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Rationale and Research Questions

Harmful algal blooms (HABs) are characterized by rapid algae population growth coupled with toxin production in an aquatic system (NOAA, 2016). In recent history HABs have been shown to be increasing in prevalence with documented observations throughout the U.S. and the world (U.S. National Office for HABs, n.d.). This increased prevalence of HABs poses a threat to both public and ecosystem health (U.S. EPA, 2022a). Generally, HABs are associated with an influx of environmental nutrients into an aquatic system; however, other regional or lake-specific variables such as temperature, physical chemical properties, and lake structure can influence the development of HABs (CDC, 2022). Although HABs have been largely stated to have increased through time, many of these variables are challenging to generalize across water bodies due to the complexity of algal bloom formation. It is for this reason that this report will focus on HAB development in one water body: Lake Erie.

Lake Erie has been affected by seasonal HABs since the 1990s (NSF, 2019). Lake Erie is adjacent to multiple metropolitan areas with populations that exceed 50,000 people and provides drinking water for 12 million people (U.S. EPA, 2022b). In 2015 Lake Erie had a bloom which covered over 300 square miles, thus making it one of the largest algal blooms documented in recent history (LEF, n.d.). Algae and toxin production has public health implications for surrounding populations as exposure can occur through recreation and consumption of contaminated drinking water (Dierkes, 2014; U.S. EPA, 2022b). Algal blooms can also create anoxic conditions when algae undergo decomposition in the environment which also influences ecosystem health (CDC, 2022). Due to the historical and current public health and ecosystem prevalence, data collection efforts have been implemented within Lake Erie to aid with forecasting future bloom severity. These data in the western basin are evaluated in this report.

Lake Erie is the shallowest of the great lakes with an average depth of 19 meters (m); the western portion, which comprises approximately 20% of the lake, has an average depth of 7.4 m and a maximum depth of 19 m (U.S. EPA, 2022b). Western Lake Erie is expected to undergo stratification for a short period of time during the summer months, leading to a warmer surface layer (epilimnion) and cooler bottom layer (hypolimnion; U.S. EPA, 2022b). Nutrient inputs come from a variety of sources which include wastewater treatment plants and agriculture which can influence algal bloom production (Dean, 2022). Microcystis is the most common species and microcystin, a potent hepatotoxin, is the most common toxin documented in HABs in Lake Erie. Considering the characteristics of Western Lake Erie, this report evaluates the following questions:

What are the drivers of harmful algal blooms in western Lake Erie?

1. How does Microcystis and microcystin concentration change over time?
2. Which variables (i.e., temperature, nitrate/nitrite, and/or phosphorus) contribute to microcystin production, Microcystis population growth, and dissolved oxygen?
3. Are there differences between toxin, chlorophyll a, or dissolved oxygen concentration at different lake depths?

Dataset Information

The National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory (NOAA GLERL) is a federal research laboratory designed to monitor and research the ecology and hydrology of the Great Lakes Region. The NOAA GLERL provides data critical to studying the presence and harmful impacts of algal blooms in the great lakes region.

The NOAA GLERL studies the movement, size, and concentration of toxins and nutrients typically associated with HABs, such as microcystin, nitrogen, phycocyanin, and chlorophyll. They also measure other factors that impact HABs, such as temperature and Dissolved oxygen (DO) concentrations. The lab's primary goal is to characterize the growth and abundance of microcystin concentrations and how their presence affects the toxicity of the lake.

The data from Western Lake Erie comes from nine sites sampled weekly, four of which have buoys collecting data continuously at 15-minute intervals. Only some sampled areas gather data on the same parameters, resulting in occasional missing data.

The sourced data set contains information on parameters ranging from 2012 - 2018 and a final data set that monitors the toxin and nutrient concentration from 2022. The variables we will analyze are displayed below with their units of measurement.

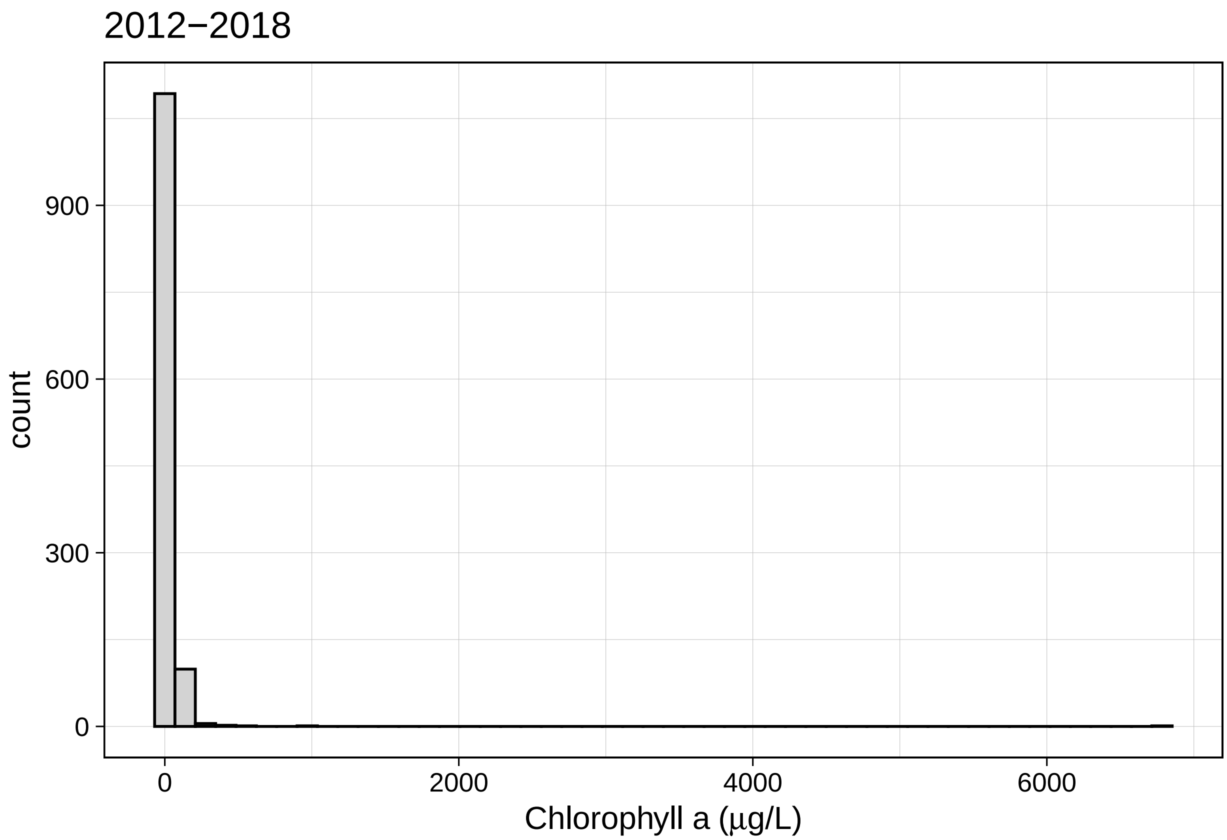
Table ?. Variables of interest and associated units

Variables of Interest

	Unit
Dissolved Oxygen	milligrams/Liter
Temperature	Celsius
Dissolved Microcystin	micrograms/Liter
Chlorophyll a	micrograms/Liter
Nitrate + Nitrite	milligrams of Nitrogen/Liter
Total Dissolved Phosphorus	micrograms of Phosphorus/Liter

Exploratory Analysis

We created histograms to illustrate the distribution of our variables of interest. Chlorophyll a values from 2012-2018 are largely concentrated below 100 $\mu g/L$ (Fig. 1). We discovered an outlier from August 2015, when chlorophyll a was measured at 6784 μg/L. [sentence about how it was a historic algal bloom year] We removed this outlier in the second histogram to better display the distribution of data.



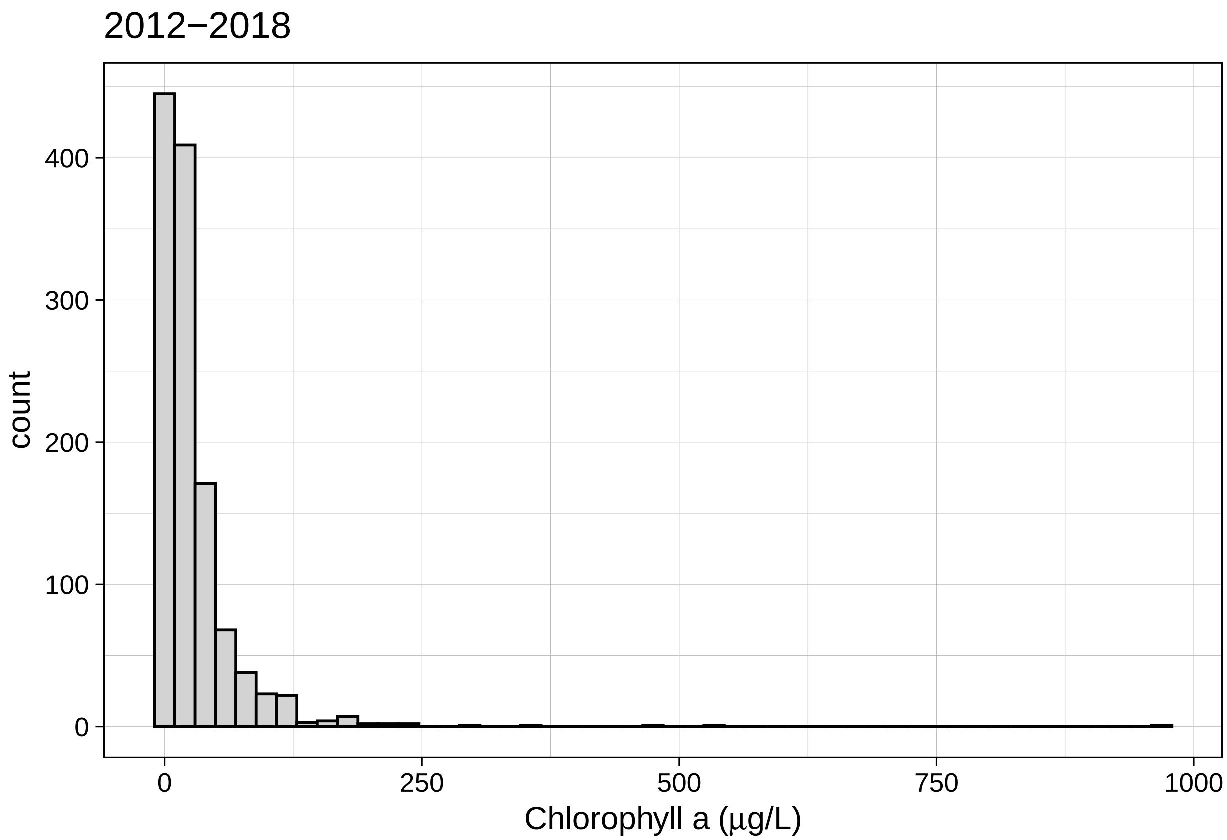


Figure 1. Chlorophyll a distribution from 2012-2018. Bottom figure excludes 6784 μg/L$ outlier from August, 2015.

Similarly, chlorophyll a measurements from 2022 are clustered below 100 $\mu g/L$, with few observations between 150 and 272 $\mu g/L$ (Fig. 2).

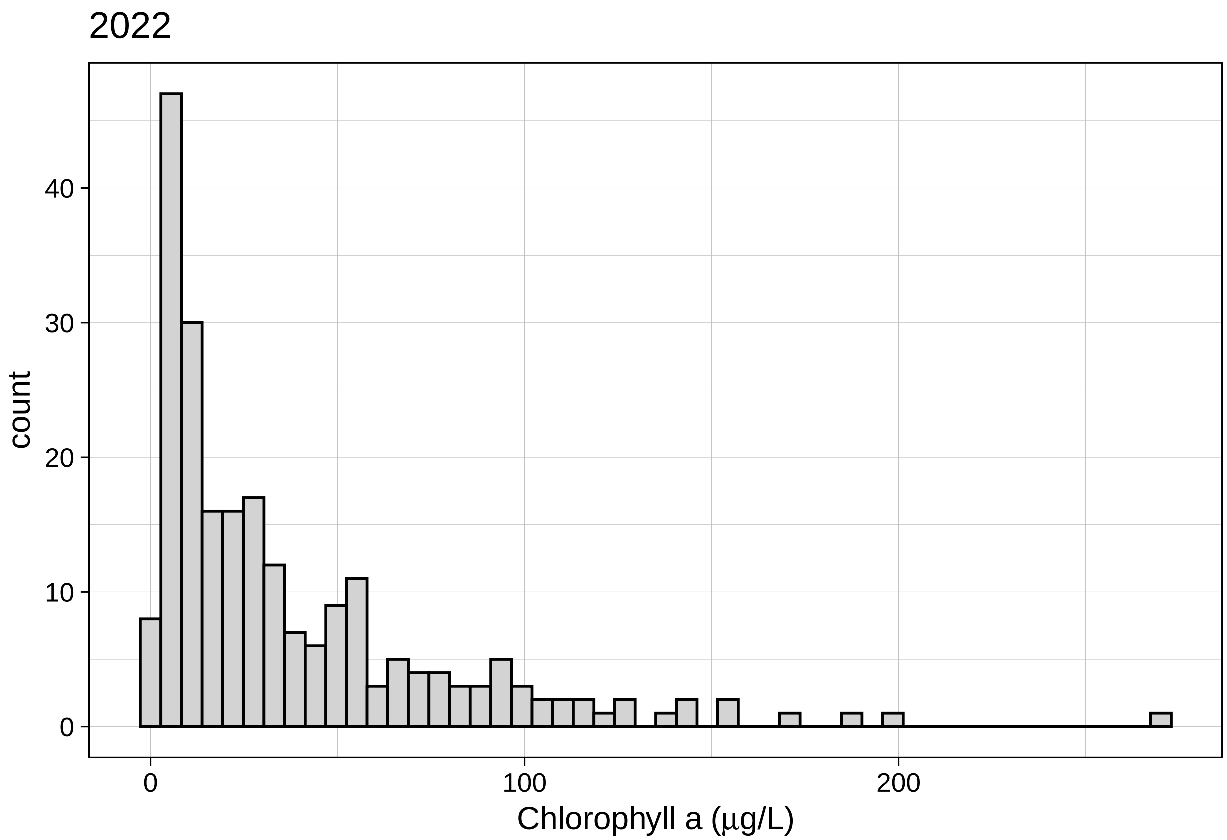
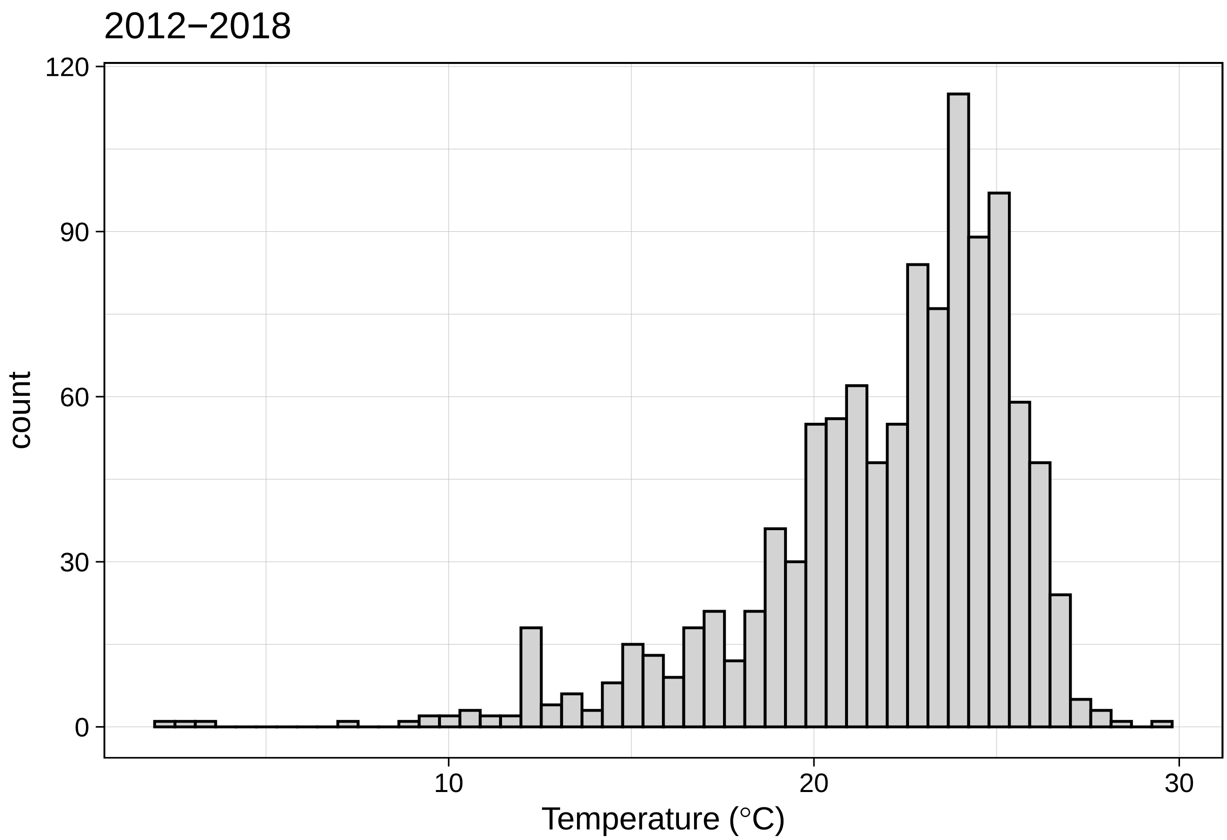


Figure 2. Chlorophyll a distribution in 2022.

Temperature measurements in both the 2012-2018 and 2022 datasets predominantly fall between 20 and 25 degrees Celsius (Fig. 3).


2012−2018
120
90
60
30
0
count
10
20
30
Temperature (°C)

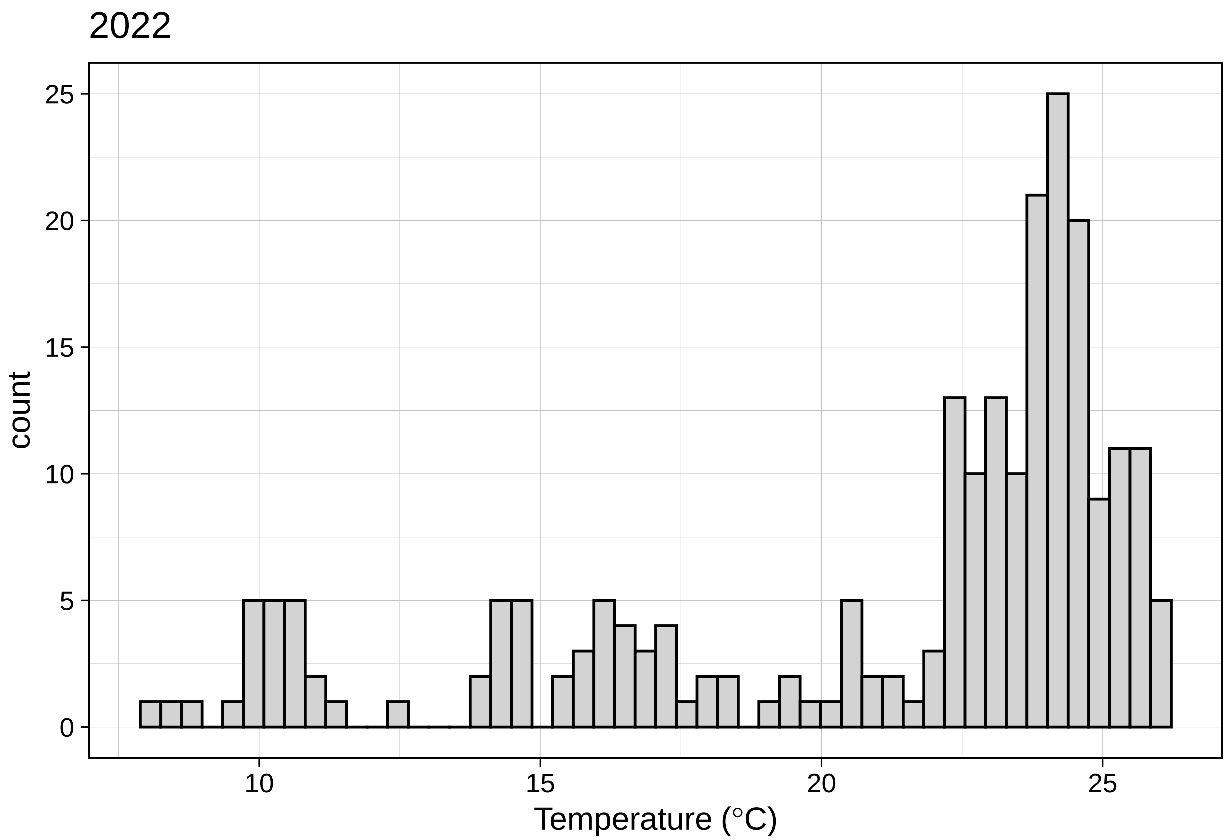
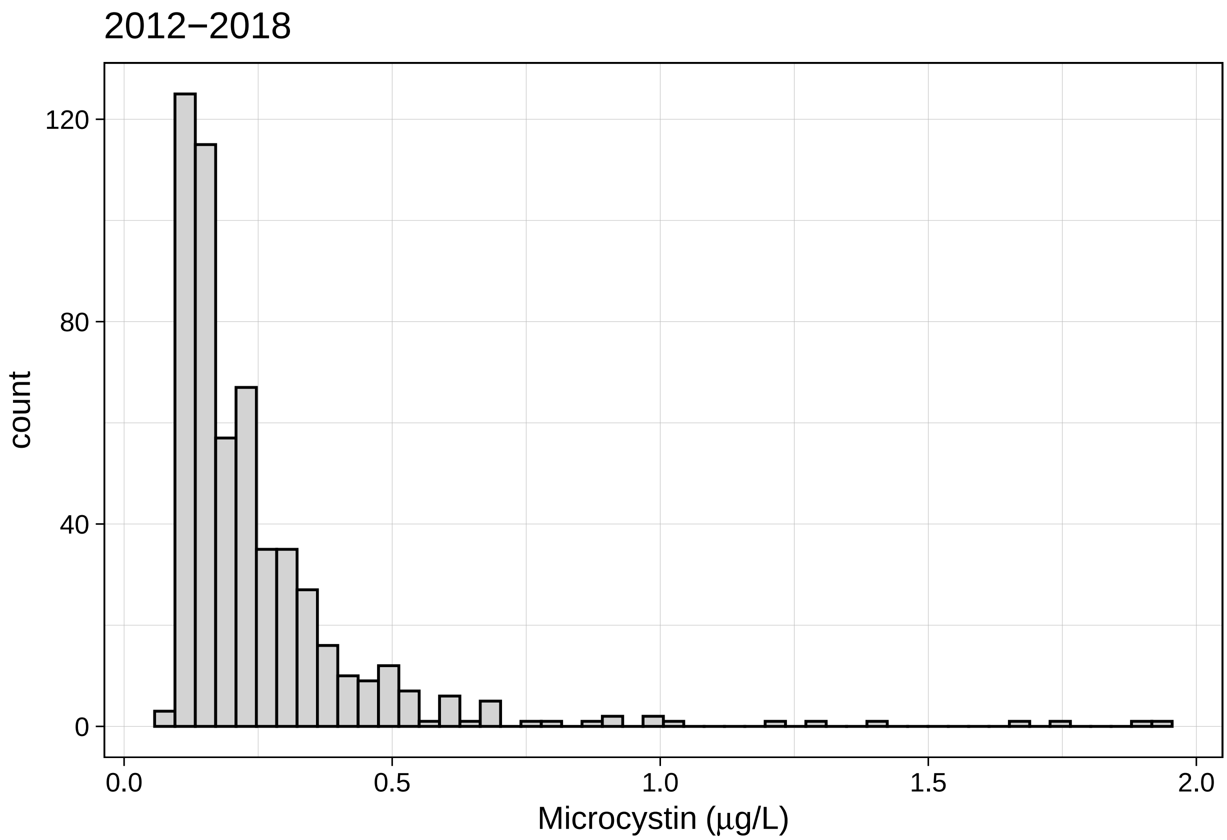


Figure 3. Temperature distribution from 2012-2018 (top) and in 2022 (bottom).

Dissolved microcystin concentrations between 2012 and 2018 were strongly right-skewed, with the majority of observations falling below 0.25 $\mu g/L$ and very few between 1.3 and 2 $\mu g/L$. Microcystin measurements in 2022 are mainly below 0.5 $\mu g/L$ and exhibit a narrower range of values (Fig. 4).


2012−2018
count
120
80
40
0
0.0
0.5
1.0
1.5
2.0
Microcystin (μg/L)

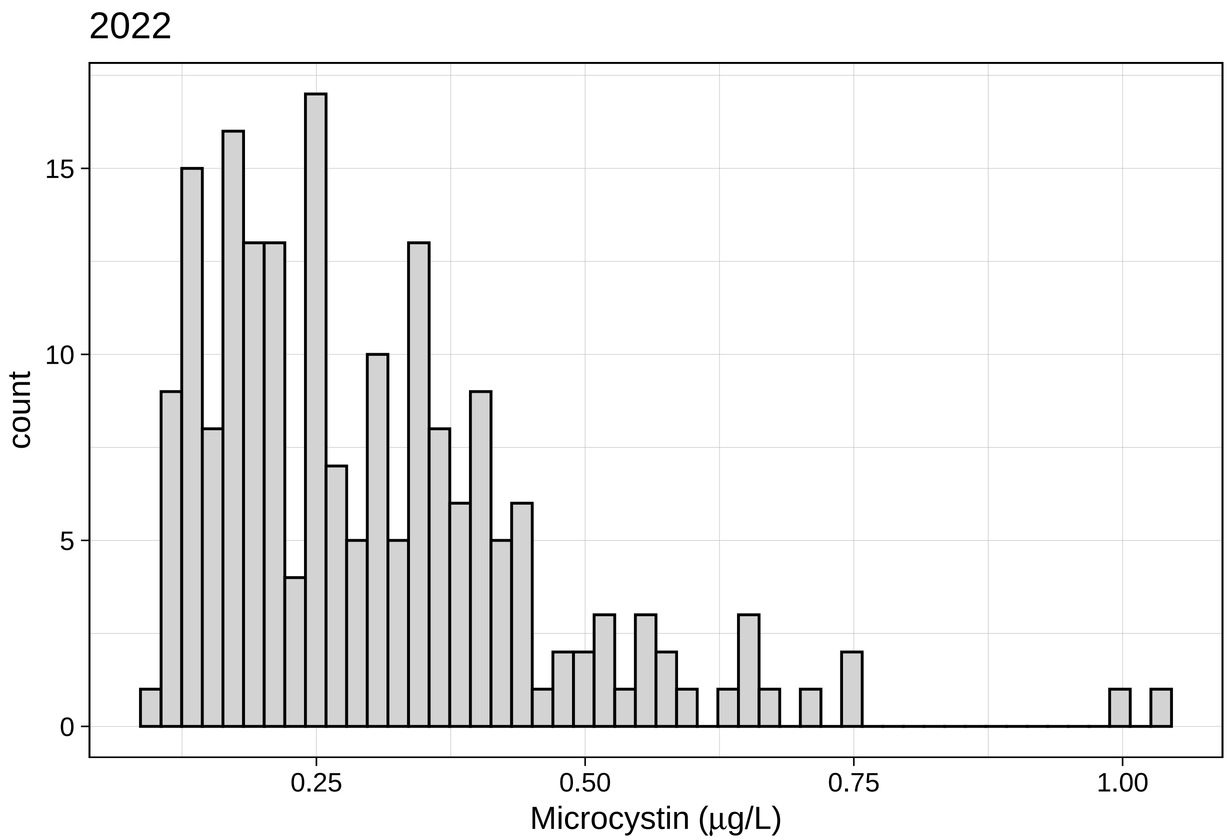
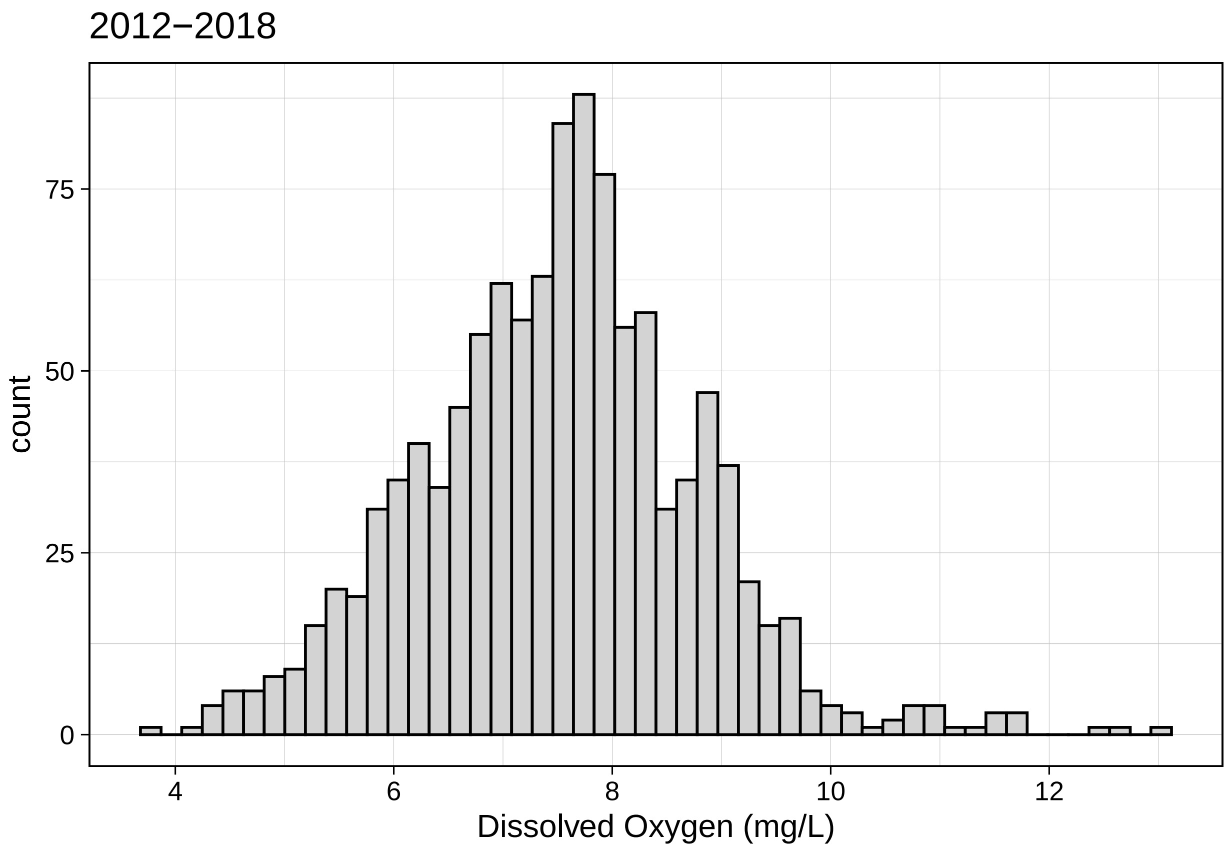


Figure 4. Microcystin distribution from 2012-2018 (top) and in 2022 (bottom).

Dissolved oxygen measurements from 2012-2018 are concentrated around 8 mg/L, while 2022 seems to have overall lower dissolved oxygen values, mainly concentrated between 7 and 8 mg/L (Figure 5).


2012−2018
count
75
50
25
0
4
6
8
10
12
Dissolved Oxygen (mg/L)

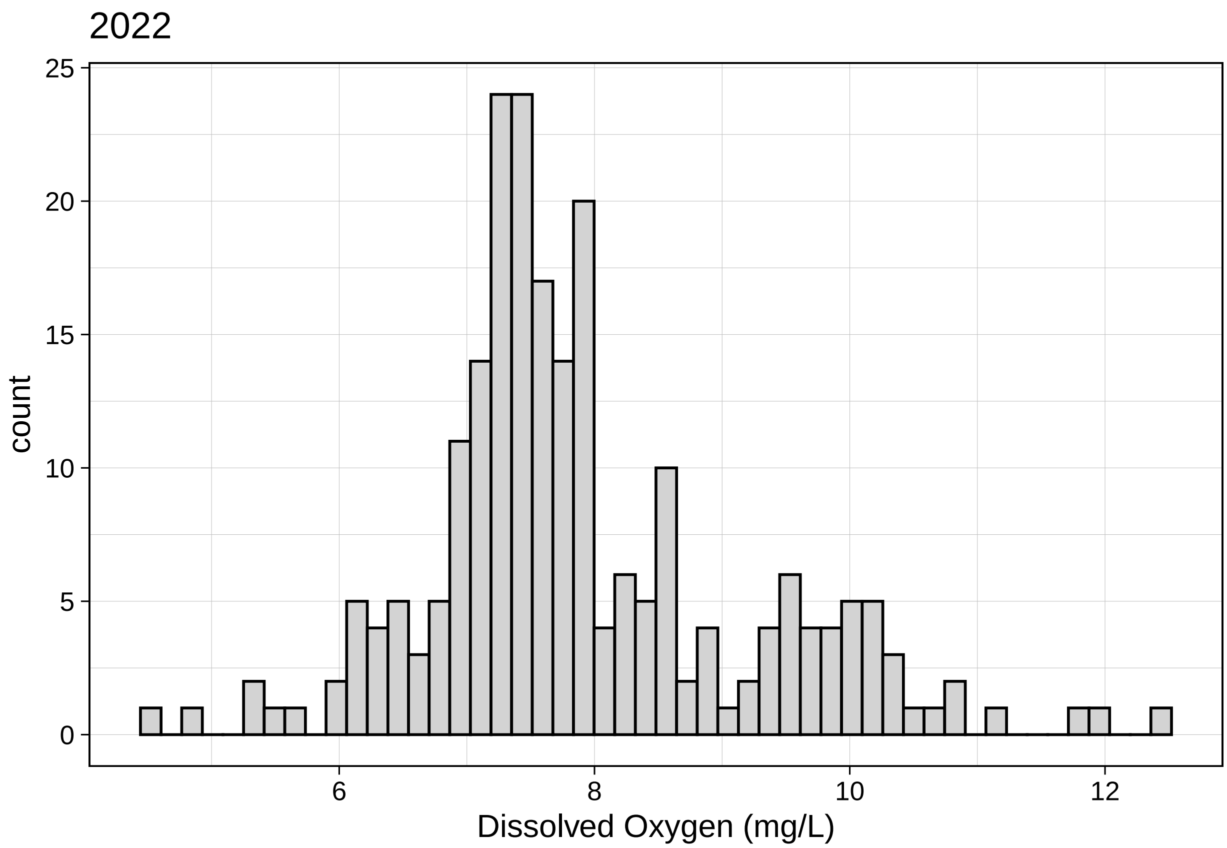


Figure 5. Dissolved oxygen distribution from 2012-2018 (top) and in 2022 (bottom).

To begin exploration of the questions, a summary statistics table (Table 1) was generated to show the number of observations, mean, standard deviation, median, maximum, and minimum values within each year for all variables of interest (i.e., microcystin concentration, chlorophyll a concentration, dissolved oxygen concentration, nitrate/nitrite concentration, dissolved phosphorus, and temperature. This was conducted to evaluate balance within the data regarding the number of observations but also to get a glimpse into trends occuring within given years.

Table 1. Summary Statistics: Harmful Algal Bloom and Lake Characteristics of Lake Erie 2012 through 2018

Summary Statistics: Lake Erie Harmful Algal Bloom Characteristics in 2012 through 2018

	Oberservations	Mean	St Deviation	Median	Max	Min
2012						
Chlorophyll a (ug/L)	62	33.58	49.87	16.18	290.52	2.21
Nitrate/Nitrite Concentration (mg/L)	51	0.31	0.28	0.32	1.85	0.00
Dissolved Phosphorus (ug/L)	60	10.89	6.69	9.68	35.36	2.07
2013						
Dissolved Oxygen (mg/L)	96	7.37	0.54	7.50	8.10	5.30
Temperature (deg C)	93	22.01	3.53	22.60	29.70	12.10
Chlorophyll a (ug/L)	97	52.66	54.74	36.53	243.81	0.71
Nitrate/Nitrite Concentration (mg/L)	92	1.29	1.69	0.64	6.31	0.01
Dissolved Phosphorus (ug/L)	92	13.35	15.24	7.66	80.82	0.16

2014						
Dissolved Oxygen (mg/L)	114	8.16	1.08	8.20	11.70	5.30
Temperature (deg C)	114	20.20	4.73	22.05	26.10	7.40
Dissolved Microcystin (ug/L)	49	0.50	0.45	0.31	1.94	0.09
Chlorophyll a (ug/L)	126	27.28	47.15	12.76	466.50	1.14
Nitrate/Nitrite Concentration (mg/L)	124	0.48	0.87	0.19	6.55	0.00
Dissolved Phosphorus (ug/L)	125	10.72	9.59	7.38	71.50	0.63
2015						
Dissolved Oxygen (mg/L)	248	8.23	1.18	8.21	11.68	4.48
Temperature (deg C)	248	21.49	3.32	22.10	26.40	10.10
Dissolved Microcystin (ug/L)	125	0.24	0.13	0.20	0.69	0.08
Chlorophyll a (ug/L)	248	67.81	434.36	24.62	6,784.00	1.01
Nitrate/Nitrite Concentration (mg/L)	134	1.06	1.50	0.35	7.42	0.00
Dissolved Phosphorus (ug/L)	145	34.37	46.06	13.42	273.58	0.55
2016						
Dissolved Oxygen (mg/L)	226	7.38	1.04	7.45	9.77	4.30
Temperature (deg C)	226	23.02	3.12	23.80	27.20	14.40
Dissolved Microcystin (ug/L)	143	0.25	0.22	0.19	1.76	0.10
Chlorophyll a (ug/L)	227	16.30	19.97	7.77	114.57	1.00
Nitrate/Nitrite Concentration (mg/L)	135	0.65	1.14	0.27	9.45	0.00
Dissolved Phosphorus (ug/L)	151	15.46	14.59	9.80	72.90	0.80
2017						
Dissolved Oxygen (mg/L)	237	6.97	1.61	6.77	13.04	3.79
Temperature (deg C)	237	21.11	4.01	22.00	26.40	2.40
Dissolved Microcystin (ug/L)	116	0.23	0.13	0.18	0.76	0.08
Chlorophyll a (ug/L)	242	25.47	43.43	15.75	531.70	0.77
Nitrate/Nitrite Concentration (mg/L)	164	1.29	1.64	0.56	8.33	0.00
Dissolved Phosphorus (ug/L)	168	22.11	29.78	7.83	142.27	1.46
2018						
Dissolved Oxygen (mg/L)	190	7.12	0.84	7.14	8.96	4.85
Temperature (deg C)	190	23.46	2.29	24.10	28.00	17.20
Dissolved Microcystin (ug/L)	113	0.18	0.07	0.17	0.60	0.10
Chlorophyll a (ug/L)	200	17.88	12.15	15.70	92.51	1.75
Nitrate/Nitrite Concentration (mg/L)	134	0.95	1.31	0.55	8.64	0.00
Dissolved Phosphorus (ug/L)	134	18.38	21.88	9.21	112.30	1.01

To explore the third question, a summary statistics table (Table 2) was generated to show the number of observations, mean, standard deviation, and median within each group of interest (i.e., surface and bottom depth categories). This was conducted to evaluate balance within the data regarding the number of observations but also to get a glimpse into trends for both bottom and surface depth observations.

Table 2. Summary Statistics: Harmful Algal Bloom and Lake Characteristics of Lake Erie at Bottom and Surface Depths

Summary Statistics: Lake Erie Harmful Algal Bloom Characteristics at Bottom and Surface Depths

	Oberservations	Mean	St Deviation	Median	Max	Min
Bottom						
Dissolved Oxygen (mg/L)	295	6.88	1.38	6.63	12.61	3.79
Temperature (deg C)	295	22.20	2.87	22.90	26.70	12.10
Dissolved Microcystin (ug/L)	160	0.22	0.12	0.18	0.76	0.08
Chlorophyll a (ug/L)	300	21.40	58.27	12.47	969.60	1.00
Surface						
Dissolved Oxygen (mg/L)	587	7.70	1.19	7.73	13.04	4.30
Temperature (deg C)	587	22.21	3.69	23.20	28.00	2.40
Dissolved Microcystin (ug/L)	327	0.24	0.17	0.18	1.76	0.08
Chlorophyll a (ug/L)	598	38.94	279.14	15.92	6,784.00	0.77
Nitrate/Nitrite Concentration (mg/L)	566	1.00	1.44	0.41	9.45	0.00
Dissolved Phosphorus (ug/L	598	22.57	31.15	9.91	273.58	0.55

Analysis

Question 1: How does Microcystis and microcystin concentration change over time?

Upon initial analysis of the data, there seems to be variation in bloom activity between different months and years. Chlorophyll a, as mentioned above, was highest in 2015, and seems to be declining overall from from 2012 to 2018, which had the lowest peaks in chlorophyll a of all the years (Fig. ###).

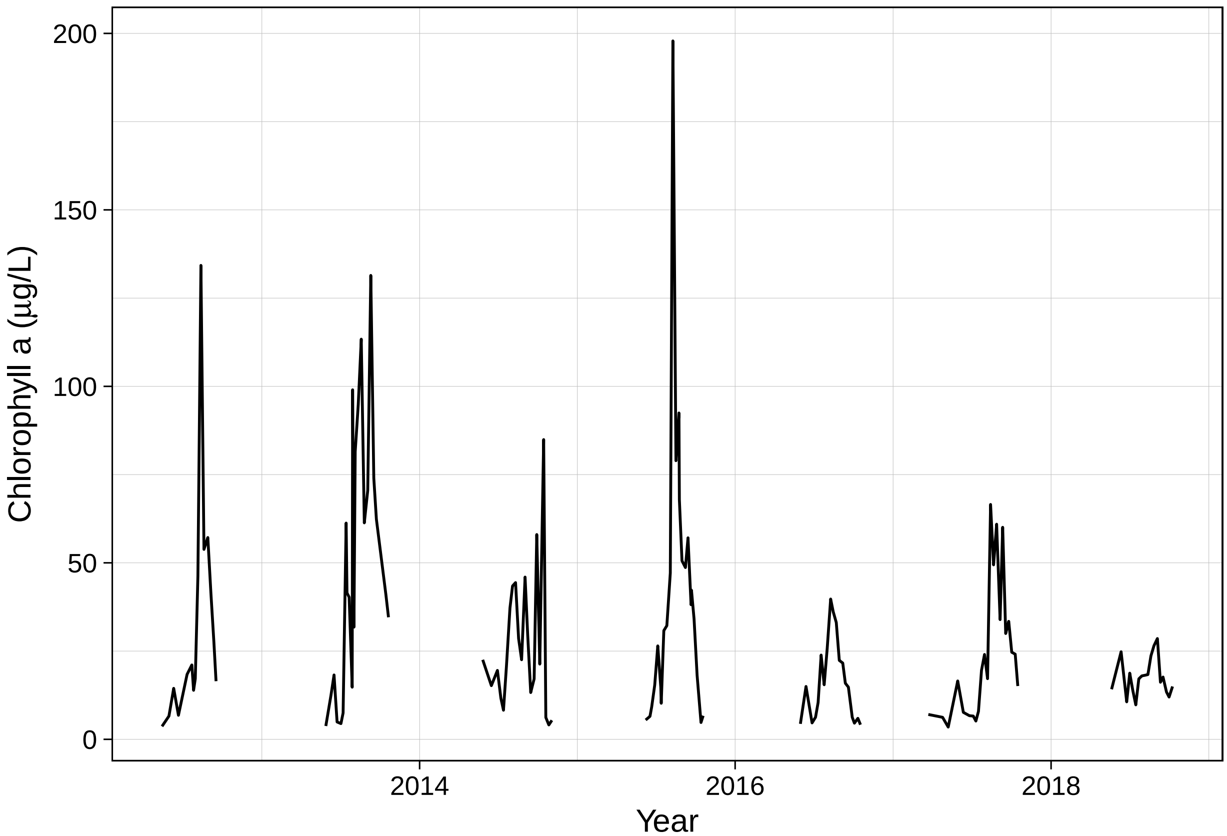


Figure ###. Chlorophyll a concentrations from 2012-2018

Temperature, by contrast, appears to have remained relatively constant between 2012 and 2018 (Fig. ##).

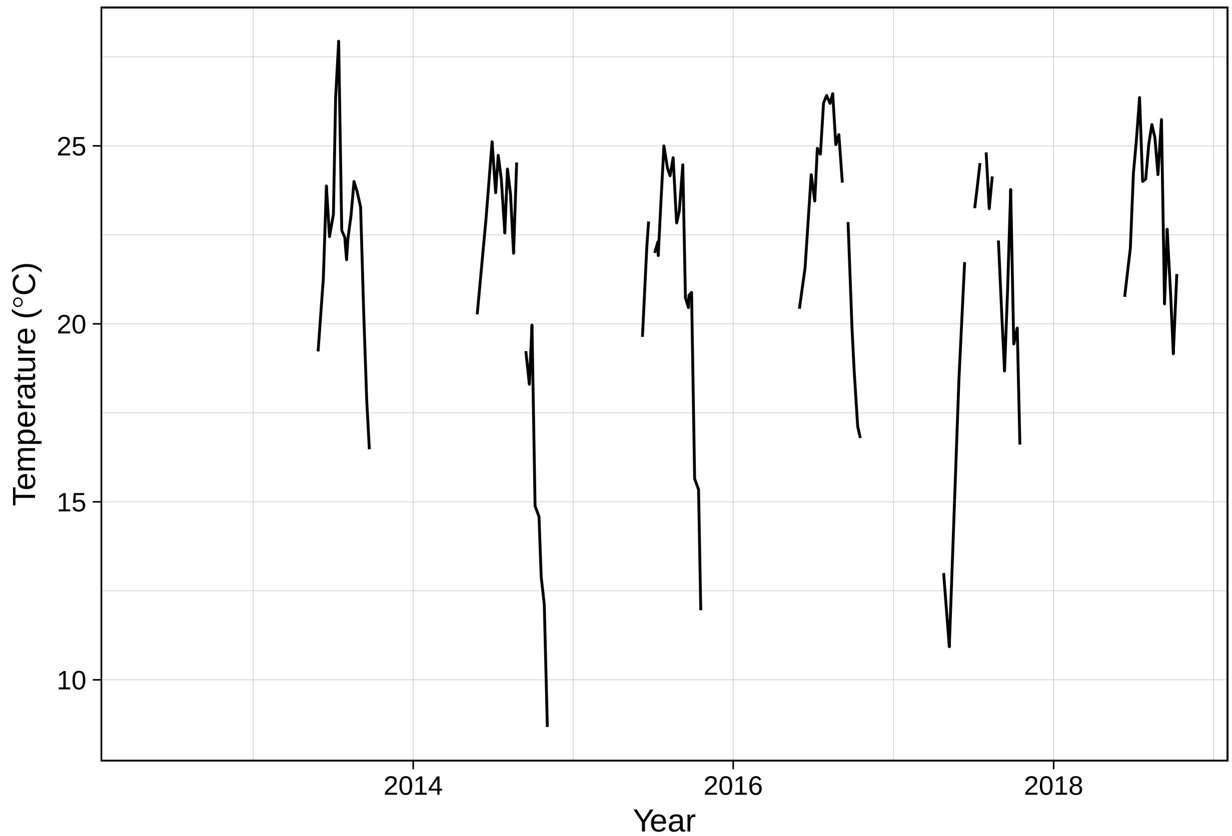


Figure ###. Water temperature from 2012-2018

It was difficult to visualize annual trends in microcystin, nitrate and nitrite, and total dissolved phosphorus concentrations since data collection is sporadic throughout the seven-year period.

We averaged chlorophyll a by month for each year to examine monthly trends. The monthly trends in chlorophyll a were similar across 2014, 2018, and 2022, with chlorophyll a peaking in August. This peak was greater in 2022 than in 2014 and 2018 (Fig. #).

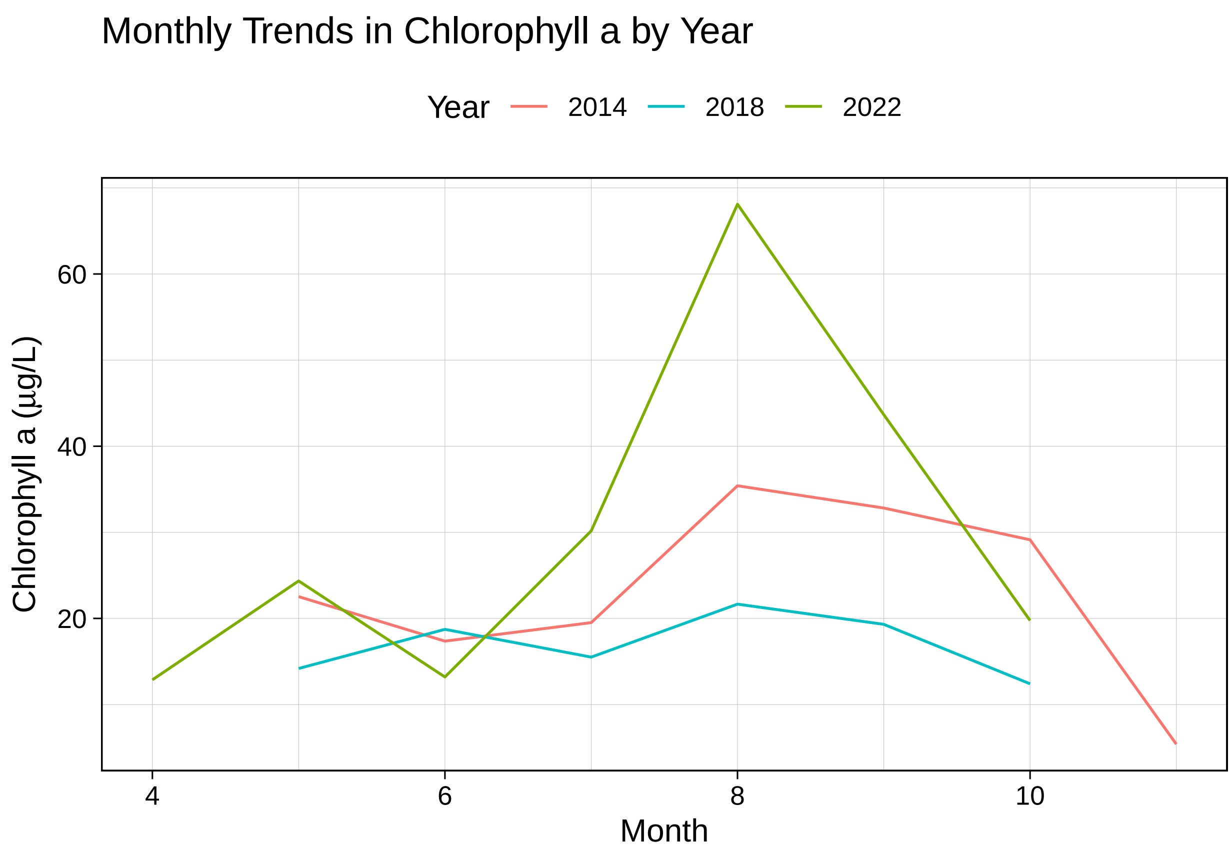


Figure ###. Monthly trends in chlorophyll a in 2014, 2018, and 2022.

It was difficult to visualize annual and monthly trends in microcystin, nitrate and nitrite, and total dissolved phosphorus concentrations since data collection is sporadic throughout the seven-year period.

To assess whether differences in chlorophyll a and temperature between months and years were statistically significant, we conducted two-way ANOVA tests.

[ANOVAs here]

Question 2: Which variables (i.e., temperature, nitrate/nitrite, and/or phosphorus) contribute to microcystin production, Microcystis population growth, and dissolved oxygen?

Generalized linear modeling To determine the variables driving chlorophyll a and microcystin concentration in Western Lake Erie, we conducted generalized linear modelling, taking into account temperature, nitrate and nitrite concentration, and total dissolved phosphorus concentration. We analyzed these trends for the entire 2012-2018 dataset, and for the years 2014 and 2018 specifically.

The linear model results demonstrate a statistically significant negative relationship between microcystin concentration and temperature for the total dataset, but a significant positive relationship for data collected in 2014. Microcystin concentrations in 2018 were negatiely associated with nitrate and nitrite concentration (Table #).

In 2018, chlorophyll a was positively associated with both water temperature and nitrate and nitrite concentration. However, in 2014 and across the total dataset, chlorophyll a was not significantly related to any of our explanatory variables (Table #).

Table ###. Linear model results of relationships between response variables: chlorophyll a and microcystin, and explanatory variables: temperature, nitrate and nitrite, and total dissolved phosphorus concentration

2012-2018 chlorophyll a and microcystin linear model results

Explanatory variable	Coefficient	Standard error	p-value
Total - Chlorophyll a			
Temperature	3.24669	1.72512	0.060
Nitrate + Nitrite	−5.57870	5.98369	0.351
Total Dissolved Phosphorus	−0.17240	0.29150	0.554
Total - Microcystin			
Temperature	−0.00515	<0.01	0.039
Nitrate + Nitrite	−0.00516	0.01370	0.706
Total Dissolved Phosphorus	−0.00038	<0.01	0.442
2014 - Chlorophyll a			
Temperature	0.43864	0.97542	0.654
Nitrate + Nitrite	3.16845	4.94999	0.523
Total Dissolved Phosphorus	−0.27746	0.44364	0.533
2014 - Microcystin			
Temperature	0.04842	0.01676	<0.01
Nitrate + Nitrite	−0.69183	0.87234	0.432
Total Dissolved Phosphorus	<0.01	<0.01	0.100
2018 - Chlorophyll a			
Temperature	1.01142	0.38701	<0.01
Nitrate + Nitrite	1.85375	0.86440	0.034
Total Dissolved Phosphorus	0.07431	0.05220	0.157
2018 - Microcystin			
Temperature	<0.01	<0.01	0.672
Nitrate + Nitrite	−0.01988	<0.01	0.040
Total Dissolved Phosphorus	−0.00057	<0.01	0.196

The plots below illustrate the linear model results. As shown in Fig. #, the nonsignificant positive relationship between temperature and chlorophyll a from 2012 to 2018 is fairly weak and may be influenced by extremely high observations, like those in 2015. The lack of significant relationship between chlorophyll a and temperature in 2014 which was present in 2018 may be due to the temperature range. There seems to be less variety in temperature measurements in 2018 than 2014 (Fig. #).

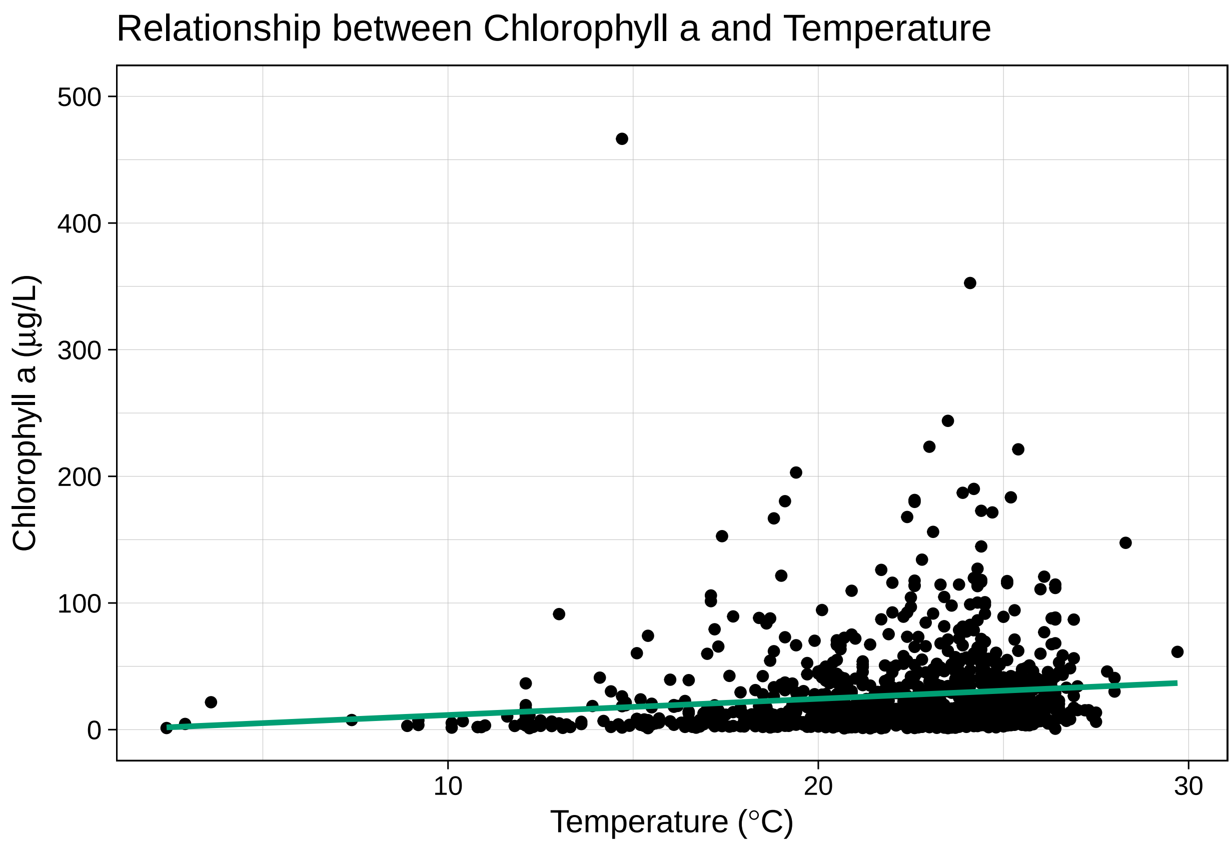


Figure #. Line plot showing relationship between chlorophyll a (y axis) and water temperature (x axis) between 2012 and 2018. Observations above 500 were removed to improve data visualization

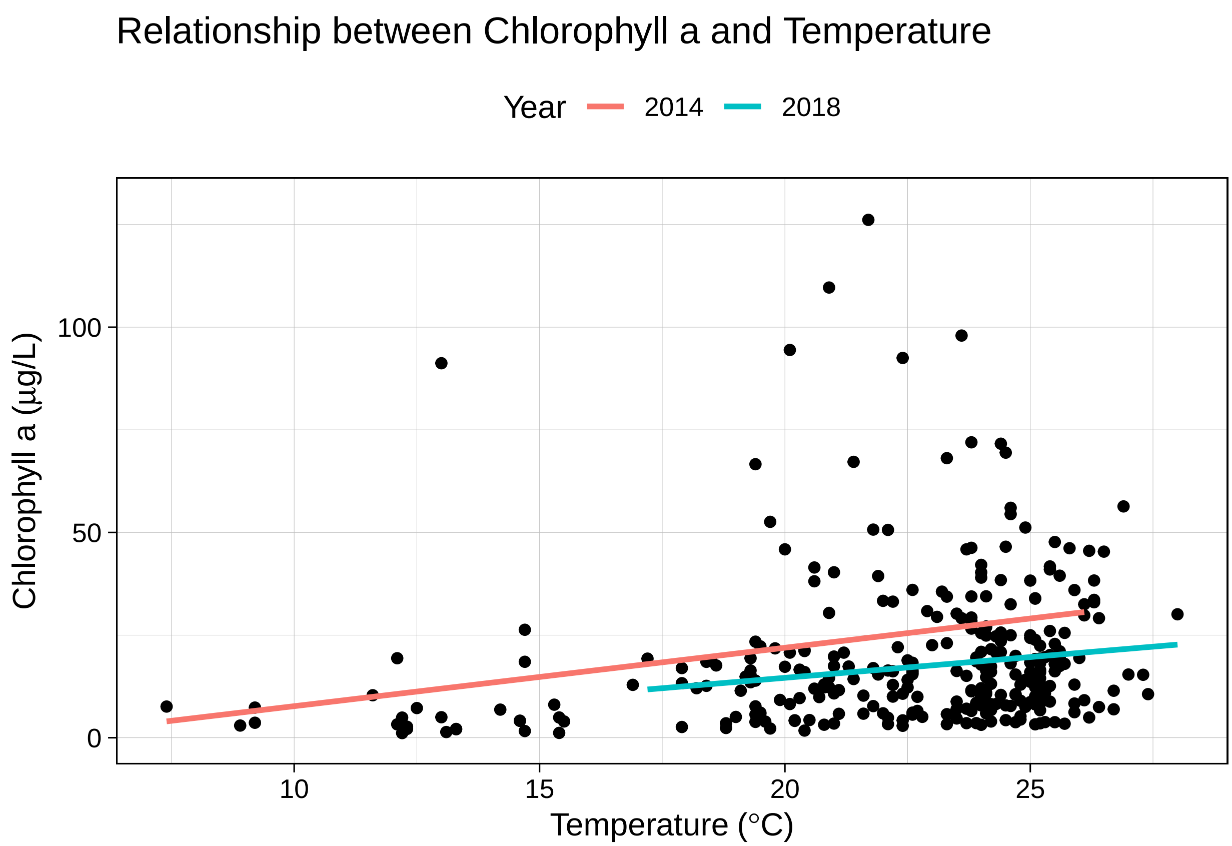


Figure #. Line plot showing relationship between chlorophyll a (y axis) and water temperature (x axis) in 2014 (red line) and 2018 (blue line).

While microcystin concentrations between 2012 and 2018 show a negative trend with temperature overall (Fig. #), there was a significant, positive association between microcystin and temperature in 2014 (Fig. #). As discussed above, microcystin collection was sporadic throughout the study period, and the low sample size may affect our ability to detect relationships between microcystin concentration and water quality variables.

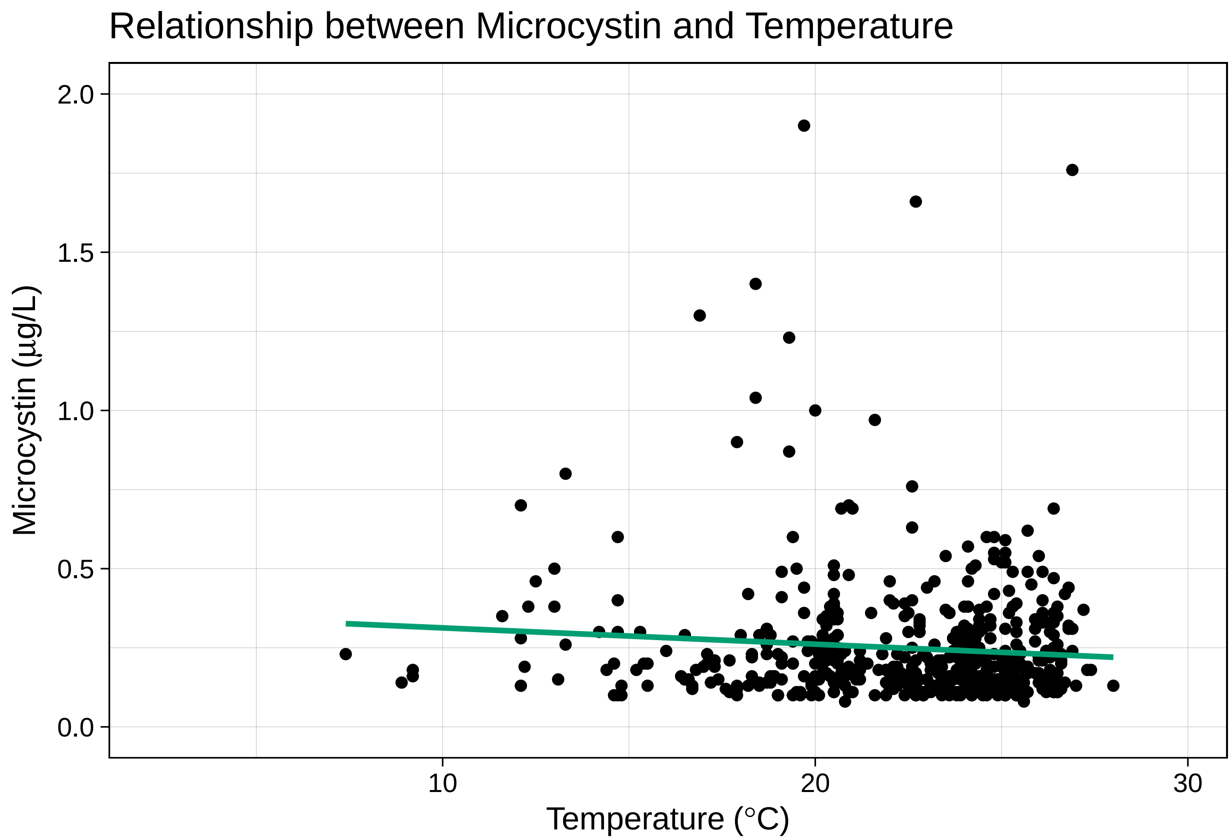


Figure #. Line plot showing relationship between microcystin (y axis) and water temperature (x axis) between 2012 and 2018.

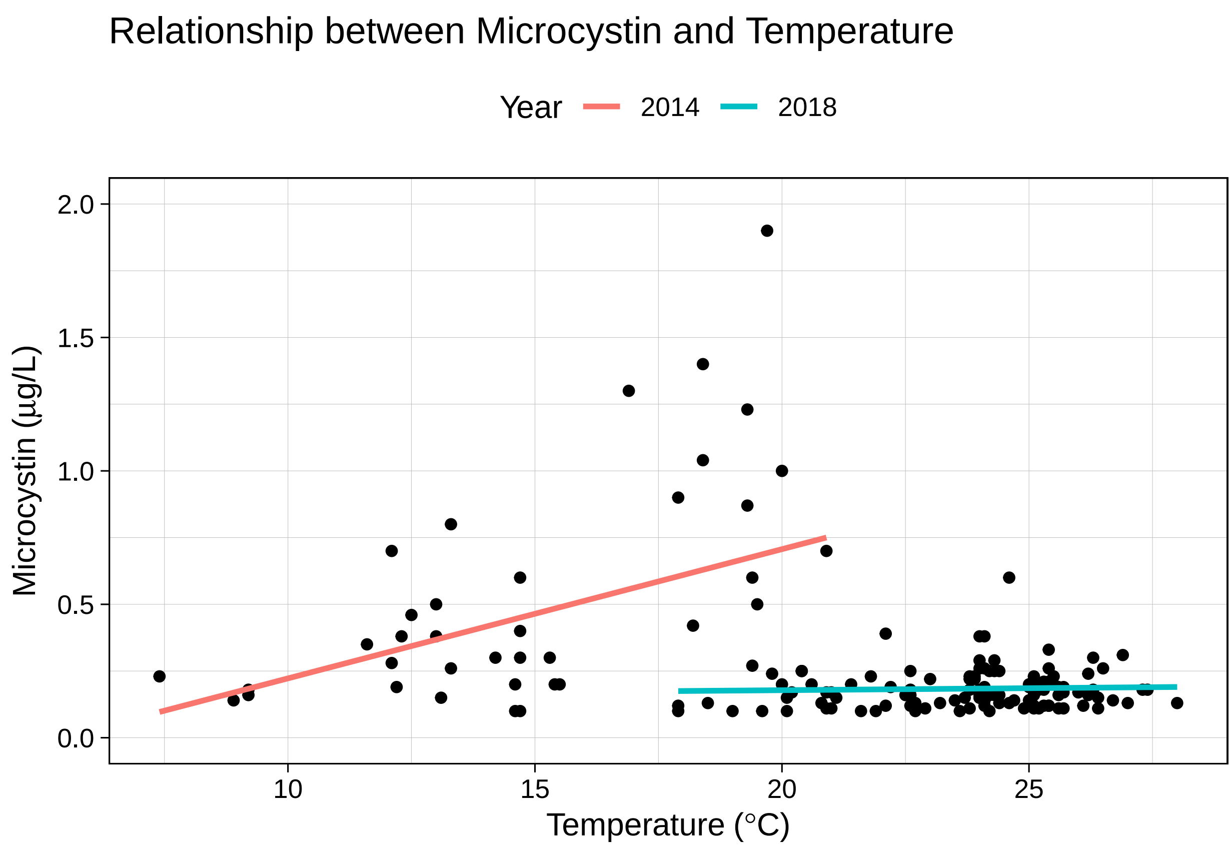
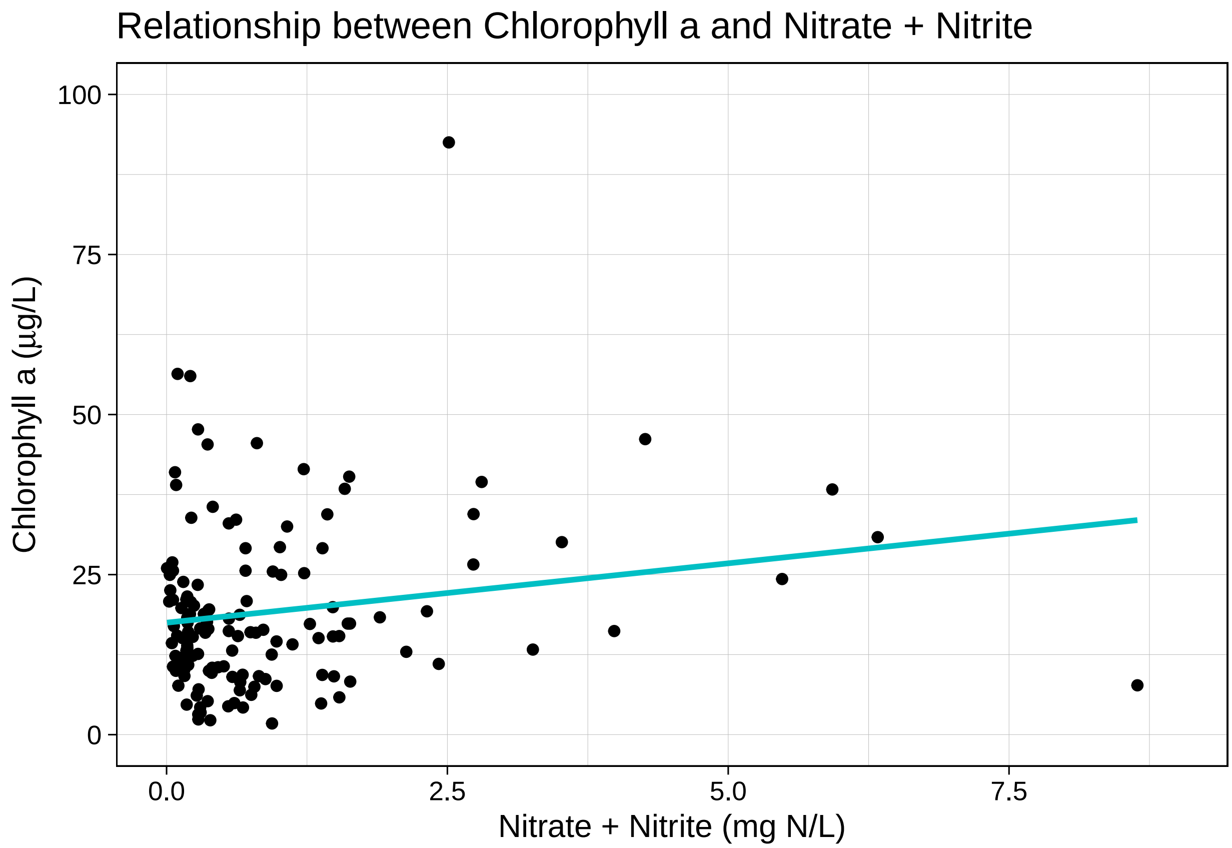


Figure #. Line plot showing relationship between microcystin (y axis) and water temperature (x axis) in 2014 (red line) and 2018 (blue line).

In 2018, chlorophyll a was positively associated with nitrate and nitrite concentrations, but microcystin was negatively associated with nitrate and nitrite (Fig. #). This result was unexpected, as we hypothesized that both chlorophyll a and microcystin would respond similarly to water quality variables like nutrient concentration.


Relationship between Chlorophyll a and Nitrate + Nitrite
Chlorophyll a (µg/L)
100
75
50
25
0
0.0
2.5
5.0
7.5
Nitrate + Nitrite (mg N/L)

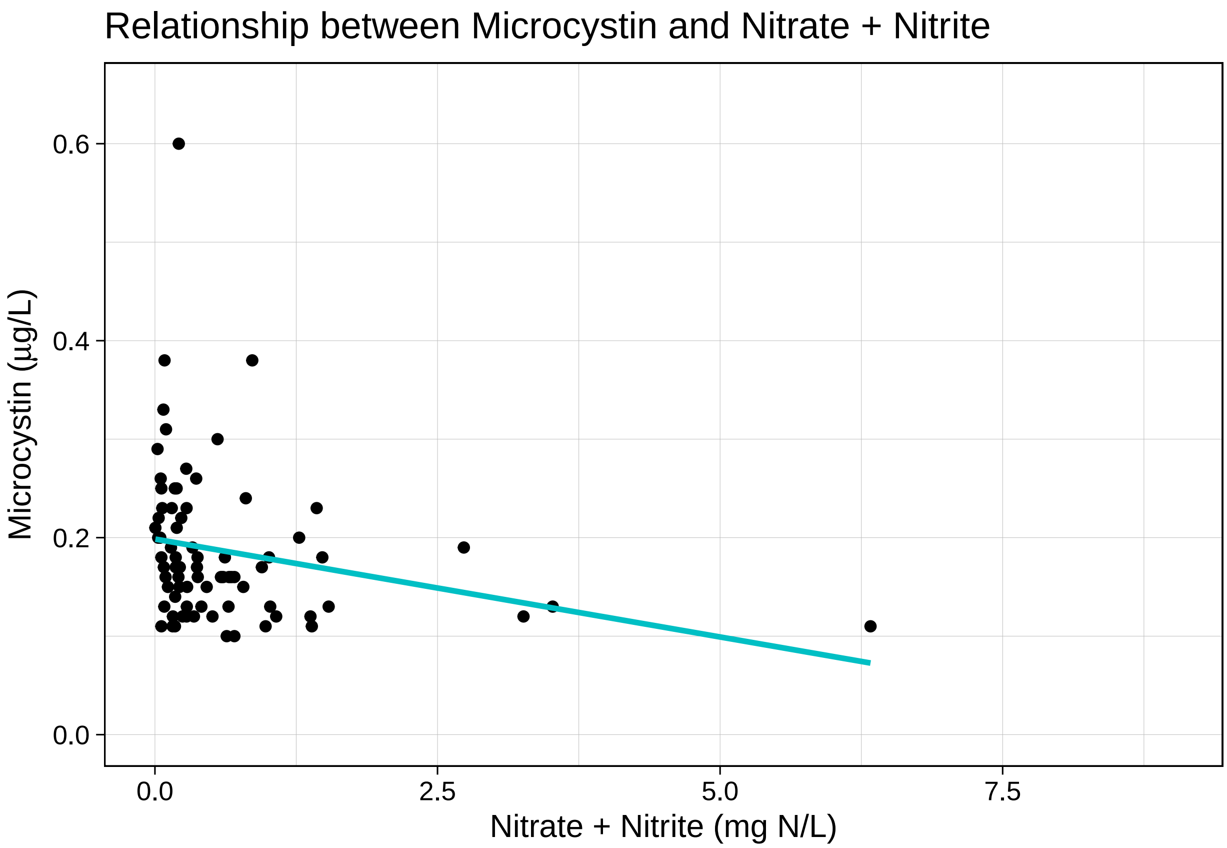


Figure #. Line plot showing relationship between microcystin (y axis) and nitrate + nitrite concentration (x axis) in 2018.

We further used linear modeling to assess the relationships between chlorophyll a and microcystin and water temperature in 2022. In line with our hypotheses, both chlorophyll a and microcystin are positively related to water temperature (Table #).

Table #. Linear model results of relationships between response variables: chlorophyll a and microcystin, and temperature in 2022

2022 temperature linear model results

Response variable	Coefficient	Standard error	p-value
Chlorophyll a	3.01425	0.53903	<0.01
Microcystin	0.01024	<0.01	<0.01

Question 3: Are there differences between toxin, chlorophyll a, or dissolved oxygen concentration at different lake depths?

Regarding the third question it is hypothesized that both microcystin, chlorophyll a, and dissolved oxygen concentrations will be greater at surface depths opposed to bottom depths in Lake Erie. These hypotheses are stated below:

Hypotheses for microcystin concentration at surface vs. bottom depth

Ho: Surface depth microcystin concentrations are <= bottom depth microcystin concentrations

HA: Surface depth microcystin concentrations are > bottom depth microcystin concentrations

Hypotheses for chlorophyll a concentration at surface vs. bottom depth

Ho: Surface depth Chlorophyll a concentrations are <= bottom depth microcystin concentrations

HA: Surface depth Chlorophyll a concentrations are > bottom depth microcystin concentrations

Hypotheses for dissolved oxygen concentration at surface vs. bottom depth

Ho: Surface depth dissolved oxygen concentrations are <= bottom depth microcystin concentrations

HA: Surface depth dissolved oxygen concentrations are > bottom depth microcystin concentrations

Assessing distribution of data Before assessing these claims, a Shapiro-Wilk test for normality was conducted for the microcystin, chlorophyll a, and dissolved oxygen data. The test rejected the null hypothesis which states that the data are normally distributed in all cases as shown in Table ###. In result, the Wilcoxon Rank Sum test was employed to evaluate the means between surface and bottom layers for each variable. These results can be found in Table ###.

Table ###. Shapiro-Wilk Test for Normality Results

Shapiro-Wilk Test Results

Data	Statistic	P-Value
Dissolved Microcystin	0.667	0
Chlorophyll a	0.055	0
Dissolved Oxygen	0.989	0

Table ###. Wilcoxin Rank Sum Test for Bottom versus Surface Depths

Wilcoxin Rank Sum Test Results

Data	Statistic	P-Value
Dissolved Microcystin	24799.5	0.175
Chlorophyll a	78211.5	0.001
Dissolved Oxygen	51923.5	0.000

When looking at microcystin concentrations at surface and bottom depths, the Wilcoxin Rank Sum test showed a nonsignificant result and thus a failure to reject the null hypothesis which states that microcystin concentrations at surface depth are less than or equal to microcystin concentrations at bottom depth (W = 24800, p-value = 0.1753). Figure ### shows these data. When looking at chlorophyll a concentrations at surface and bottom depths, the Wilcoxin Rank Sum test showed a significant result and a rejection of the null hypothesis which states that chlorophyll a concentrations at surface depth are less than or equal to chlorophyll a concentrations at bottom depth (W = 78212, p-value = 0.0008634). Figure ### shows these data. Lastly, when looking at dissolved oxygen concentrations, the Wilcoxin Rank Sum test showed a significant result and a rejection of the null hypothesis which states that dissolved oxygen concentrations at surface depth are less than or equal to dissolved concentrations at bottom depth (W = 51924, p-value < 2.2e-16). Figure ### shows these data.

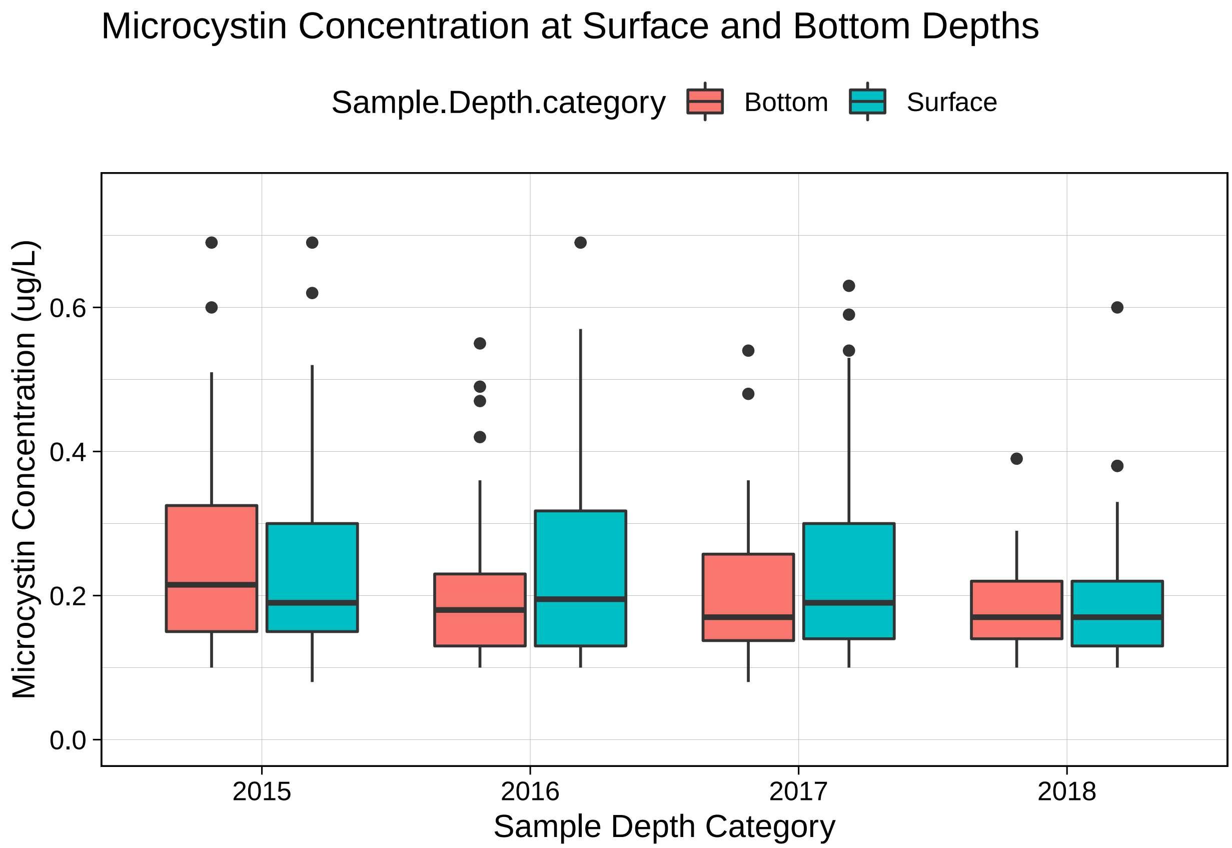


Figure ###. Microcystin Concentrations at Surface and Bottom Depth for years 2015 through 2018

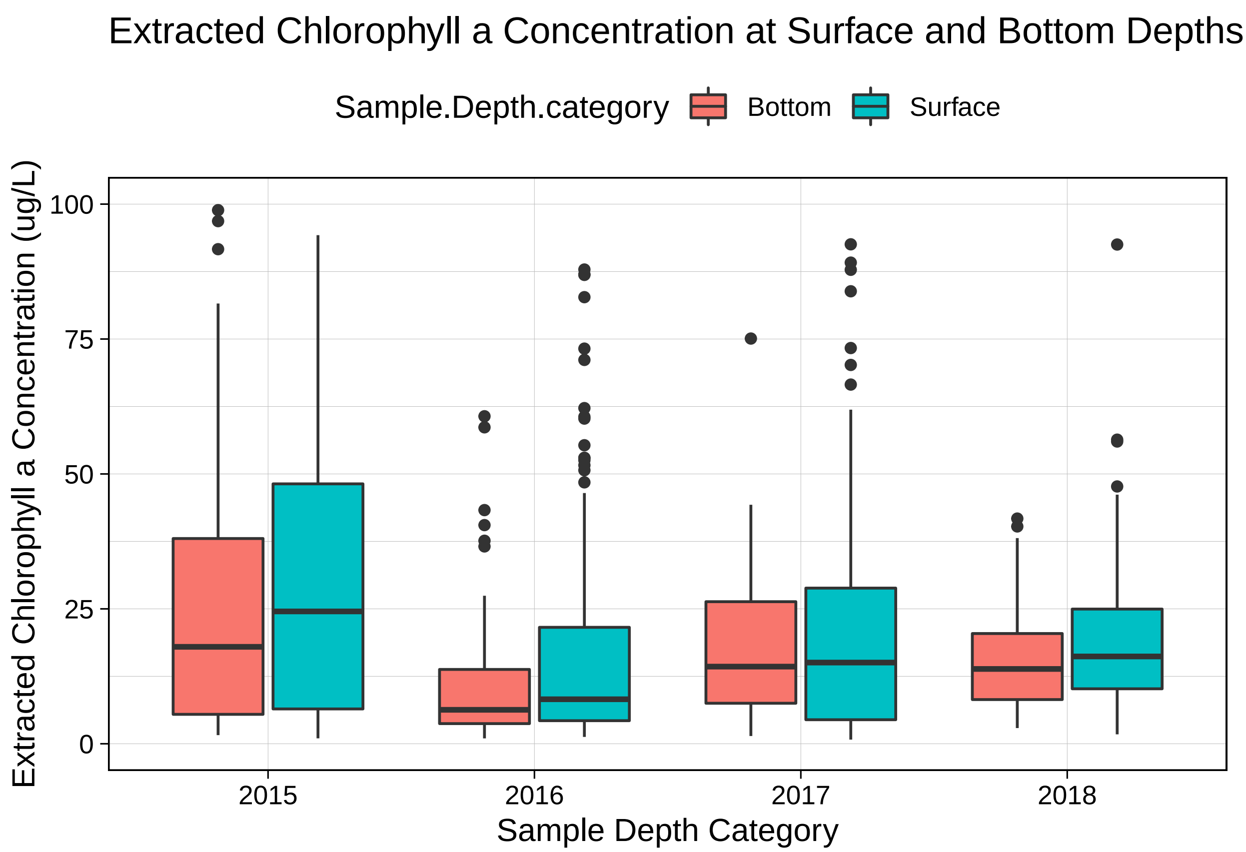


Figure ###. Chlorophyll a Concentrations at Surface and Bottom Depth for years 2015 through 2018

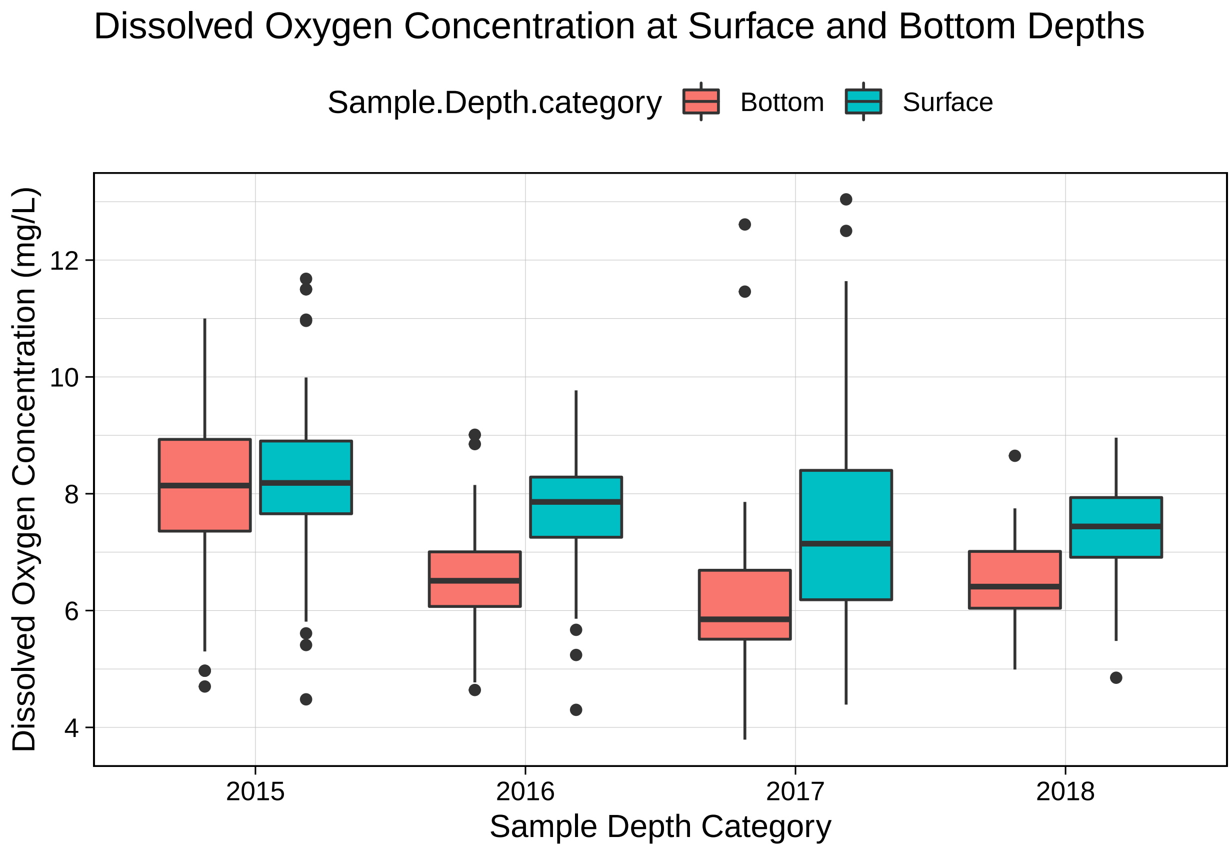


Figure ###. Dissolved Oxygen Concentrations at Surface and Bottom Depth for years 2015 through 2018

Summary and Conclusions

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