitat surveys in CCB conducted annually from January – May. Data summarized herein together with other data collected by MWRA continue to support the conclusion that MWRA's wastewater outfall does not negatively impact Massachusetts and Cape Cod Bays.

The physical environment, water chemistry, plankton communities, and whale sightings differed among years with no clear interannual patterns. The average surface and average bottom temperatures for all three years were slightly warmer than previous years. Salinity was variable and closely correlated with both precipitation and river flow: the lower salinities during summer of 2020 were due to higher than average precipitation and river flow and the higher salinities during 2022 were a reflection of lower precipitation and river flow during much of that year.

The most notable event in the physical environment during these three years occurred in the fall of 2022 when bottom dissolved oxygen levels at F02 fell below 3 mg/L, the lowest ever recorded at this station. Although there was no evidence of high organic material as occurred during a 2019 low oxygen event, the warmer than average water temperatures and the stronger gradient of stratification were likely enough to drive oxygen concentrations down to these near-hypoxic levels.

While there was some variation among years in water chemistry, patterns were similar to those that were observed in the 2014-2016 and 2017-2019 reports. Dissolved inorganic nutrients (nitrogen, phosphorus, and silica) were lower than the long-term averages at both near surface and bottom depths. Redfield ratios indicate phytoplankton productivity in the Bay was nitrogen limited relative to both phosphorus and silicate.

Annual average phytoplankton biomass (measured as chlorophyll *a*) at the surface was similar among all three years. Elevated chlorophyll *a* in the bottom waters was seen during 2020, driven by the high concentrations at F01 and F02 (~20 µg/L) during September. A corresponding phytoplankton sample was collected at depth at F01 with a cell density of over 1.7 million cells/liter, 45% of which were the invasive species, *Karenia mikimotoi*.

Phytoplankton cell counts, again averaged annually, were highest in 2022. 2022 was the only year where there was evidence of a spring bloom. Cell counts during the summer were also higher in 2022 compared to 2020 and 2021. *Phaeocystis* did appear but only in low to moderate numbers during this 3-year period. Despite the high numbers of *Karenia mikimotoi* cells in 2020, the abundance and duration of the occurrence of this species declined over this three-year period.

Annual average zooplankton abundance was highest in 2020 due to a bloom of urchin larvae during the summer. Average zooplankton abundances in 2021 and 2022 were similar to previous years. Acantharians, a group of heterotrophic microplankton, have not been included in counts prior to 2020 so although they were counted, their abundance was not included in the calculation of averages for this report. In 2021 and 2022, they dominated the summer and fall counts, peaking at over 85,000 organisms/m^3 in July 2021. Their presence in Cape Cod Bay suggests the intrusion of offshore waters, likely driven by more frequent northeast wind events.

Highest abundances of calanoid copepods occurred in the late winter/early spring. The timing and occurrence of these species are of particular importance in the Cape Cod Bay ecosystem because they provide a winter food resource for right whales. During this three-year period, only in 2022 was zooplankton abundance in samples taken around feeding right whales higher than the long-term average of approximately 8,000 organisms/m^3.

The number of sightings of individual right whales was high across all three years. The number of sightings in 2020 was higher than any year since aerial surveillance of Cape Cod Bay began, excluding 2011, and accounted for 75% of the estimated population. The longest residency time occurred in 2021 of 147 days, and the highest number of sightings in one day (94 right whales) occurred in 2022. The spatial distribution varied among years but appeared to be more spread out over Cape Cod Bay than typical. The period of peak sightings during all three years was much earlier than typical occurring in February/March rather than mid-April.

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1. INTRODUCTION

As part of the environmental monitoring program implemented by MWRA in Massachusetts and Cape Cod Bays in support of MWRA's Deer Island Treatment Plant outfall in Massachusetts Bay, the Center for Coastal Studies (CCS) has continued the ambient water column monitoring required at three locations by adding these three stations to CCS's ongoing Cape Cod Bay monitoring program. Two of the stations are located in Cape Cod Bay (CCB) and one in Stellwagen Bank National Marine Sanctuary (SBNMS). All three stations have been monitored since 1994.

CCB and SBNMS are both ecologically diverse and highly productive areas. They encompass essential habitats for commercially valuable species of finfish and shellfish as well as many species of endangered birds and mammals. Both these areas serve as feeding grounds for the critically endangered North Atlantic right whale, *Eubalaena glacialis*. Several other species of whales including humpback, fin, and minke migrate to these waters each year to feed.

The environmental monitoring work conducted by CCS in collaboration with MWRA provides the data necessary to track the health of these waters. Water quality data, such as that collected as part of this project, are needed to safeguard these areas, and for tracking changes in them that may affect the whales and fisheries of the systems.

This report summarizes the finding of the monitoring work conducted by CCS from 2020-2022. The monitoring results for the three MWRA stations are presented in the context of other work CCS does in this region, including the concurrent, year-round water quality monitoring surveys at nine additional stations in CCB and the right whale aerial and right whale habitat surveys in CCB conducted annually from January – May. For certain variables, the 2020-2022 period was also examined in context with some of the earlier data collected in the region by MWRA.

2. METHODS

Over the past three years, CCS has monitored MWRA's three stations in CCB and SBNMS (Figure 1, Table 1) as part of their on-going program to monitor for possible outfall impacts on areas downstream of the outfall. The three sites have been sampled nine times per year, targeting the same sampling days that surveys are conducted at stations in Massachusetts Bay (Table 2).

Water quality monitoring at these stations included measurements of surface photosynthetically active radiation (PAR); water column measurements of temperature, salinity, dissolved oxygen, fluorescence; nutrient concentrations; phytoplankton biomass (chlorophyll *a* and phaeophytin), and phytoplankton and zooplankton (identification and enumeration).

During each survey, hydrographic data were collected from all three stations, and samples were collected for analysis for dissolved inorganic nutrients (nitrate/nitrite, ortho-phosphate, silicate, ammonia), total nitrogen, total phosphorous, and chlorophyll from near surface (1-2 m from surface) and near bottom (3-5 m from bottom). Near surface water was also collected for phytoplankton analysis, and a zooplankton sample was collected with an oblique net tow (Table 3). All samples were processed according to SOPs included in the project QAPP. Near bottom samples are also referred to as "depth" samples in tables and figures. A complete description of methods is provided in the project QAPP (Costa *et al*. 2020).

Table 1. Locations of MWRA and CCS stations

Station	Latitude	Longitude	Average Depth (m)
	MWRA		
F01	41.8508	-70.4533	26
F02	41.9082	-70.2283	32
F29	42.1167	-70.2900	65
	CCS		
5N	42.0093	-70.1387	23
6M	41.9352	-70.2287	34
5S	41.9100	-70.1398	18
5SX	41.8830	-70.1400	9
6S	41.8572	-70.2283	26
7S	41.8408	-70.3135	28
9S	41.8415	-70.4677	22
9N	42.0202	-70.4937	38
8M	41.9457	-70.4002	42

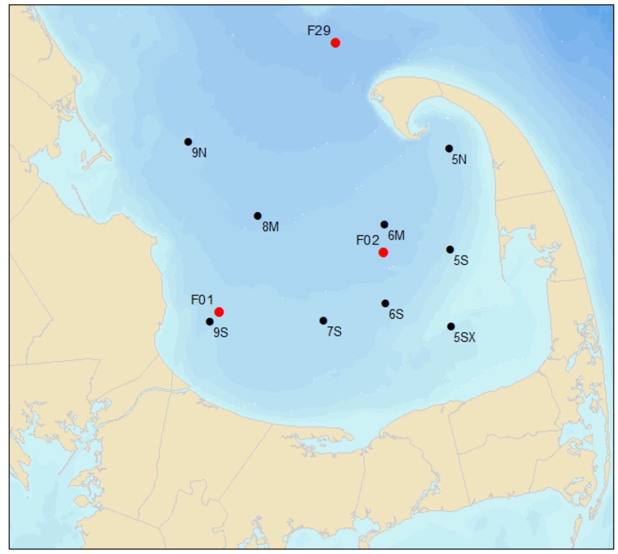

Figure 1. Sampling locations in CCB and SBNMS. CCS stations are in black; MWRA stations are in red

Table 2. Sampling dates of surveys, 2020-2022.

2020			**2021**			**2022**		
Survey	Targeted	Actual	Survey	Targeted	Actual	Survey	Targeted	Actual
WN201	2/10/2020	2/11/2020	WN211	2/9/2021	2/9/2021	WN221	2/8/2022	2/7/2022
WN202	3/17/2020	3/28/2020	WN212	3/23/2021	3/23/2021	WN222	3/22/2022	3/23/2022
WN203	4/7/2020	4/4/2020	WN213	4/13/2021	4/14/2021	WN223	4/12/2022	4/13/2022
WN204	5/12/2020	5/17/2020	WN214	5/18/2021	5/18/2021	WN224	5/17/2022	5/13/2022
WN205	6/16/2020	6/16/2020	WN215	6/22/2021	6/22/2021	WN225	6/21/2022	6/28/2022
WN206	7/21/2020	7/16/2020	WN216	7/27/2021	7/27/2021	WN226	7/26/2022	7/26/2022
WN207	8/18/2020	8/19/2020	WN217	8/24/2021	8/25/2021	WN227	8/23/2022	8/23/2022
WN208	9/1/2020	8/31/2020	WN218	9/7/2021	9/7/2021	WN228	9/6/2022	9/20/2022
WN209	10/20/2020	10/19/2020	WN219	10/26/2021	11/2/2021	WN229	10/25/2022	10/21/2022

Table 3. Routine measurements conducted at the three stations

Type of measurement	Depth	Parameter
Hydro profile	From near surface (approximately 0.5-1.5 m) to near bottom (3-5 m from bottom). Profiling at 0.5 m intervals	Surface PAR Temperature Salinity Dissolved oxygen Depth of sensor Chlorophyll fluorescence PAR
Water chemistry	Two depths: Near surface Near bottom	Nitrate + nitrite Ammonia Ortho-phosphate Silicate Total nitrogen Total phosphorus Extracted chlorophyll
Phytoplankton	Near surface	Enumeration + Identification
Zooplankton	Oblique net tow	Enumeration + Identification

3. RESULTS AND DISCUSSION

3.1 Hydrographic Data

Annual average water temperatures and salinities did not vary significantly during the three years (2020, 2021, and 2022) (Figure 2). Average surface temperature during this time period was nearly 13°C. Average bottom temperature was just over 8°C. These averages are approximately 1°C higher than the average surface and bottom temperatures during the previous three-year period, 2017-2019 (Costa et al. 2021). Average annual salinities were lowest in both the surface and bottom waters in 2020 and highest in both surface and bottom waters in 2022.

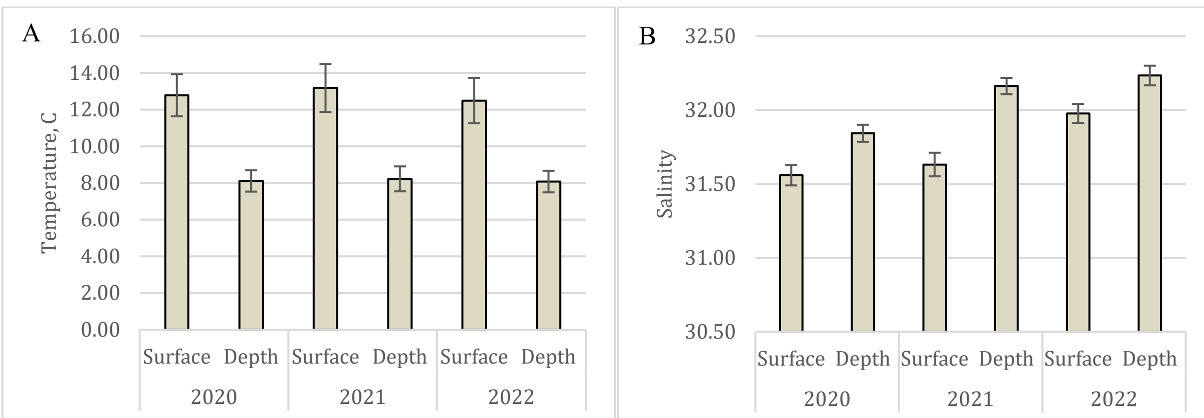

Figure 2. Average annual A) water temperature and B) salinity recorded in the surface and near bottom waters from 2020-2022

Although the annual average temperatures among the three years were not significantly different, 2021 experienced the highest surface temperatures, averaging over 20°C during July and August and the highest bottom temperatures, averaging over 13°C during October (Figure 3A). Unusually warm water temperatures were also observed in Massachusetts Bay during 2021 (Libby et al. 2022). Although annual average surface salinities were similar for 2020 and 2021, surface salinity during the summer months of 2021 was notably lower than 2020 (Figure 3B), likely due to the high amount of precipitation recorded in June, July and August (Figure 4) and the highest river flows in July, August, and September observed over the course of this 30-year monitoring program (Libby *et al.* 2022). 2022 however had lower precipitation and lower river flow (Figure 5) which is reflected in both the higher annual average surface salinity and the higher surface salinity recorded during eight of the nine surveys in 2022 compared to both 2020 and 2021.

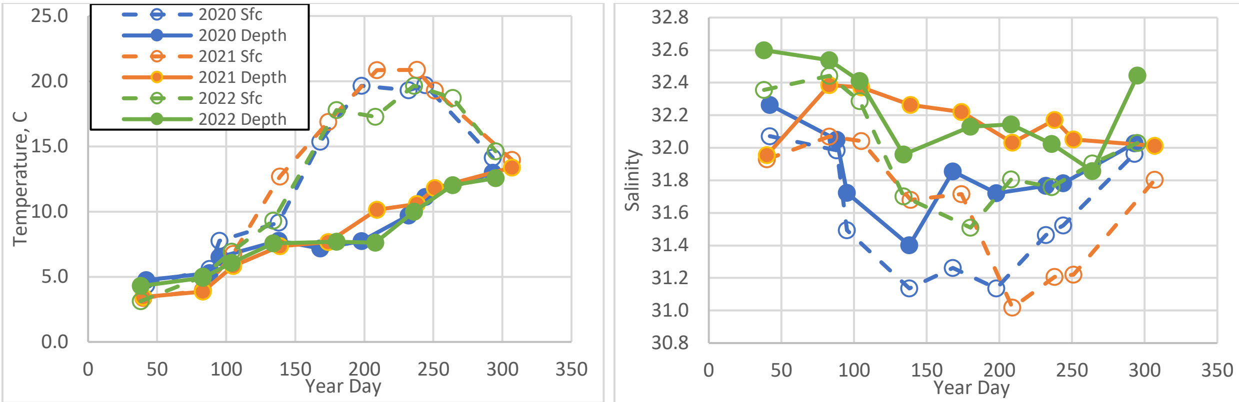

Figure 3. Average A) water temperatures and B) salinities for each survey recorded in the surface (dashed) and near bottom waters (solid) from 2020-2022.

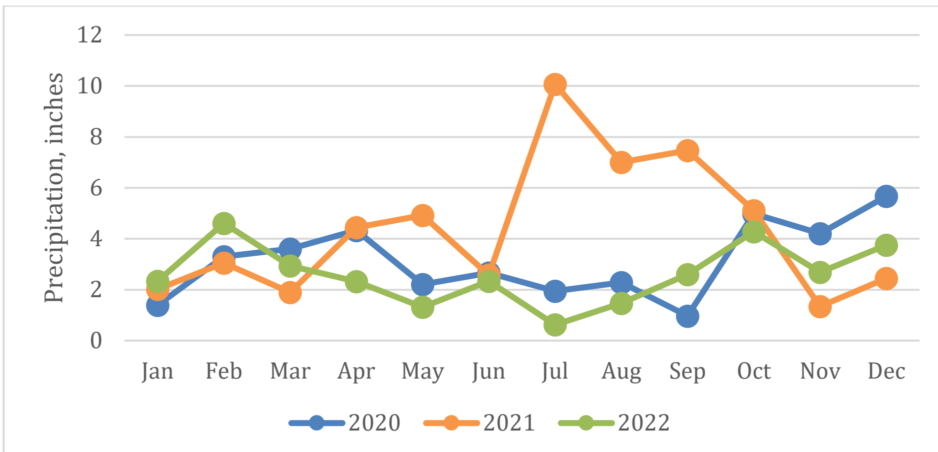

Figure 4. Sum of Boston Area precipitation by month during 2020-2022. Data from https://www.weather.gov/wrh/Climate

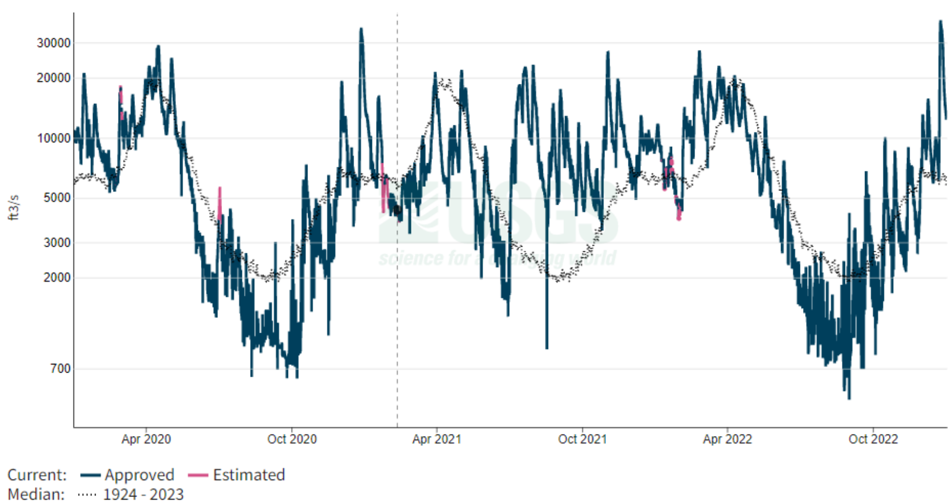

Figure 5. Streamflow of the Merrimack River, 2020 - 2022. Dotted line indicates median flow. Pink is estimated. Data from https://waterdata.usgs.gov/monitoring-location/01100000

During all three years stratification was greatest between days 170 to 270, with the exception of July 2022 at F01 when a significant wind event mixed the water column (Figure 6). The strongest stratification (bottom density – surface density) of the water column was recorded in 2021 at F29 and F01 during July and at F02 during August.

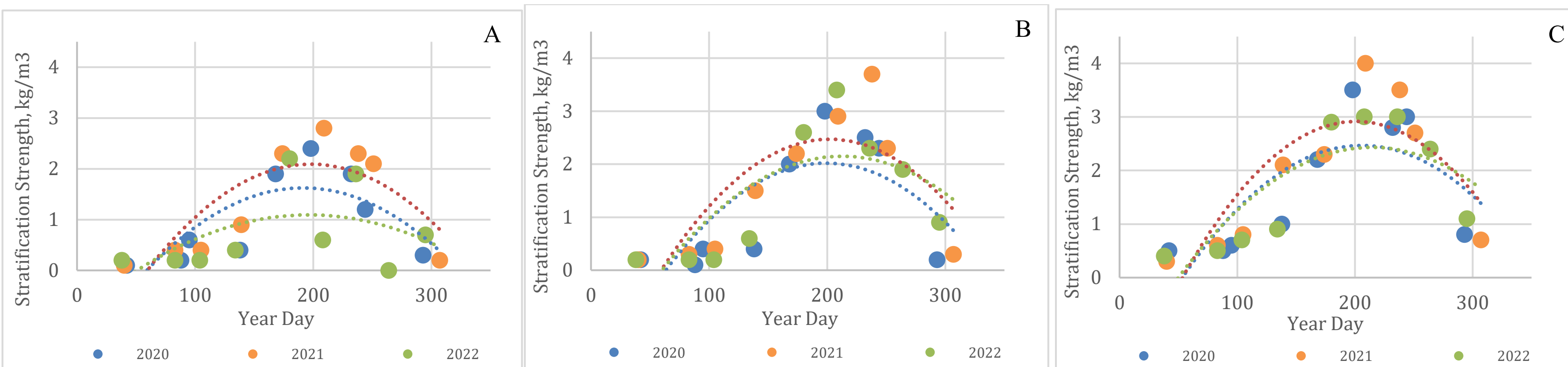

Figure 6. Average stratification strength (bottom density - surface density) for each survey at A) F01, B) F02, and C) F29 from 2020-2022

Surface dissolved oxygen (DO) concentrations followed expected seasonal patterns being highest during the winter and spring and lower during the summer and fall (Figure 7). Warmer waters hold less dissolved oxygen, so as the temperatures warmed, there was a coincident decline in dissolved oxygen. This was also apparent in the bottom waters but amplified by stratification. As the water column became more stratified, DO concentrations declined more rapidly than in the surface waters.

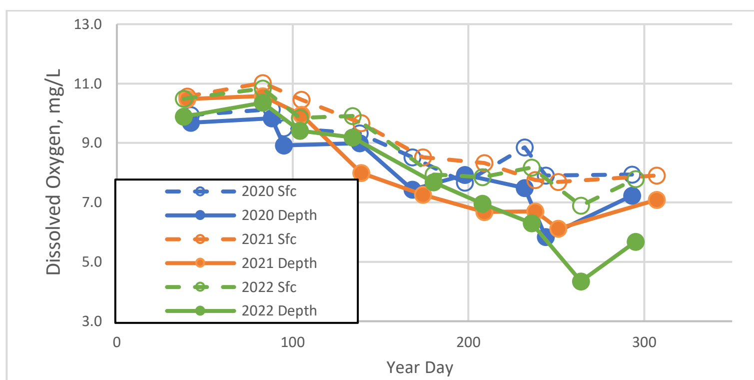

Figure 7. Average dissolved oxygen concentrations for each survey recorded in the surface and near bottom waters from 2020-2022.

DO concentrations in the bottom waters of the Bay have been shown to be determined by the strength and duration of stratification (Jiang *et al.* 2007). Lowest DO concentrations were typically seen when stratification strength was strongest in August and September (Figure 8).

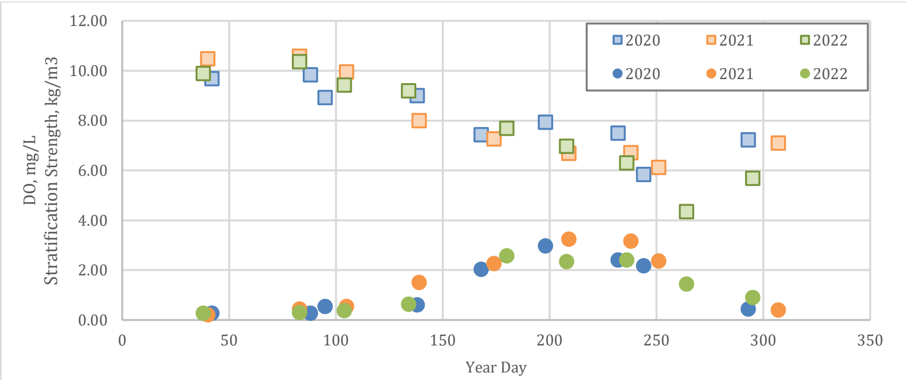

Figure 8. Comparison of stratification strength and near bottom dissolved oxygen levels, 2020-2022, averaged for the three stations. Squares = Dissolved Oxygen, Circles = Stratification.

The one anomaly to this was seen during the 2022 season at F02. Bottom dissolved oxygen levels were the lowest recorded since CCS started monitoring this station in 2011, falling just below 3 mg/L during the September survey. Although the water column was still stratified, stratification was weaker than the previous two surveys (Figure 9).

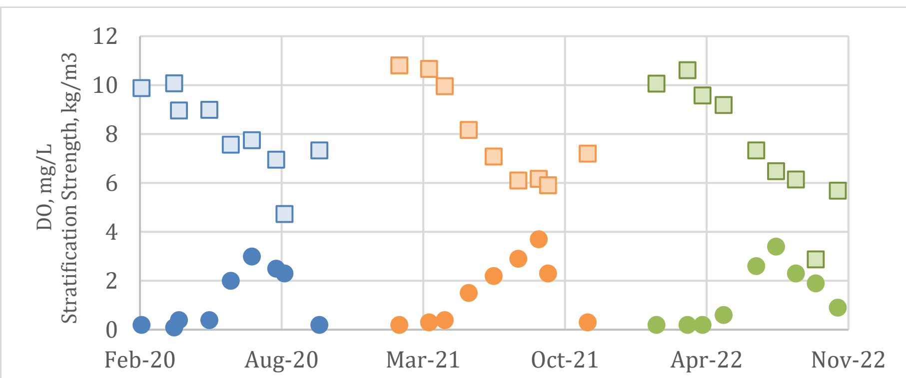

Figure 9. Comparison of stratification strength and near bottom dissolved oxygen levels at F02, 2020-2022. Squares = Dissolved Oxygen, Circles = Stratification.

The method used to determine stratification strength is based on the difference in density between the surface and bottom waters. This method does not however capture the gradient. For example, in July and August, the change in density occurs gradually over a much larger part of the water column whereas in September, the change is more rapid and over a small portion of the water column, compressing the bottom waters to a thinner layer (Figure 10). This deepening and intensification of the thermocline could contribute to lower DO concentrations by limiting vertical mixing and concentrating biological oxygen demand in this thinner layer (Scully et al. 2022).

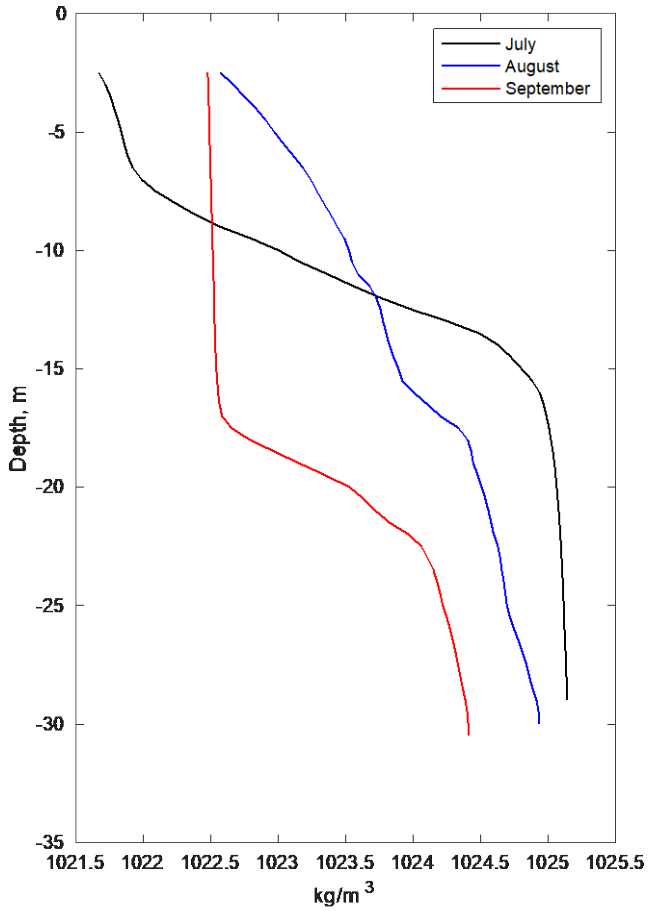

Figure 10. Density profiles at F02 during July, August, and September of 2022

3.2 Water Chemistry

3.2.1 Nutrient Concentrations

In the surface waters, average concentrations of dissolved inorganic nutrients were highest in 2020. Dissolved inorganic nitrogen (DIN) and silicate in the surface waters declined steadily over the course of these 3 years with lowest concentrations seen in 2022 (Figures 11A and C). Ortho-phosphate was variable (Figure 11B). In the bottom waters, annual average DIN and ortho-phosphate were lowest in 2020 and increased steadily over the course of these 3 years with highest concentrations seen in 2022 Figure 11A, B). Silicate concentrations remained fairly constant (Figure 11C).

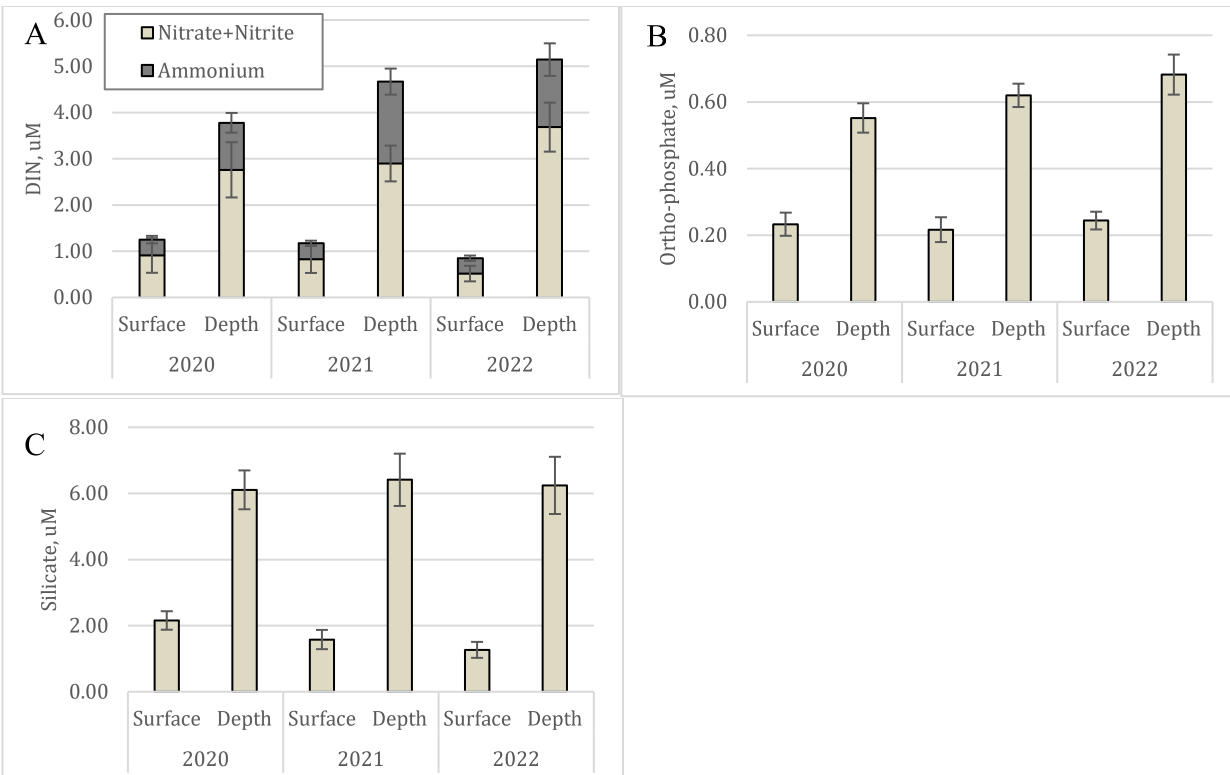

Figure 11. Average annual A) dissolved inorganic nitrogen (DIN), B) ortho-phosphate and C) silicate concentrations measured in the surface and near bottom waters from 2020-2022. Note varying scale of Y-axis.

Overall nutrient concentrations from 2020-2022 were lower than the long-term average. The MWRA has been monitoring these three stations since 1994 (F01 and F02 since 1992). The long-term average DIN concentrations (1994-2022) were 2.07 µM and 5.48 µM for surface and bottom, respectively. The 2020-2022 surface averages continued to fall below the average of 2.07 µM for the full period, continuing a declining trend observed since 2010 (Figure 12). Although there was an increase in bottom values of DIN during this 3-year period, the concentrations were also below the long-term average (5.48 µM) during all three years.

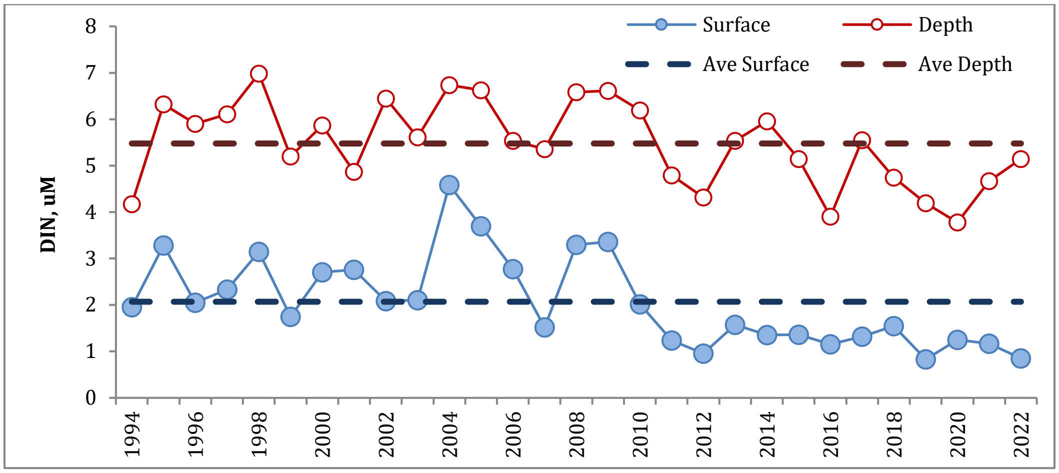

Figure 12. Average annual DIN concentrations in surface and near bottom waters at F01, F02 and F29 from 1994-2022. Long-term averages are indicated with the dashed line.

The 2020-2022 surface and bottom ortho-phosphate concentrations values fell below or at their long-term averages of 0.37 µM and 0.70 µM for the 1994 -2022 period (Figure 13). Similarly, for silicate concentrations, although surface values were close to the long term averages, both the surface and bottom values during 2020-2022 fell below the long-term averages of 2.64 µM and 6.47 µM for surface and bottom respectively (Figure 14).

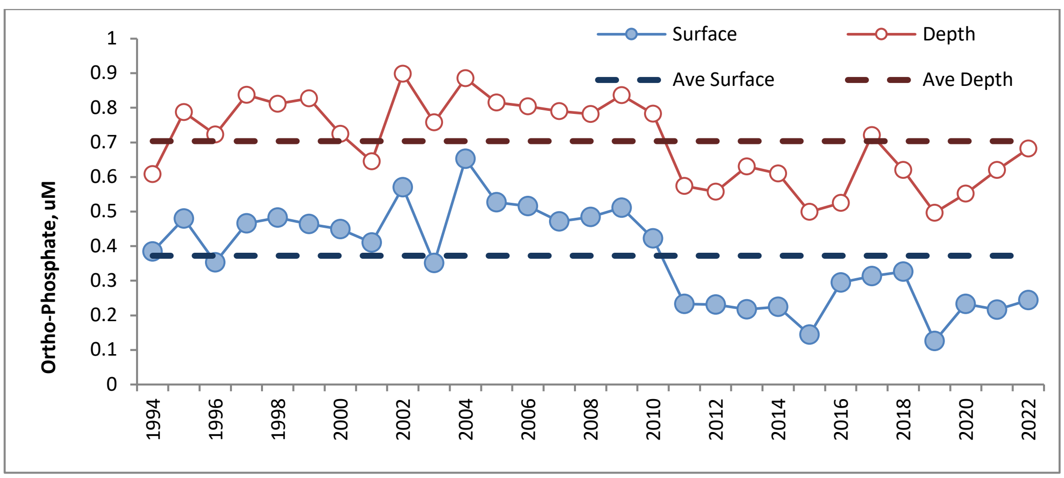

Figure 13. Average annual ortho-phosphate concentrations in surface and near bottom waters at the three MWRA stations from 1994-2022. Long-term averages are indicated with the dashed line.

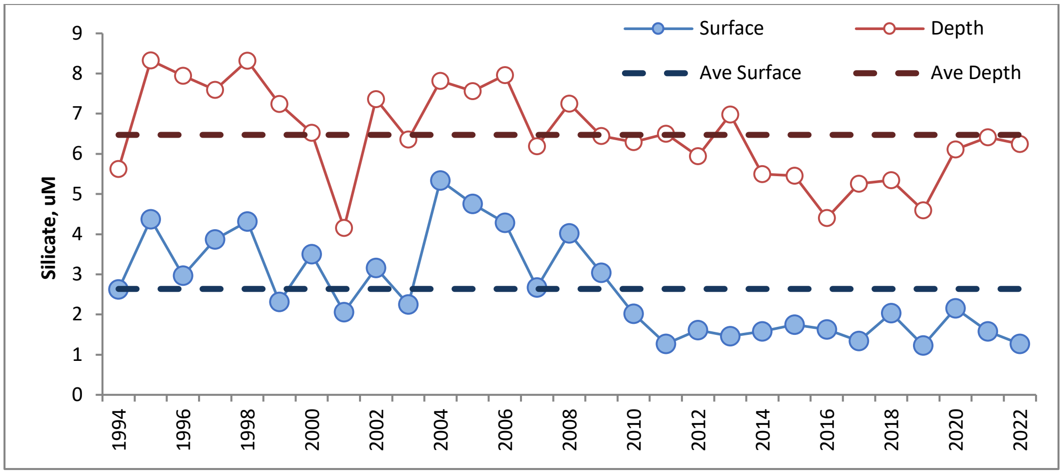

Figure 14. Average annual silicate concentrations in surface and near bottom waters at the three MWRA stations from 1994-2022. Long-term averages are indicated with the dashed line.

3.2.2 Nutrient Concentration Ratios

The ratio of dissolved inorganic nitrogen to phosphorus to silicate (DIN:DIP:DISi) provides information about which nutrient is potentially limiting production. This ratio, known as the Redfield ratio, is 16:1:1.07. For 2020-2022, the average DIN:DIP was less than 16:1 in both the surface and near bottom waters, indicating that the Bay's pelagic primary production was N relative to P limited and therefore especially sensitive to increased N inputs (Figure 15).

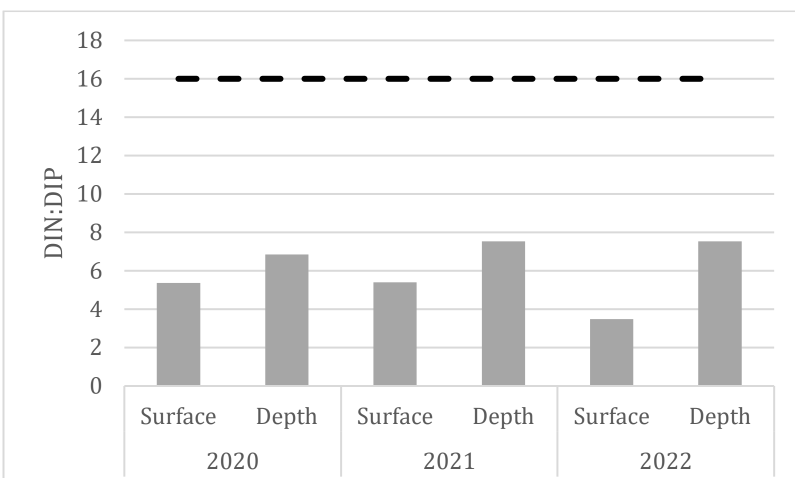

Figure 15. Average ratio of DIN to DIP for surface and near bottom waters from 2020-2022. The dashed line indicates the Redfield Ratio.

Since monitoring of these three stations began in 1994 the average annual ratio of DIN to DIP has always been well below (and one half or less of) the Redfield Ratio of 16:1 for both surface and bottom waters (Figure 16).

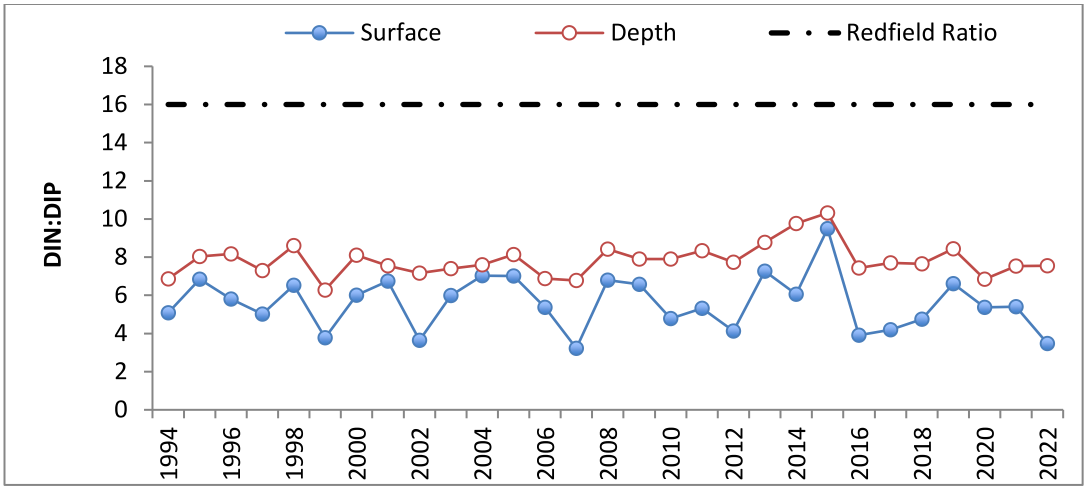

Figure 16. Average annual ratio of DIN:DIP at the three MWRA stations since 1994. The dashed line indicates the Redfield Ratio.

The ratio of DIN:DISi is particularly important for diatoms since they require silicate to form their external shell. If this ratio falls below 1.07, diatom productivity is N relative to Si limited. For all three years between 2020-2022, and especially at the surface, the annual average DIN:DISi ratios were less than Redfield (Figure 17) indicating that diatom production is not limited by Si availability.

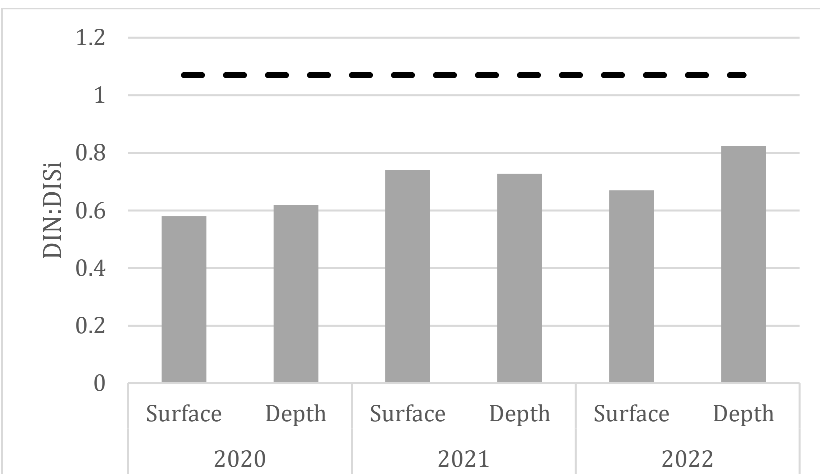

Figure 17. Average ratio of DIN to DISi for surface and near bottom waters from 2020-2022. The dashed line indicates the Redfield Ratio.

The longer time series of average annual DIN to DISi ratios shows that with only three exceptions in the surface waters (2001, 2009, and 2013) and two exceptions at depth (2001 and 2014), DIN:DISi ratios were less than 1.07:1 (Figure 18).

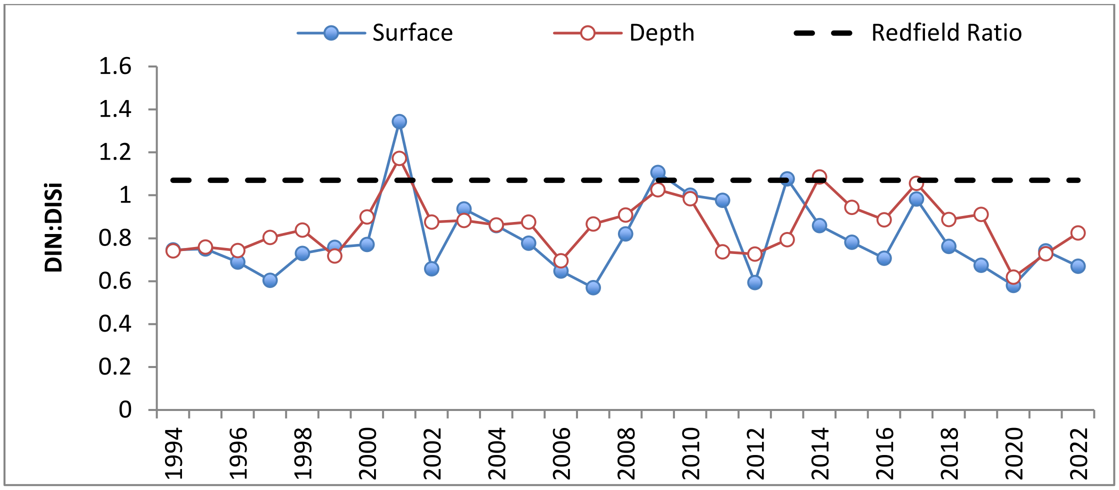

Figure 18. Average annual ratio of DIN:DISi at the three MWRA stations since 1994. The dashed line indicates the Redfield Ratio.

Seasonal patterns of dissolved inorganic nutrient concentrations followed typical patterns (Figure 19). DIN, ortho-phosphate, and silicate were highest in the surface waters during the winter when the water column was well-mixed, decreased during the spring and summer as the water column stratified and primary production increased, and increased again in the fall as the water column became mixed, bringing nutrient rich bottom water to the surface. Bottom nutrient concentrations were high in the winter but declined through the spring as primary production increased. As the water column became stratified in the summer, sequestering nutrients below the thermocline and therefore inaccessible to phytoplankton, nutrient concentrations at depth increased. In October, fall mixing with nutrient-poor surface waters caused concentrations to decline at depth.

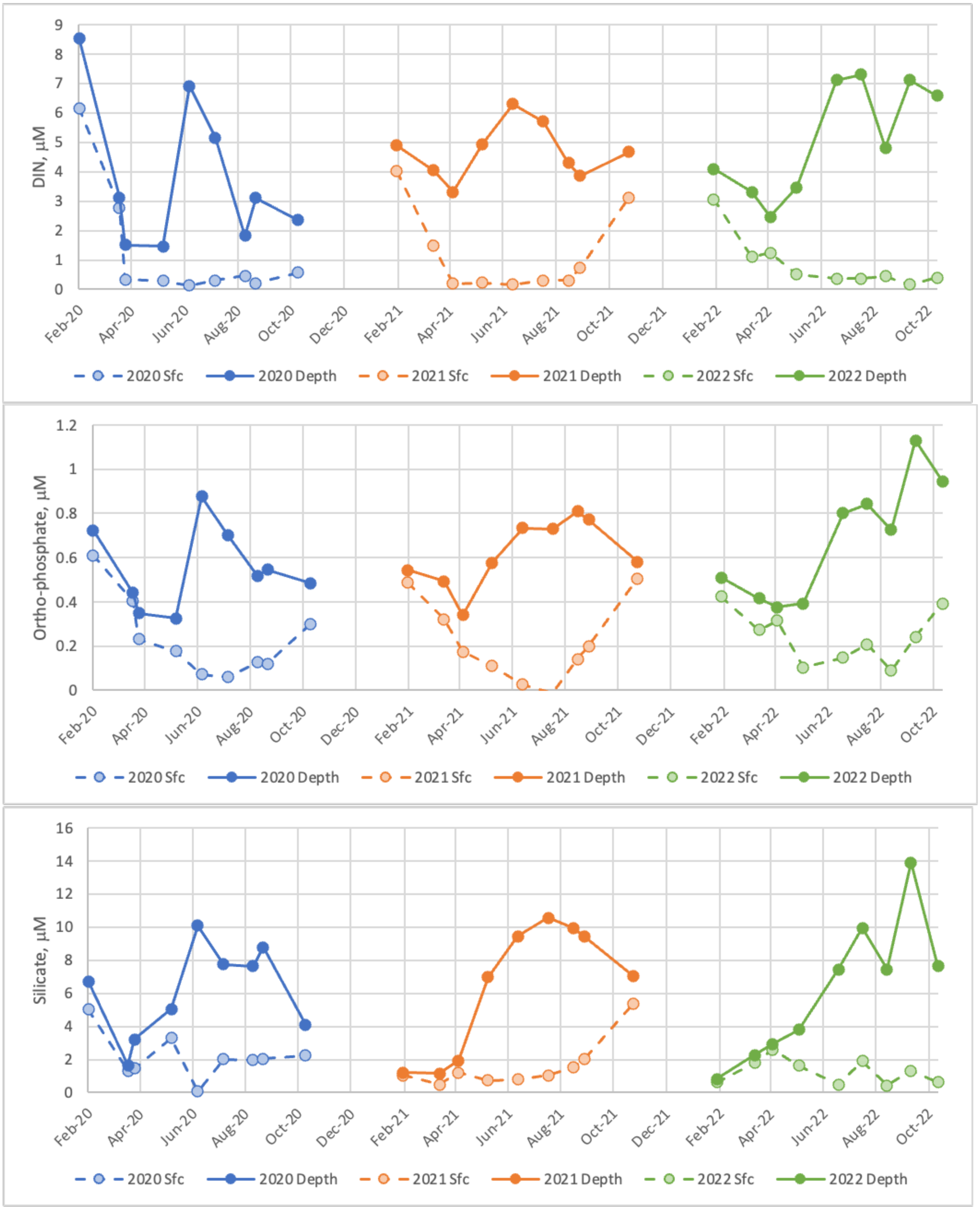

Figure 19. Average dissolved inorganic nutrient concentrations measured during each survey, 2020-2022: A) dissolved inorganic nitrogen (nitrate, nitrite, and ammonium), B) ortho-phosphate, and C) silicate

3.2.3 Phytoplankton Biomass (Chlorophyll a)

Chlorophyll *a* (chl-*a*) concentrations averaged for the three stations were fairly consistent for surface and depth during each year averaging ~2-3 µg/L with the exception of bottom concentrations in 2020 (Figure 20).

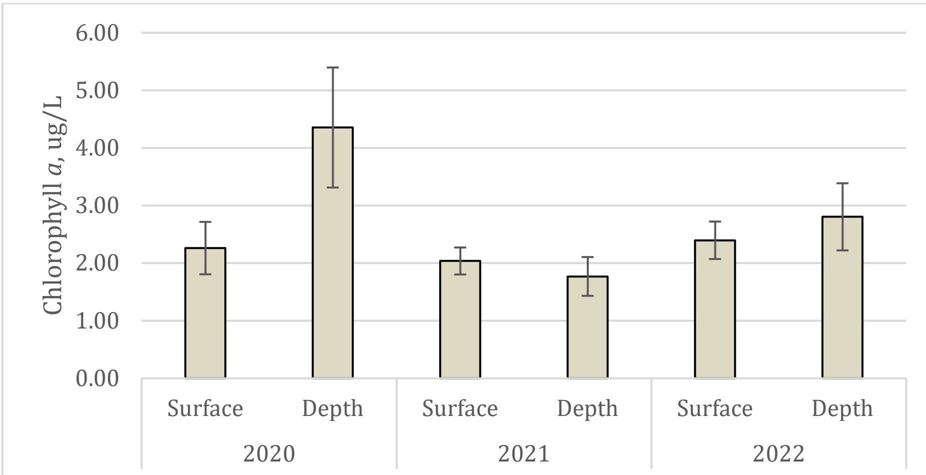

Figure 20. Average annual concentrations of chlorophyll *a* measured in the surface and near bottom waters from 2020-2022

Figure 21 shows average chl-*a* concentrations at surface and depth for the three stations combined during each survey. Increased concentrations at the surface occurred each spring and fall, indicative of spring and fall blooms. The large peak at depth during September 2020 was driven by high concentrations at F01 and F02 (~20 µg/L) and was the cause of the high annual average at depth for 2020. This was similar to what was seen in 2019 (Costa *et al*. 2021). A coincident sample was taken from depth at F01 for phytoplankton identification. The cell density of this sample was greater than 1.7 million cells/L, 45% of which were identified as *Karenia mikimotoi*.

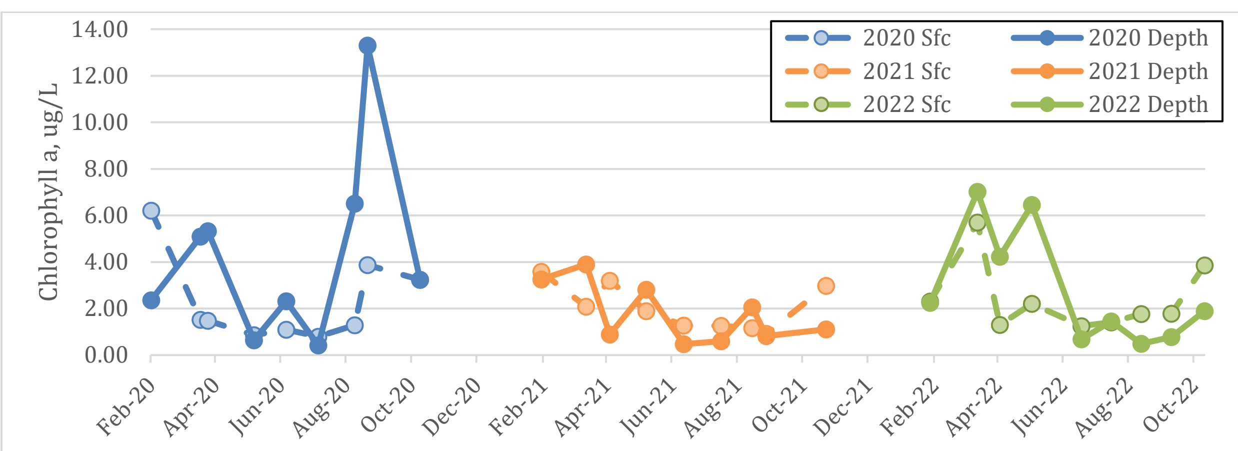

Figure 21. Average surface chl-a concentrations measured during each survey from 2020-2022

3.3 Phytoplankton and Zooplankton

3.3.1 Phytoplankton

Phytoplankton samples are only collected from the surface waters. For the two CCB stations and one SBNMS station combined, average annual phytoplankton abundance was lowest in 2020 and increased only slightly each year over this 3-year period (Figure 22).

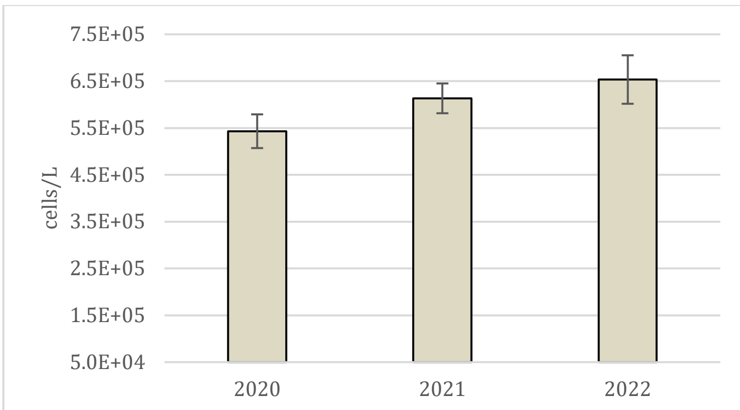

Figure 22. Average annual phytoplankton abundance, 2020-2021

In Cape Cod Bay, the winter/spring bloom typically occurs during February or March and is usually driven by an increase in diatoms in response to increasing light intensities and water temperatures. In 2020 and 2021, there was no evidence of a bloom, suggesting that the timing of the surveys did not capture the bloom. In 2022 there was a peak in phytoplankton indicative of a spring bloom (Figure 23).

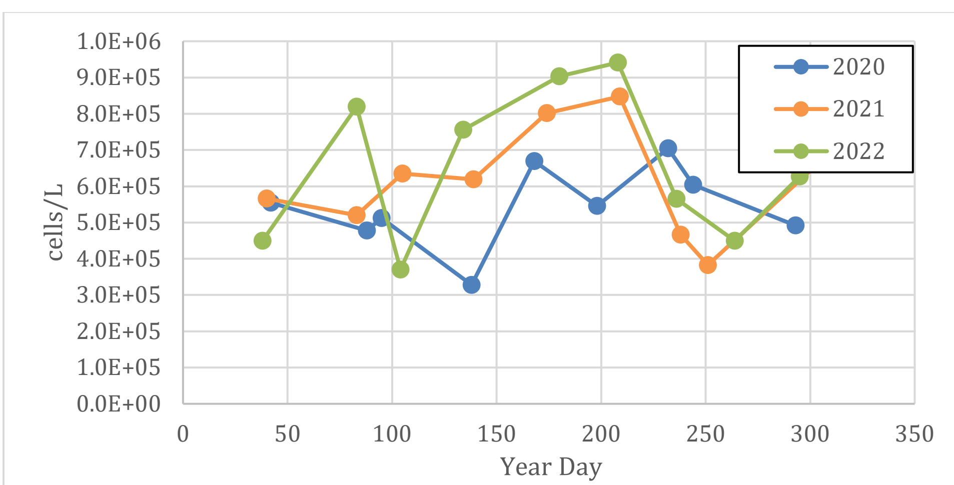

Figure 23. Average phytoplankton abundances during each survey, 2020-2022.

The composition of the phytoplankton community during the spring varied from year to year (Table 4). During the two years when the bloom was not observed, diatoms were scarce. In CCB (F01 and F02) there were virtually no diatoms; at F29, *Guinardia* comprised only about 10% of the abundance in 2020. During the winter/spring of 2021, *Thalassiosira* and *Guinardia* appeared in higher numbers than seen in 2020, but still only comprised <25% of the abundance of phytoplankton cells. In 2022, when there was more of a spring bloom than observed in the previous two years, there was an increase in the presence of diatoms during both February and March. *Skeletonema* dominated in February and persisted into March at F01 but was replaced by *Guinardia* at F02 and F29 making up 54% and 44% respectively of the phytoplankton counts.

Table 4. Dominant genera of centric diatoms during the winter/spring bloom period

Month	Station	Centric Diatoms	Percent of Total Cells	Dominant Genera
2020				
Feb	F01	18,974	4%	*Guinardia*
Feb	F02	90,588	14%	
Feb	F29	83,301	16%	
Mar	F01	9,915	2%	
Mar	F02	67,184	12%	
Mar	F29	15,220	4%	
2021				
Feb	F01	33,714	7%	*Guinardia & Thalassiosira*
Feb	F02	158,703	24%	
Feb	F29	32,452	6%	
Mar	F01	5,767	1%	
Mar	F02	6,462	1%	
Mar	F29	80,381	14%	
2022				
Feb	F01	159968	24%	*Skeletonema & Guinardia*
Feb	F02	46680	15%	
Feb	F29	124325	33%	
Mar	F01	197941	24%	
Mar	F02	468896	54%	
Mar	F29	326828	44%	

Phaeocystis did appear but only in low to moderate numbers of cells during this 3-year period. Overall phytoplankton abundances were highest each year during the summer (Jun-Aug) due primarily to the high numbers of microflagellates and centric diatoms (*Leptocylindrus danicus* in 2020 and 2021, *Dactyliosolen fragilissimus* in 2022) during these months (Figure 23).

Of note is the occurrence of *Karenia mikimotoi*. This species was first identified in surface samples from CCB in low numbers in the late summer/early fall of 2017. It has appeared each year since then (Figure 24). From 2017-2020, both abundances and duration increased with a maximum duration of 8 of the 9 months samples were collected and a maximum abundance of over 138,000 cells/L in 2020 at F01. In 2021, although *Karenia* was seen during 8 of the 9 surveys, abundances were never high. In 2022, *Karenia* was only recorded during 4 of the 9 surveys and abundances remained low.

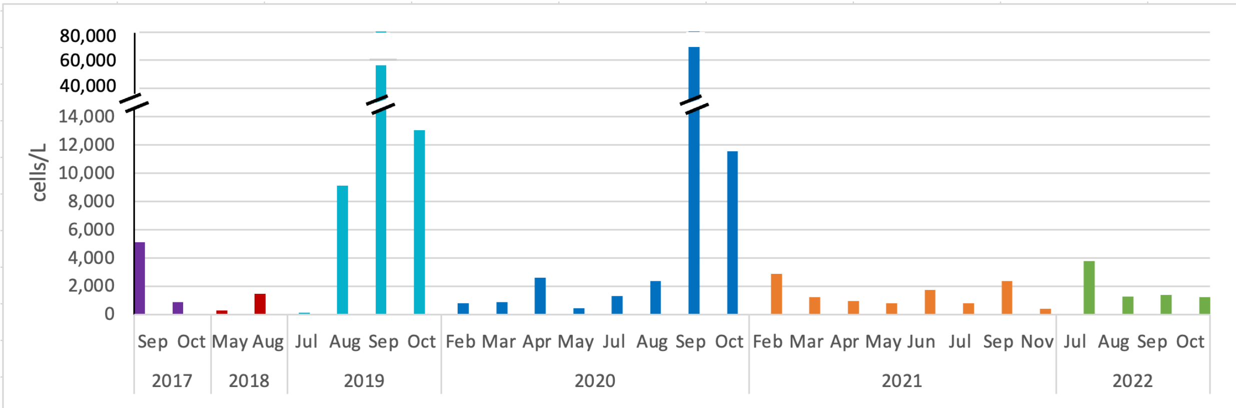

Figure 24. Average *Karenia mikimotoi* abundances recorded in surface counts, 2017-2022 in CCB. Note: September 2019 and 2020 abundances are higher than the maximum range.

3.3.2 Zooplankton

Annual average total zooplankton abundances in CCB and SBNMS was relatively high in 2020 compared to previous years (Costa et al. 2021) (Figure 25). During 2020 the survey in July, a high abundance of urchin larvae was recorded in the samples (~30,000 organisms/m^3 at F01) which skewed the averages for the year. In 2021 and 2022 zooplankton abundance dropped to levels consistent with the last several years.

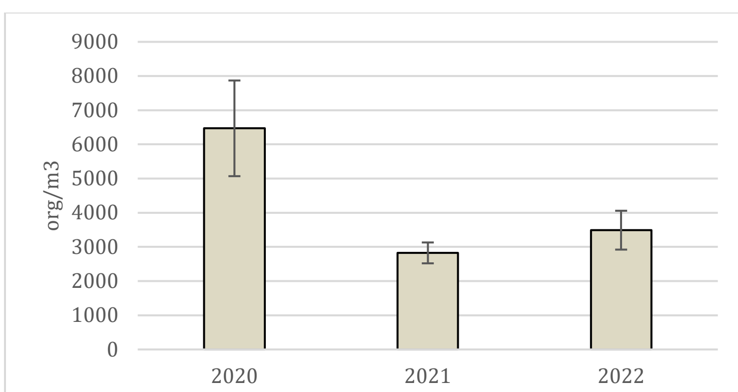

Figure 25. Average annual zooplankton abundance, 2020-2022. Acantharians are not included (see text below).

Excluding the peak in July of 2020 attributed to urchin larvae, highest abundances of zooplankton occurred during the winter (Feb) in 2020 and 2022 and the spring (May) in 2021 (Figure 26). Calanoid copepods were most abundant during these surveys.

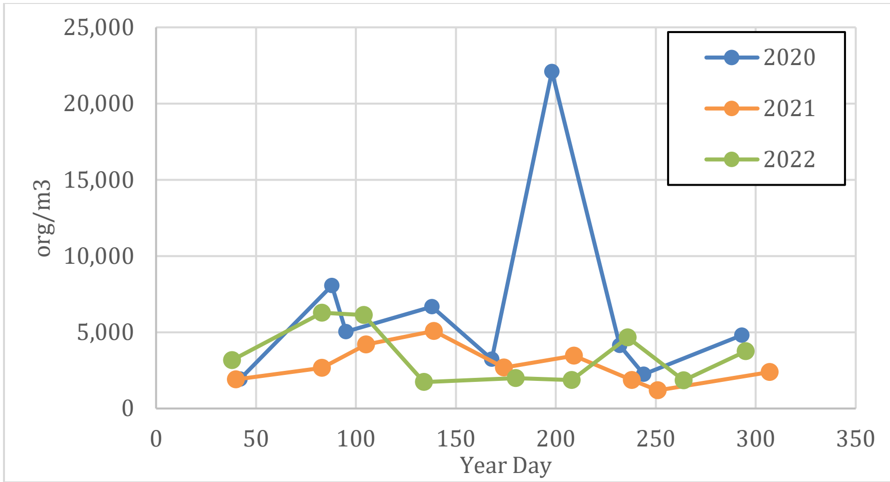

Figure 26. Average zooplankton abundance during each survey, 2020-2022, excluding Acantharians

Acantharians were not included in the annual averages or survey averages (Figures 25 & 26). Acantharians are a group of radiolarian protozoa which are classified as heterotrophic marine microplankton. Although they have likely been overlooked in previous years because they were not abundant in the samples, in 2021 and 2022, numbers of acantharians in the summer and fall dominated the zooplankton, peaking at over 85,000 organisms/m^3 in July 2021 (Figure 27). According to Libby, *et al.* (2022) high abundances of radiolarians were also seen in their zooplankton tows during July and November of 2021, suggesting an intrusion of water from offshore. They attributed this to the frequent northeast wind events in July and the storm in November which would have transported offshore waters into the bay.

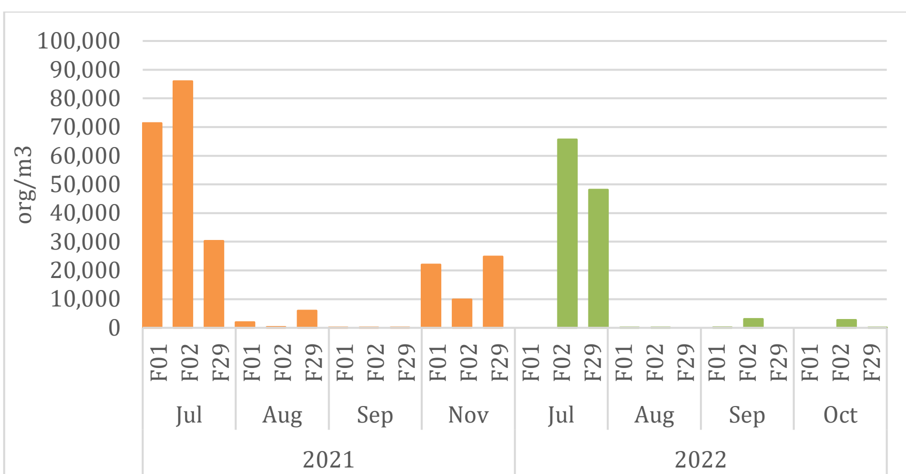

Figure 27. Abundance of Acantharians documented in 2021 and 2022.

3.3.2.1 Right Whales and Zooplankton

In Cape Cod Bay, zooplankton counts during the winter and spring months (Jan-May) are of particular interest. During this time, the Bay is the only known feeding ground for the critically endangered North Atlantic right whale. Separate from the MWRA monitoring program, CCS conducts weekly boat-based surveys to document the zooplankton resource and aerial surveys to locate, document and identify the whales. Zooplankton samples are taken in the vicinity of right whales using a 333 µm mesh net. This has been done routinely since 2000. Over the course of these 23 years, the long-term average zooplankton density was approximately 8,000 organisms/m^3. Samples have typically been dominated by calanoid copepods including *Centropages* spp., *Pseudocalanus* spp., and *Calanus finmarchicus*. Average zooplankton abundances collected within 100 m of feeding right whales during 2020 and 2021 fell below the long-term average (Figure 28). In 2022, however, average zooplankton abundance was the highest seen since 2014.

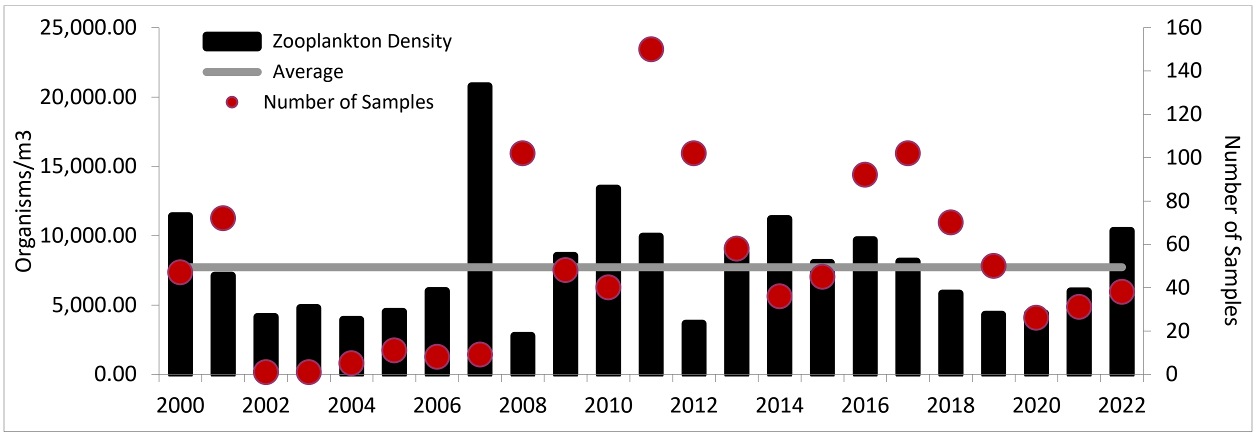

Figure 28. Average zooplankton density and number of samples taken in the vicinity of right whales. The gray line indicates the long-term average zooplankton density of these samples, 2000-2022.

Right whale use of the bay was highly variable from year to year. Since 2007, there has been an increase both in individuals identified and in the sightings per unit effort compared to the previous 9 years (Figure 29).

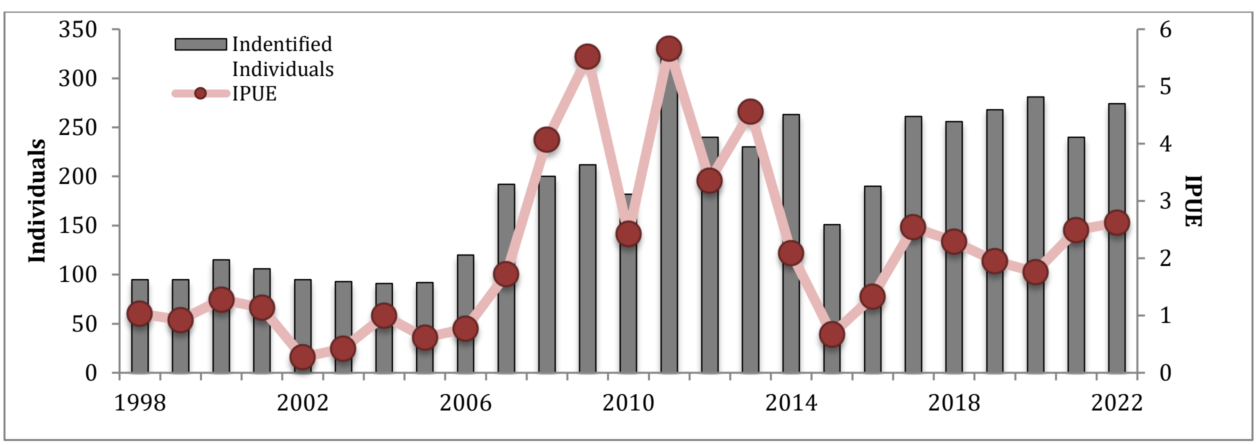

Figure 29. The number of right whales identified in Cape Cod Bay each year. The red line indicates the number of individuals per unit effort (IPUE) sighted during the aerial surveys.

The number of sightings in 2020 was higher than any year since aerial surveillance of Cape Cod Bay began, excluding 2011, and accounted for 75% of the estimated population. This was despite a 16-day gap of survey effort (March 19-April 4) due to Covid-19. This high number of sightings did not coincide with what would be expected based on the zooplankton data which indicated lower than average densities in 2020 sampled in the vicinity of right whales compared with other years.

In 2021, although the number of identified individuals was the lowest of this 3-year period, residency time was the longest with whales occupying the bay 147 days compared to 110 in 2020 and 127 in 2022 (Table 5). Zooplankton abundance was up slightly from that of 2020, but still fell well below the average abundance documented in Cape Cod Bay around right whales.

In 2022, individual sightings were the third highest observed since the program began in 1998 falling just below the number sighted in 2020. Zooplankton abundance was higher than the long-term average recorded over the last 23 years. Also, the highest number of sightings in one day of 94 right whales – almost one third of the entire population - occurred in 2022. In previous year, the peak in sightings typically occurs in mid-April. During this 3-year period, peak sightings were all much earlier with the peak in 2022 occurring in February.

Table 5. Right whale sightings and residency time, 2020-2022.

Season	First Sighting	Last Sighting	Residency (days)	Individuals	Population Estimate	Calves	Peak Sightings	
2020	1/6/20	4/25/20	110	281	374	10	53	mid-Mar*
2021	12/11/20	5/7/21	147	240	348	19	85	3/21/21
2022	12/29/21	5/5/22	127	274	340	15	94	2/26/22

*May have missed actual peak due to Covid-19

The distribution of right whale sightings was fairly evenly distributed throughout Cape Cod Bay, especially during 2021 and 2022 (Figure 30). Previous years have seen sightings concentrated more often in the eastern part of the bay (similar to 2020) and sometimes along the western part of the bay (Costa et al 2021).

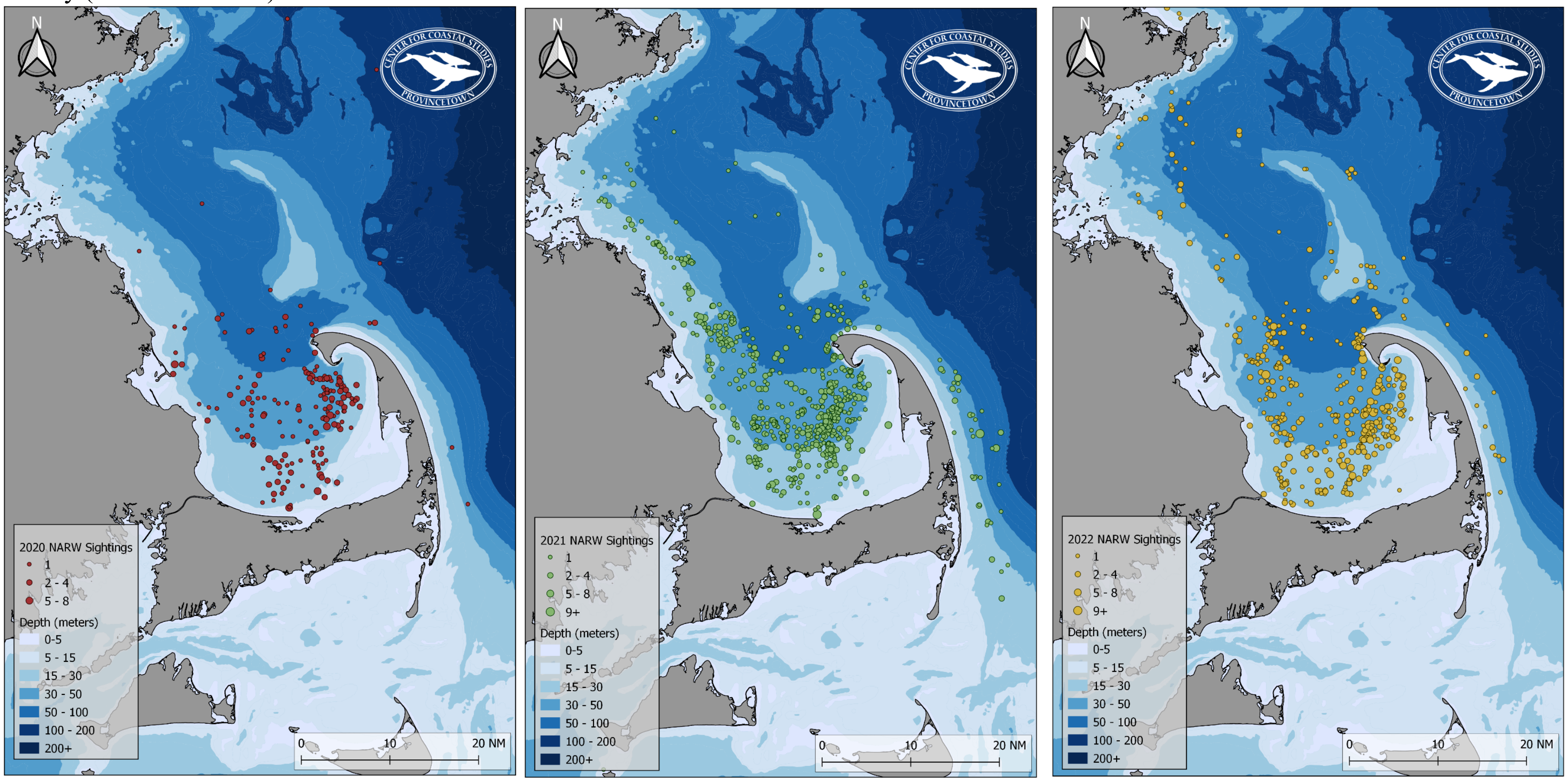

Figure 30. Distribution of right whale sightings each year, 2020-2022. CCS Image, NOAA Permit 14603 and 14603-1

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