Lake Murray Little Saluda River and Bush River Arms 2022 Nutrient Study

Final Report of the Field Program

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Executive Summary

In 2022, South Carolina Department of Health and Environmental Control Bureau of Water completed the second year of a lake arm study in upper Lake Murray. The project provides a second consecutive year of water quality data collection from three routine and two periodic lake sites in upstream reaches of the lake. Specifically, this study focused on providing important year over year insights into the relationships and spatial variations among nutrient inputs, physical conditions, algal activity, and metabolically driven water column response variables in the Little Saluda River/Clouds Creek and Bush River lake arms.

As with 2021, the 2022 Lake Murray program objectives were achieved conducting biweekly (every other week) water quality (nutrients, physical parameters, and phytoplankton photosynthetic pigments) sampling and vertical hydrographic profiling at a routine lake site in each target lake arm: Little Saluda River, Clouds Creek, and Bush River. Further, a series of three continuous monitoring systems were used to provide a comprehensive and diurnal dataset of physical/hydrographic parameters and biological responses in those lake arms. Field sampling was expanded on four occasions to include two additional sites as part of a US Environmental Protection Agency partnership investigating nutrient limitation on phytoplankton growth. Coupled with results from 2021, the data collected as part of this study provided further resolution into the links between physical conditions and nutrients and algal responses such as phytoplankton biomass and toxin production.

This report discusses the successes and challenges of the field program and summarizes the data collected as part of the biweekly sampling and continuous monitoring project components. Generally, all field program objectives were achieved as nearly all targeted data were successfully collected.

Summary of observations:

- Many of the physical features observed in the vertical profiling and continuous records in 2021 were also observed in 2022 with a few notable differences. For example, in 2022, the Clouds Creek lake arm maximum daily average temperature was reached in early July, while the 2021 maximum occurred at the end of the month. In addition, the remnants of Hurricane Ian moved through central South Carolina at the end of September which may have cooled, flushed, and mixed the water column of upper Lake Murray.
- Among the lake arms, average total chlorophyll-a in biweekly sampling was highest in the Little Saluda River. Average total chlorophyll-a concentrations in Clouds Creek and Bush River lake arms were similar in 2022 compared to 2021 while Little Saluda River increased by ~20% in 2022.
- Cyanobacteria comprised, on average, a larger percentage of chlorophyll-a in 2022 (46%) compared to 2021 (25%). In 2022, cyanobacteria were the largest relative phytoplankton group among the six groups considered. In 2021, chlorophytes represented, on average, more chlorophyll-a than any other group (53% compared to 33% in 2022). As with 2021, diatoms represented a smaller component of chlorophyll-a (averages of 9.3% in 2021 and 7.3% in 2022).
- Total phosphorus and total nitrogen concentrations were on average higher in 2022 than 2021 at all lake sites. The 2022 averages are influenced by relatively high April nutrient concentrations following heavy rainfall events. High turbidity, elevated lake levels, and lake debris were observed during this time. Total organic carbon was also elevated during the April sampling events with concentrations 1.5 to 3x higher than were observed from May through October on a site-by-site basis.

Overview of the 2021 and 2022 Upper Lake Murray Studies

The Little Saluda River/Clouds Creek and Bush River lake arms in upper Lake Murray, SC, are designated priority 2016-2022 restoration areas in The State of South Carolina's 2018 Integrated Report. Eleven locations in these watersheds are listed as impaired for one or multiple parameters including total phosphorus (TP), total nitrogen (TN), dissolved oxygen (DO), chlorophyll-a, pH, *E. coli*, or biological/macroinvertebrates:

Little Saluda River/Clouds Creek Watersheds

- Lake S-222 for TP and pH
- Lake RL-110333 for chlorophyll-a and pH
- Stream S-855 for bio/macro
- Stream RS-12077 for DO
- Stream S-123 for DO
- Stream S-050 for DO

Bush River Watershed

- Lake S-309 for TN, TP, chlorophyll-a, pH, and *E. coli*
- Stream S-102 for DO
- Stream RS-01044 for bio/macro
- Stream S-044 for DO
- Stream S-042 for DO

These impairments and the underlying data are evidence of eutrophic conditions in the lake arms of upper Lake Murray stemming from elevated nutrient inputs. Previous modeling estimated that 46% of the TP load to upper Lake Murray is delivered from these three watersheds despite representing just over 13% of total stream flow.[1] Potential contributors of the high phosphorus loadings to these watersheds include point source discharges, agricultural activities, and watershed development.

Phosphorous is traditionally thought to be the primary limiter of algal growth in freshwaters. As such, nutrient management strategies for lakes have historically focused on reducing phosphorus inputs to protect ecological/aquatic integrity and human health. More recently, in a shifting paradigm, research guiding management efforts of inland waters has moved towards the position of dual control of both nitrogen and phosphorus, instead of phosphorus alone, to regulate algal activity.[2,3,4] Further, as the N:P

[1] Sawyer, A.F. and R.J. Ruane. 2006. Calibration of the CE-QUAL-W2 Model for Lake Murray. Prepared for SCE&G by Reservoir Environmental Management, Inc. Chattanooga, TN.

[2] Müller, S. and S.M. Mitrovic. 2015. Phytoplankton co-limitation by nitrogen and phosphorus in a shallow reservoir: progressing from the phosphorus limitation paradigm. Hydrobiologia 744, 255-269. https://doi.org/10.1007/s10750-014-2082-3.

[3] Lewis Jr., W.M., W.A. Wurtsbaugh and H.W. Paerl. 2011. Rationale for control of anthropogenic nitrogen and phosphorus to reduce eutrophication of inland waters. Environmental Science and Technology 45, 10300-10305. https://doi.org/10.1021/es202401p.

[4] Harpole W.S., J.T. Ngai, E.E. Cleland, E.W. Seabloom, E.T. Borer, M.E. Bracken, J.J. Elser, D.S. Gruner, H. Hillebrand, J.B. Shurin and J.E. Smith. 2011. Nutrient co-limitation of primary producer communities. Ecology Letters 14(9), 852-862. doi: 10.1111/j.1461-0248.2011.01651.x.

transport and export ratio of stream water increases with changing land use across the United States, dual management of nitrogen and phosphorus in lakes may become critical in protecting human and ecological health.[5] This may be particularly important if excessive phosphorus is already present in eutrophic lake sediments.[6]

In 2022, South Carolina Department of Health and Environmental Control (DHEC) Bureau of Water (BOW) completed the second year of a lake arm study in upper Lake Murray. The objectives of the project were largely consistent with the 2021 study focusing on key locations in the Little Saluda River arm, Clouds Creek arm, and Bush River arm of upper Lake Murray:

- Support updated nutrient evaluation of Lake Murray and better define the spatial distribution of nutrients and nutrient-related parameters across the lake,
- Provide a comprehensive data set describing nutrient conditions in these lake arms,
- Determine what nutrients (nitrogen or phosphorus) may limit phytoplankton growth throughout the growing season,
- Develop a continuous record of key physical and biological parameters in each lake arm,
- Understand vertical hydrographic structure and light availability in the water column,
- Characterize the seasonal succession of phytoplankton biomass (i.e., chlorophyll-a), phytoplankton community structure, and potential emergence of cyanotoxins, and
- Support future watershed nutrient loading and nutrient TMDL determinations and better define the spatial extent for these determinations.[7]

Concurrent with the 2022 lake arm study, DHEC BOW conducted a study to develop an understanding of how the various land use types deliver nutrients to the streams of the upper Lake Murray watersheds during wet weather, high discharge events.[8] These data are in addition to the routine monthly baseflow sampling conducted as part of the ambient monitoring program. Taken together, these projects and routine ambient monitoring provide important insights into the relationships and spatial variations among nutrient inputs, physical conditions, algal activity, and metabolically driven water column response variables. The results of the combined data set will inform forthcoming system modeling/TMDL development.

This report summarizes the results of the 2022 upper Lake Murray lake arm study. Because the 2021 and 2022 lake arm projects were similar in field study design, year-over-year comparisons provide important information regarding interannual variability among key parameters underpinning the impairments in these lake arms.

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[5] Manning, D.W.P., A.D. Rosemond, J.P. Benstead, P.M. Bumpers and J.S. Kominoski. 2020. Transport of N and P in U.S. streams and rivers differs with land use and between dissolved and particulate forms. Ecological Applications 30(6), e02130. https://doi.org/10.1002/eap.2130.

[6] Robertson, D.M. and M.W. Diebel. 2020. Importance of accurately quantifying internal loading in developing phosphorus reduction strategies for a chain of shallow lakes. Lake and Reservoir Management 36, 391-411. DOI: 10.1080/10402381.2020.1783727.

[7] Baumann, M.S. 2022. Lake Murray Little Saluda River and Bush River Arms 2021 Nutrient Study, Final Report of the Field Program. DHEC Technical Report No. 003-2022.

[8] Matsuzuru, Y. 2022. Upper Lake Murray Watershed Synoptic Sampling Quality Assurance Project Plan (QAPP). Data of initiation: May 1, 2022.

Nutrient Study Project/Task Description

Field Logistics

The 2022 Upper Lake Murray Program spanned 31 weeks from the end of March through the end of October 2022. The study focused on a series of five strategic locations in the upper Lake Murray to meet the objectives described above (Table 1, Figures 1,2):

1. RL-19154 – Lake Murray Big Creek Arm (lake arm site in Little Saluda River embayment)
2. S-326 – Lake Murray Clouds Creek Arm (lake arm site)
3. S-309 – Lake Murray Bush River Arm (lake arm site)
4. S-222 – Lake Murray Little Saluda Arm (lake arm site)
5. S-279 – Lake Murray at Marker 63 (open lake site)

Table 1. Field program site coordinates and descriptions.

Station ID	Lat./Long.	County	Site Description
RL-19154	34.06953 / -81.61858	Saluda	Lake Murray Big Creek Arm across lake from Shinner Lane
S-326	34.06818 / -81.58687	Saluda	Lake Murray Clouds Creek arm off Ruby Riser Road
S-309	34.13146 / -81.60481	Newberry	Lake Murray Bush River arm, 4.6 km from SC 391
S-222	34.08016 / -81.56254	Saluda	Lake Murray Little Saluda River arm at SC 391
S-279	34.07627 / -81.47241	Saluda	Lake Murray at Marker 63

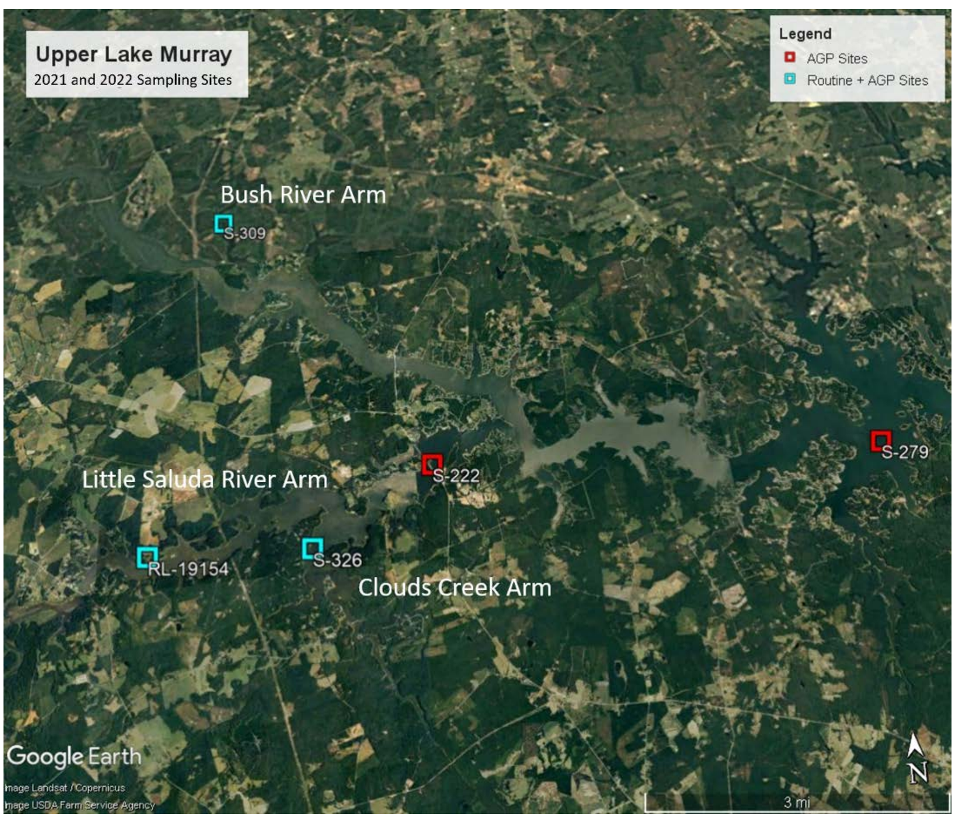

Figure 1. Site locations in upper Lake Murray. Blue squares indicate routine sampling sites and red squares indicate additional sites sampled as part of the algal growth potential test component.

Biweekly (every other week) surface (0.3 m) grab sampling was conducted at RL-19154, S-326, and S-309. Continuous monitoring systems were installed at these sites as well. Continuous monitoring systems were serviced every other week. Stations S-222 and S-279 were sampled four times over the course of the project as part of the biweekly grab sampling component to coincide with algal growth potential testing (AGPT). AGPT was scheduled for four sampling events over the course of the program (4/19, 6/14, 8/8, and 10/4/2022). Routine surface grab sample parameters included:

- 5-day biochemical oxygen demand,
- Turbidity,
- Ammonia-nitrogen,
- Nitrate/nitrite-nitrogen,
- Total Kjeldahl Nitrogen,
- Total phosphorus,
- Orthophosphate,
- Total suspended solids,
- Total and filtered total organic carbon,
- Total chlorophyll-a,
- Photosynthetic pigment suite, and
- Cyanotoxins (microcystins)

Field surface sensor measurements were recorded at each grab sample site along with vertical profiles using a YSI EXO2 and photosynthetically active radiation (PAR) penetration using a LI-COR light meter:

- Water temperature,
- Dissolved oxygen,
- pH,
- Turbidity,
- Specific conductivity,
- Chlorophyll-a fluorescence, and
- Phycocyanin fluorescence.

Continuous monitoring systems recorded surface measurements (~0.5 m) at 30-minute intervals at the three lake locations. Continuous parameters are the same as the field sensor measurements listed above except that Hydrolab DS5Xs were used until the end of June. During the period, YSI EXO2s collected continuous chlorophyll-a and phycocyanin data at RL-19154 and S-309. Starting in mid-July, YSI EXO2s were used exclusively for continuous monitoring.

Sensor Data

Surface Parameters

Surface physical parameters were collected at a depth of 0.3 m at each stream and lake site using a calibrated YSI EXO2. These measurements accompany routine grab sampling. Sampling was conducted from mid-morning through early afternoon (0930-1415). Routine physical parameters included pH (SU), optical dissolved oxygen (DO, mg/L), water temperature (°C), specific conductivity (µS/cm), and turbidity (FNU) (Table 2). Data from 2021 are included in the table for comparison. These data cover approximately the same calendar year period as 2022.

Table 2. Range (surface minimum and surface maximum) for each primary field parameter over the 4/7/2022 – 10/18/2022 period at the stream and lake sites. Generally, each range consists of 15 sampling events. Note that stations S-222 and S-279 were sampled four times during routine field sampling events. The period for these two stations is 4/19/2022 through 10/4/2022. Results from 2021 cover 4/6/2021 – 10/19/2021. Stations S-222 and S-279 were sampled five times during routine field sampling events in 2021. The period for these two stations is 4/20/2021 through 10/5/2021.

Station	Field pH (SU)	Field DO (mg/L)	Water Temp. (°C)	Spec Cond. (µS/cm)	Turbidity (FNU)
RL-19154	6.30 - 8.87	5.21 - 10.25	17.20 - 31.08	50.8 - 104.0	3.02 - 66.07
RL-19154-2021	7.12 - 8.95	5.85 - 10.22	18.24 - 32.30	75.9 - 100.2	3.94 - 10.74
S-326	6.22 - 9.25	6.33 - 11.52	17.43 - 31.67	40.4 - 92.9	1.99 - 92.27
S-326 -2021	6.97 - 9.69	6.08 - 13.13	19.57 - 31.51	70.7 - 94.9	1.99 - 12.29
S-309	6.29 - 9.26	6.68 - 12.54	15.42 - 31.77	75.3 - 226.9	5.13 - 93.16
S-309 -2021	7.38 - 9.04	7.45 - 14.09	17.98 - 32.01	103.0 - 172.4	4.12 - 11.58
S-222	6.57 - 8.97	6.55 - 9.25	18.46 - 31.06	58.0 - 86.1	2.18 - 53.49
S-222 -2021	7.72 - 8.82	8.16 - 10.41	21.42 - 30.55	73.1 - 83.1	1.76 - 3.71
S-279	6.98 - 8.36	7.23 - 8.63	18.28 - 30.11	67.0 - 87.3	1.34 - 10.88
S-279 -2021	7.58 - 8.46	7.64 - 10.18	20.58 - 30.22	70.6 - 80.1	0.93 - 2.61

An expanded suite of surface measurements was also collected at each lake site including sensor-based chlorophyll-a (RFU) and phycocyanin (RFU) (Table 3). In addition, upper water column features were measured such as penetration depth of photosynthetically active radiation (PAR, 400-700 nm wavelength, µmol m^{-2} s^{-1}) using a LI-COR light meter and a LI-1400 data logger and water clarity expressed as secchi depth (m). PAR depth was determined as the depth in which PAR decays to 1% of its ambient value. The chlorophyll-a and phycocyanin maximums were determined from the vertical profile downcast and described as either a discrete depth or vertical band where pigment fluorescence was highest. Data from 2021 are included in the Table 3 for comparison with 2022. The 2021 data span approximately the same calendar year period as 2022 except for chlorophyll-a and phycocyanin which cover 5/5/2021 through 10/19/2021 when calibration protocols were updated to be consistent with manufacturer recommendations.

Table 3. Range (minimum and maximum) for additional field parameters at the lake sites over the 4/7/2022 – 10/18/2022 study period. Generally, each range consists of 15 sampling events. Note that stations S-222 and S-279 were sampled four times during routine field sampling events. The period for these two stations is 4/19/2022 through 10/4/2022. Results from 2021 cover 4/6/2021 – 10/19/2021. Stations S-222 and S-279 were sampled five times during routine field sampling events in 2021. The period for these two stations is 4/20/2021 through 10/5/2021.

Station	Chl-a (RFU)	Chl-a Max Depth (m)	Phycocyanin (RFU)	Phycocyanin Max Depth (m)	PAR Depth (m)	Secchi Depth (m)
RL-19154	1.95 - 12.34	0.3 - 1.4	0.47 - 2.94	0.3 - 1.4	0.75 - 2.1	0.20 - 0.85
RL-19154-2021	3.04 - 8.92	0.3 - 1.5	0.49 - 2.89	0.3 - 2.0	1.4 - 2.4	0.55 - 0.90
S-326	1.78 - 5.93	0.3 - 2.0	0.62 - 2.75	0.3 - 2.0	0.65 - 2.8	0.15 - 1.00
S-326-2021	2.02 - 4.81	0.3 - 2.0	0.46 - 4.39	0.3 - 2.0	1.8 - 3.4	0.50 - 1.20
S-309	1.59 - 10.41	0.3 - 1.5	0.57 - 2.90	0.3 - 1.6	0.3 - 2.6	0.15 - 0.95
S-309 -2021	2.05 - 7.09	0.3 - 1.1	0.58 - 2.12	0.3 - 1.3	1.7 - 2.5	0.45 - 0.85
S-222	1.48 - 3.02	0.3 - 2.0	0.32 - 1.13	0.3 - 2.0	0.8 - 3.0	0.15 - 1.10
S-222-2021	1.55 - 3.26	0.3 - 1.5	0.25 - 1.00	0.3 - 1.5	2.6 - 3.9	0.90 - 1.30
S-279	1.15 - 3.11	0.3 - 4.0	0.10 - 0.62	0.3 - 4.0	2.0 - 5.2	0.65 - 1.80
S-279-2021	0.79 - 2.51	0.3 - 4.5	0.14 - 0.48	0.3 - 4.5	4.9 - 5.6	1.40 - 1.65

Vertical Profile

Vertical profiles were collected at each lake site visit using a YSI EXO2. The casts were conducted manually, but data were logged by the instrument every second. The sonde was gradually lowered through the water column (downcast) until contact was made with the lake bottom and then retrieved at a similar rate. An Excel tool was used to process raw vertical profile data. The tool extracts the downcast from the profile record by identifying when instrument descent was initiated and when retrieval began after contacting the lake bottom. The bottom depth for the profile could be manually adjusted to remove the effects of sediment resuspension on the sensor measurements. The program then averages the downcast data in half meter intervals. Eight parameters were processed for each profile: water temperature, DO concentration, DO percent saturation, pH, turbidity, specific conductivity, chlorophyll-a reflectance, and phycocyanin reflectance.

In total, 53 vertical profiles were collected as part of the 2022 Lake Program: fifteen biweekly profiles at each routine site (RL-19154, S-326, and S-309) and four profiles each at stations S-222 and S-279 as part of the algal growth potential test (AGPT) project component described below. Because profiles are collected on an approximately biweekly schedule, the data can be used to illustrate the evolution of the water column over the course of the field program.

Continuous Monitoring

Continuous monitoring systems were deployed at RL-19154, S-326, and S-309 from 3/24/2022 through 10/31/2022. Each deployment was two to four weeks in duration with data recorded at 30-minutes intervals. End of deployment verifications for all variables were largely successful (Table 4). As noted above, continuous deployments represent a combination of Hydrolab DS5X (approximately through June) and YSI EXO2 records (June through October). EXO2 chlorophyll-a and phycocyanin data were collected at RL-19154 and S-309 for the duration of the study.

Table 4. Percent of continuous monitoring deployments passing end of deployment verifications for each sensor. Assessment criteria for each parameter is identified in the column header parentheses. Note: 10% criterion for phycocyanin is not an approved accuracy rating but provides basic interpretation of sensor performance.

Station	Dissolved Oxygen (0.2 mg/L)	pH (0.2 SU)	Specific Conductivity (10%)	EXO2 Chlorophyll-a (10%)	EXO2 Phycocyanin (10%)	Turbidity (10%)
RL-19154	100% (16)[a]	100% (16)[a]	100% (16)[a]	83% (12)[b]	75% (12)[b]	94% (16)[a]
S-326	100% (12)[a]	100% (12)[a]	100% (12)[a]	100% (4)[c]	100% (4)[c]	92% (12)[a]
S-309	100% (12)[a]	100% (12)[a]	92% (12)[a]	89% (9)	78% (9)	83% (12)[a]

a: Records compiled using a combination of Hydrolab DS5X and YSI EXO2 deployments. All deployments were EXO2 instruments beginning approximately early July.

b: Hydrolab DS5X records may replace some YSI EXO2 data loss in June.

c: No early season YSI EXO2 chlorophyll-a and phycocyanin due to instrument shortage. Percentages based on four approximately month-long deployments starting in early July. Hydrolab DS5X chlorophyll-a data may complete record prior to July.

The following list summarizes end of deployment verifications and equipment challenges:

RL-19154

- Missing chlorophyll-a and phycocyanin data for 6/9-6/28/2022 due to YSI EXO2 failure. Hydrolab DS5X data may fill in data gaps

S-326

- Turbidity records failed to record on two separate consecutive two-week Hydrolab DS5X deployments (5/3-6/1/2022).

S-309

- Two turbidity records lost due to Hydrolab DS5X instrument or battery failure (4/7-4/19/2022 and 6/14-6/28/2022).

Fluorometer-Based Chlorophyll-a

A total of 53 lake samples were collected for fluorometer-based total chlorophyll-a. Samples were collected at the surface (0.3 m) at all sites during all visits. All samples were successfully analyzed

Cyanotoxins

Samples for microcystins analysis were collected at the surface along with each total chlorophyll-a sample. A total of 53 samples were collected. Two samples (S-279 and S-309 on 6/14/2022) were not successfully analyzed.

Algal Growth Potential Testing

Algal growth potential testing (AGPT) samples were collected on 4/19, 6/14, 8/8, and 10/4/2022 as scheduled with USEPA during project development. In total, 20 samples were collected and analyzed successfully.

Photosynthetic Pigments

A total of 53 lake samples were collected for HPLC-based analysis of photosynthetic pigments. Samples were collected at the surface (0.3 m) along with chlorophyll-a and cyanotoxin samples at all sites during all visits. One sample, RL-19154 on 6/14/2022, was lost.

Water Quality

Grab samples for water quality occurred biweekly from 4/7/2022-10/18/2022. Each primary lake site (RL-19154, S-326, and S-309) was sampled 15 times during the field program. S-222 and S-279 were sampled four times as part of the AGPT component described above. Overall completeness of the water quality grab sampling component is 100% as no sample event was omitted due to field team decision or error. In total, 72 grab samples at 53 site visits were successfully collected. The total includes 19 subsurface grab samples collected at S-326 and S-222. Lake sampling followed a biweekly schedule and samples were evenly distributed over the course of the study. All lake laboratory water quality samples were successfully analyzed except for one Total Kjeldahl Nitrogen sample (0.3 m RL-19154 on 5/3/2022) and one total phosphorus sample (6.0 m S-222 on 4/19/2022).

Summary of Findings

The following discussion presents observations of key parameters investigated as part of the 2022 Upper Lake Murray field program and compares present data to 2021. It is not meant to be exhaustive of all data collected during the study. As with the 2021 report, the discussion centers on broad features in the vertical and continuous profile records at S-326 in the Clouds Creek arm of Lake Murray adjacent to the Little Saluda River arm and on summary statistics for grab sample total chlorophyll-a, cyanotoxins (microcystins), phytoplankton plankton distributions, algal growth potential testing, total phosphorus, total nitrogen, and total organic carbon for all sites. Additional figures for other project sites is presented in Appendix A-C.

Vertical Profile

Section plots for temperature, dissolved oxygen, pH, chlorophyll-a reflectance, and phycocyanin reflectance for station S-326 are presented in Figures 2-6. Turbidity and discrete depth averaged points used to produce the section plots for S-326 along with complete section plots suites for RL-19154 and S-309 are presented in Appendix A. The section plots were interpolated from the 15 vertical profiles collected on a biweekly basis at each station. Because the plots are collected at approximately two-week intervals at roughly the same time of day, the interpolated data illustrate the seasonal evolution of the water column at each site for physical and biological parameters.

Many of the physical features in 2021 were observed in 2022. In 2022, early season (April) temperatures averaged 16.6°C with surface temperatures of 17.5 to 18.7°C (Figure 2). The difference between surface and bottom temperatures was 1-3°C. By early May, surface temperatures increased to approximately 26°C with surface to bottom temperature differences of 5-8°C. The early May vertical gradient in temperature may be related to high rainfall and mixing of the system that occurred in April. From July through mid-October, temperature profiles were largely homogenous with surface to bottom temperature difference of less than 1°C. Cool ambient air temperatures preceding the 10/18/2022 sampling event cooled and may have vertically mixed the water column. Average temperatures were approximately 2.5°C cooler than the 2021. These cooler temperatures may have been facilitated by flushing of the system due to the remnants of Hurricane Ian that moved over central South Carolina on 9/30/2022.

As with 2021, there was a consistent feature of lower dissolved oxygen (<2.5 mg/L) below 3-4 m for most of the field season suggesting some water column thermal stratification (Figure 3). In 2021, the low dissolved oxygen feature was first observed on 4/20/2021. The corresponding sampling event on 4/19/2022 showed bottom dissolved oxygen of 7.0 mg/L. Lower subsurface dissolved oxygen was observed first on 5/3/2022 and persisted until approximately the end of August when bottom dissolved increased to 4.3 mg/L by the 9/7/2022 sampling event (Figure 3).

The pH record largely mirrored dissolved oxygen (Figure 4). Periods of higher pH (>8.5) occurred with higher dissolved oxygen (>10 mg/L) near the surface consistent with 2021 observations. In the deeper part of the water column, pH was consistently between 6.0 and 7.5 with lower dissolved oxygen concentrations. Upper water column (<2.0 m) dissolved oxygen and pH were approximately 1.0 mg/L and 0.5 SU higher, respectively, in 2021 compared to 2022.

In general, chlorophyll-a reflectance increased throughout the season (Figure 5). Enhanced chlorophyll-a reflectance on 5/17/2022 (Figure 5) was followed on 6/1/2022 by the highest upper water column dissolved oxygen (Figure 3) and pH (Figure 4) values observed at this site in 2022. Phycocyanin reflectance (Figure 6) appeared partially decoupled from chlorophyll-a reflectance which suggests changes in phytoplankton community structure throughout the growing season.

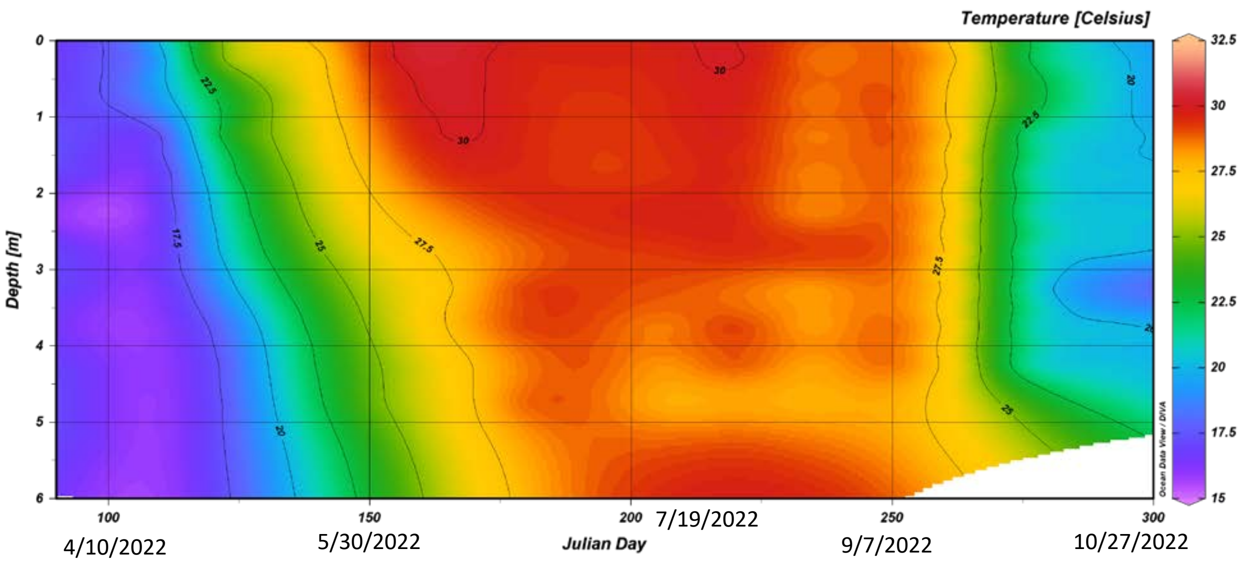

Figure 2. Temperature (°C) section plot for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

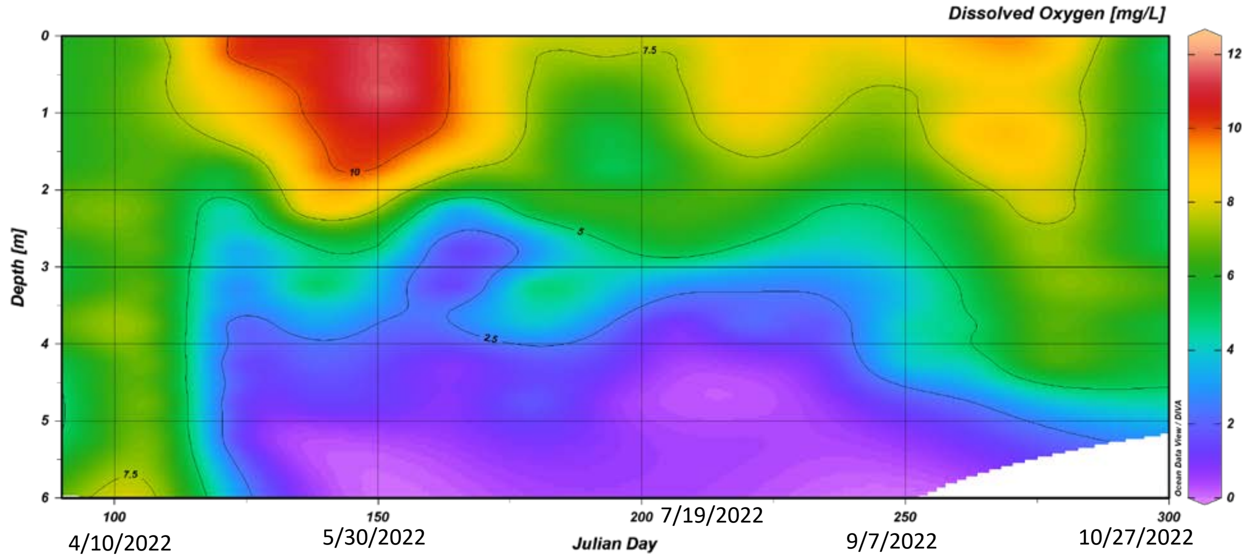

Figure 3. Dissolved oxygen (mg/L) section plot for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

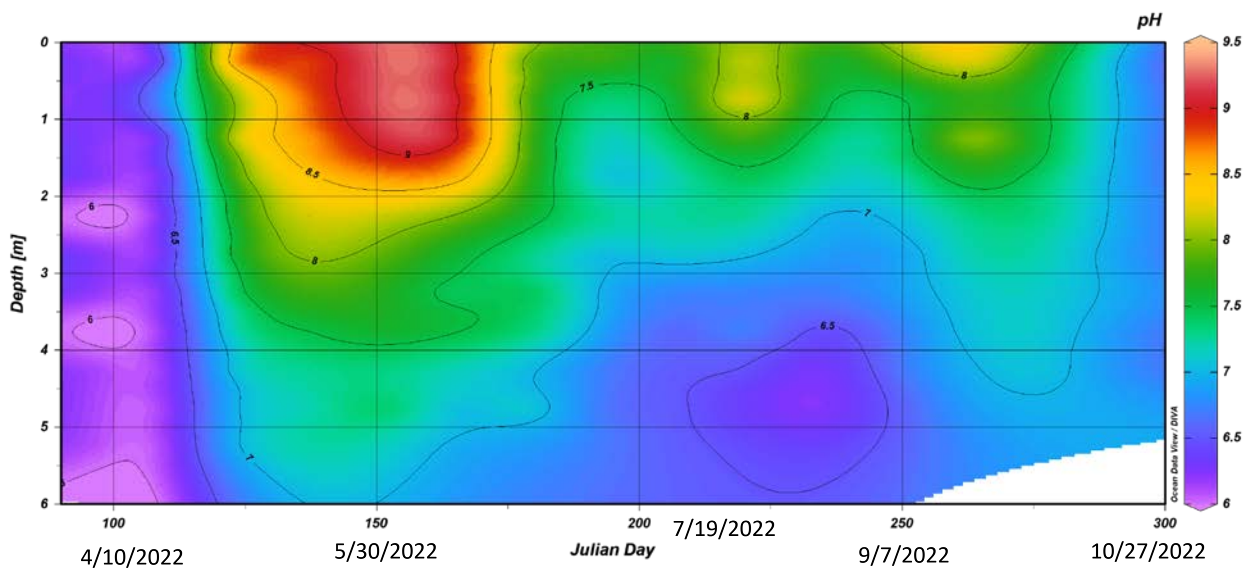

Figure 4. pH section plot for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

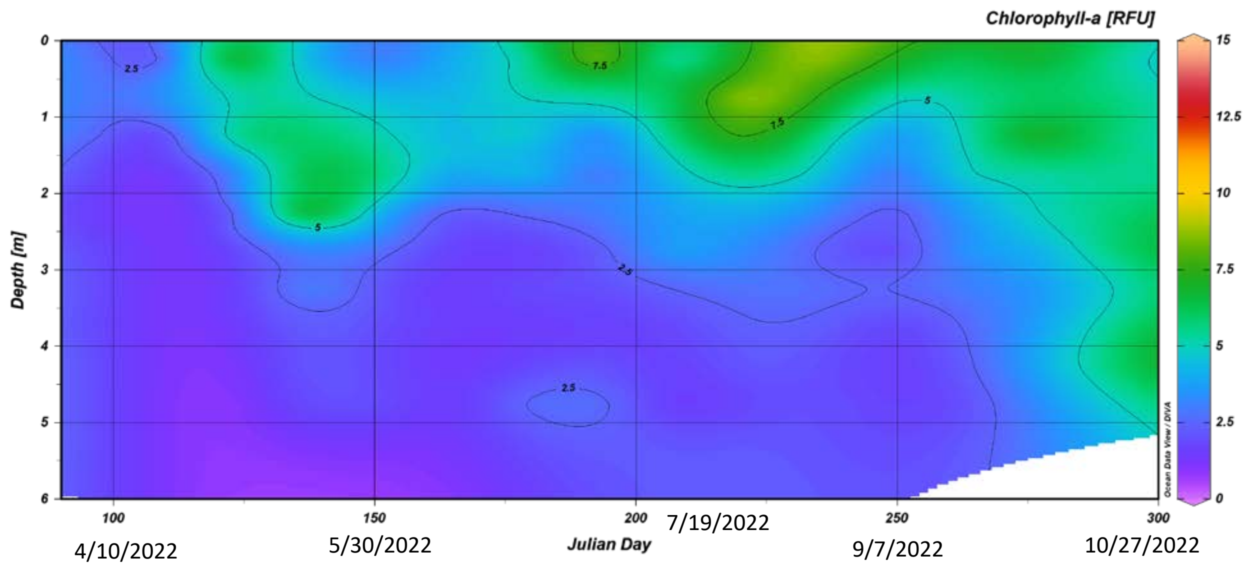

Figure 5. Chlorophyll-a fluorescence (RFU) for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels. Note: The fluorescence scales for Figures 5 and 6 are specific to the respective charts.

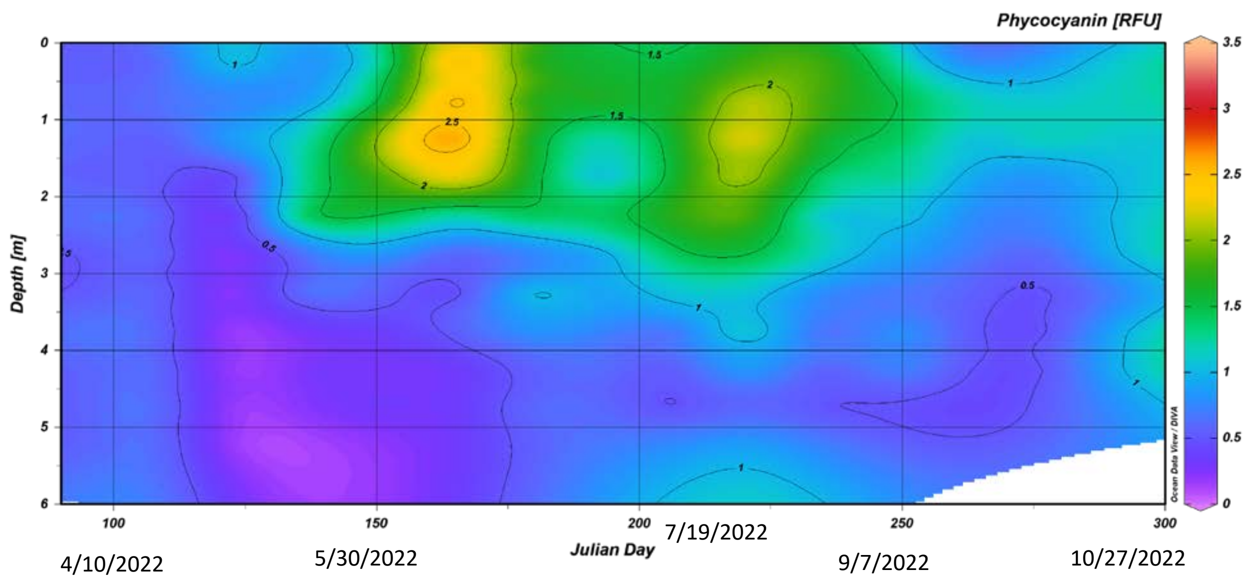

Figure 6. Phycocyanin reflectance (RFU) for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels. Note: The fluorescence scales for Figures 5 and 6 are specific to the respective charts.

Continuous Monitoring

Daily time-series plots of temperature, dissolved oxygen, pH, and chlorophyll-a are presented in Figures 7, 8, 10, and 11 along with an hourly histogram of dissolved oxygen for S-326 in 2022 (Figure 9). Time-series plots and histograms for RL-19154 and S-309 are presented in Appendix B. The progression in daily average surface temperatures in 2022 was similar to 2021 (Figure 7) with a few notable differences. In 2022 the maximum daily average temperature of 31.8°C was reached on 7/7/2022, while the 2021 maximum of 31.1°C occurred on 7/31/2021. As noted above, Hurricane Ian moved through central South Carolina at the end of September which may have cooled, flushed, and mixed the water column. This cooling feature was also observed in the continuous monitoring data (Figure 7). Surface temperatures decreased by approximately 5°C from late September to early October.

In general surface dissolved oxygen concentrations were lower in 2022 than 2021 (Table 5). June 2022 demonstrated the highest monthly average maximum dissolved oxygen concentration consistent with 2021 (Figure 7, Table 5). However, April 2022 average minimum and maximums were more than 2 mg/L lower compared to 2021, which was possibly associated with several high rainfall events and flushing of the system. Further, monthly average minimums and maximums were lower in 2022 for April through August. Average maximum dissolved oxygen in 2022 was slightly higher than 2021 in September. October 2022 average minimum and maximum values were higher than 2021 possibly associated with more rapid cooling (Figure 7) coupled with late season phytoplankton production (Figure 5). On an hour-by-hour basis, 2021 demonstrated dissolved oxygen levels approximately 0.5 mg/L higher than in 2022 (Figure 9). Daily maximums generally occurred in the late afternoon (1800h in 2021 and 1700h in 2022) with daily minimums mid-morning (0700h in 2021 and 0800h in 2022).

As with dissolved oxygen, pH in April 2022 was lower than in 2021 with differences in the average monthly maximums of approximately 1.0 SU (Table 6). The low April 2022 dissolved oxygen and pH averages are related to a sharp decrease and narrowing of the maximum and minimums for both parameters that occurred in the second week of April and persisted for several days (Figures 8, 10). The decreases for these parameters coincide with slight and temporary 1.5°C decrease in water temperature that occurred between 4/8/2022 and 4/11/2022. In both years, average maximum daily pH occurred in June where nearly all maximum daily values exceeded the State pH standard of 8.5 (Table 6; 30 days in 2022 and 27 in 2021). In total, daily maximum pH values exceeded 8.5 on 134 days of the 222-day record for 2022 (60%), which is similar to 2021 where the pH standard was exceeded on 122 of the 212 days for that record (57%).

Continuous chlorophyll-a and phycocyanin records at S-326 are limited to 7/12/2022 through 10/31/2022 (Figure 11). Therefore, this discussion will focus on phytoplankton features observed among the three lake sites. Early in the growing season, the chlorophyll-a and phycocyanin reflectance profiles were generally in-phase at RL-19154 and S-309 (Appendix B). At these sites, phycocyanin decoupled from chlorophyll-a in mid- to late July possibly indicating a shift in the phytoplankton community to a more cyanobacteria dominated assemblage. The apparent decoupling persisted until early September at these sites. At S-326, chlorophyll-a and phycocyanin remained coupled through summer, which may also suggest the prevalence of cyanobacteria.

Each site demonstrated a unique pattern shift in chlorophyll-a and phycocyanin following the remnants of Hurricane Ian in late September. At S-326 chlorophyll-a increased gradually while phycocyanin remained relatively constant which is possibly attributed to a shift to a more diverse, fall phytoplankton assemblage (Figure 11). Both chlorophyll-a and phycocyanin at RL-19154 increased from the middle of October until the end of the month (Appendix B). At S-309, both chlorophyll-a and phycocyanin increased in the middle of October; however, the chlorophyll-a increase was distinct and yielded the highest values observed at the site for 2022. The responses at both sites may represent late season sustained phytoplankton production with relatively high contributions of cyanobacteria.

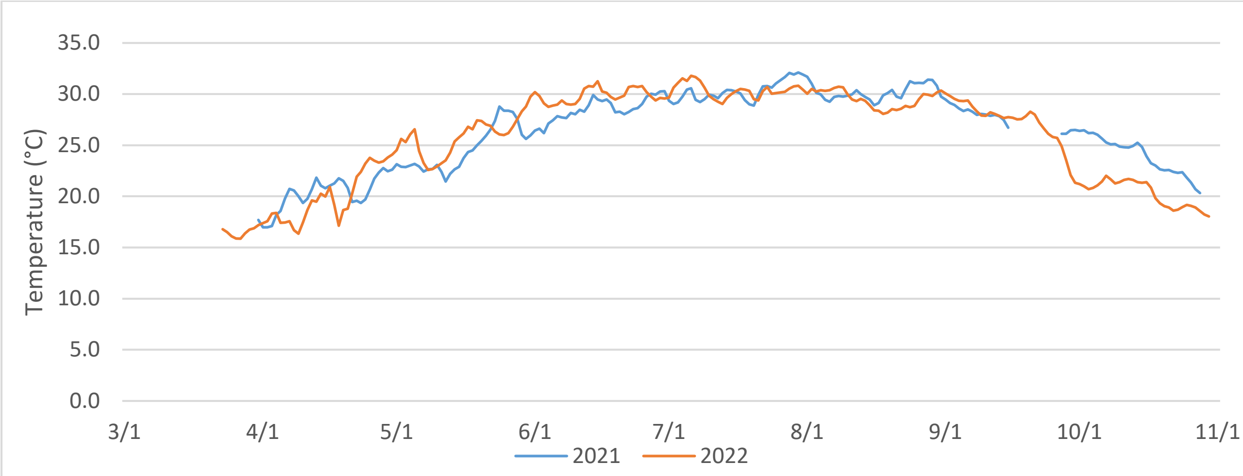

Figure 7. Average daily temperature at S-326 in Clouds Creek arm of Lake Murray for 2021 and 2022. Data loss occurred due to a temperature sensor failure for September 17-27, 2021.

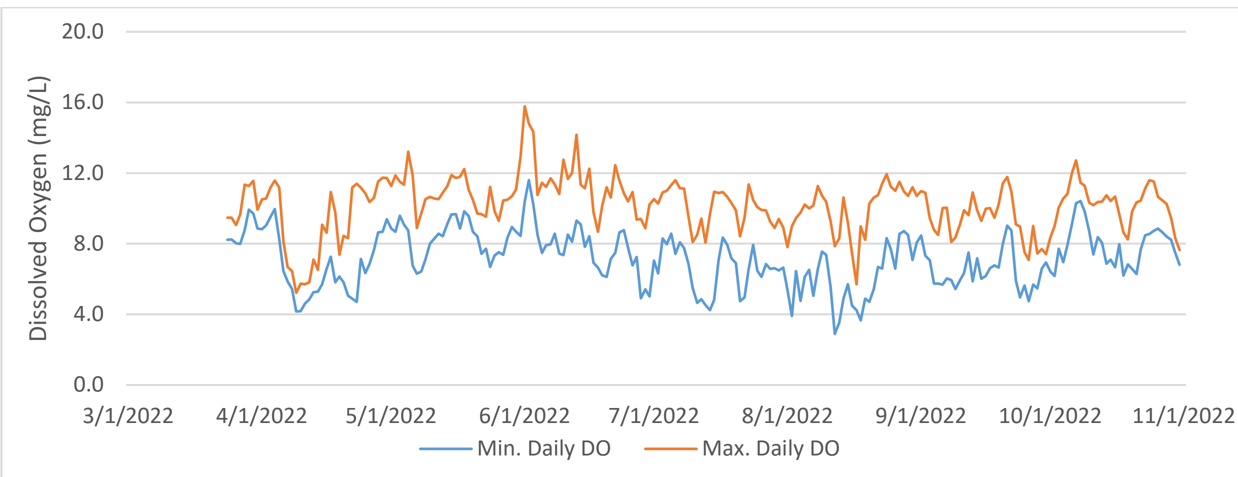

Figure 8. Daily minimum and maximum recorded dissolved oxygen concentrations (mg/L) at S-326 in Clouds Creek arm of Lake Murray.

Table 5. Month by month average minimum and maximum dissolved oxygen concentration along with average daily range in recorded values for 2022 at S-326. Summary values from 2021 are included for comparison of the data. Data loss occurred due to a temperature sensor failure for September 17-27, 2021. All units in mg/L.

Month	Avg. Daily Minimum DO	Avg. Daily Maximum DO	Avg. Δ DO	n
April	6.61	9.18	2.57	30
April-2021	9.17	11.26	2.09	30
May	8.29	10.91	2.61	31
May-2021	9.01	11.24	2.23	31
June	7.79	11.40	3.61	30
June-2021	8.02	12.45	4.43	30
July	6.59	10.03	3.44	31
July-2021	7.17	10.68	3.51	31
August	6.01	9.89	3.88	31
August-2021	6.85	10.53	3.68	31
September	6.47	9.39	2.92	30
September-2021	5.46	9.29	3.83	19
October	7.86	10.24	2.38	31
October-2021	6.36	9.56	3.20	29

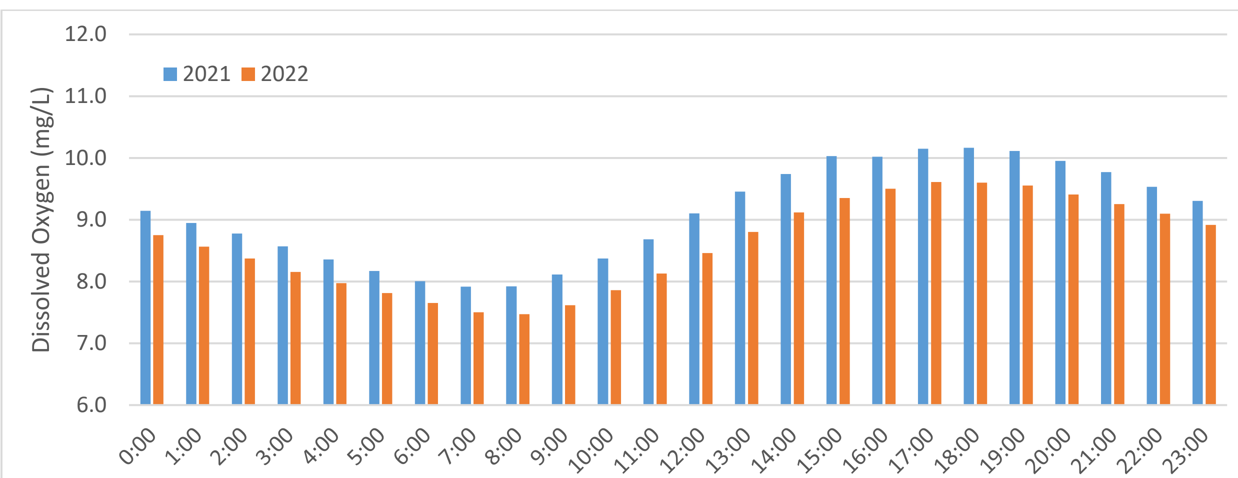

Figure 9. Hourly average dissolved oxygen concentrations (mg/L) for 2021 and 2022 at S-326 in Clouds Creek arm of Lake Murray. Data loss occurred due to a temperature sensor failure for September 17-27, 2021.

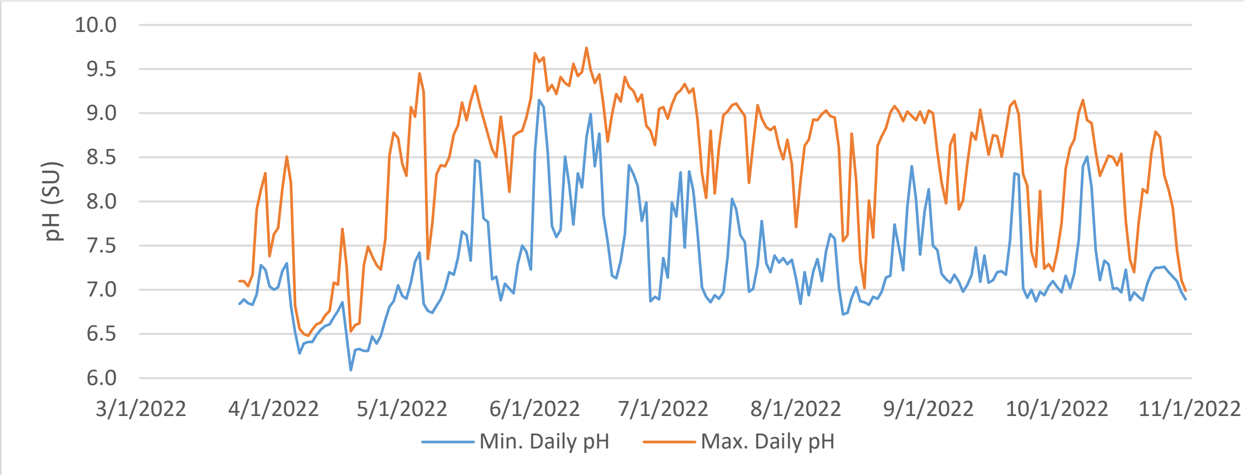

Figure 10. Daily minimum and maximum recorded dissolved pH values at S-326 in Clouds Creek arm of Lake Murray.

Table 6. Month by month average minimum and maximum pH along with average daily range in recorded values and the number of daily maximum values that exceeded 8.5 for 2022 at S-326. Summary values from 2021 are included for comparison of the data.

Month	Avg. Daily Minimum pH	Avg. Daily Maximum pH	Avg. Δ pH	Max. > 8.5	n
April	6.62	7.30	0.68	4	30
April-2021	7.23	8.33	1.10	15	30
May	7.26	8.72	1.45	23	31
May-2021	7.69	8.69	1.00	20	31
June	8.01	9.27	1.26	30	30
June-2021	7.80	9.15	1.35	27	30
July	7.44	8.84	1.40	25	31
July-2021	7.65	8.91	1.26	28	31
August	7.25	8.54	1.30	22	31
August-2021	7.35	8.65	1.30	22	31
September	7.26	8.38	1.12	17	30
September-2021	6.75	7.96	1.21	5	30
October	7.24	8.21	0.97	13	31
October-2021	6.72	7.61	0.89	5	29

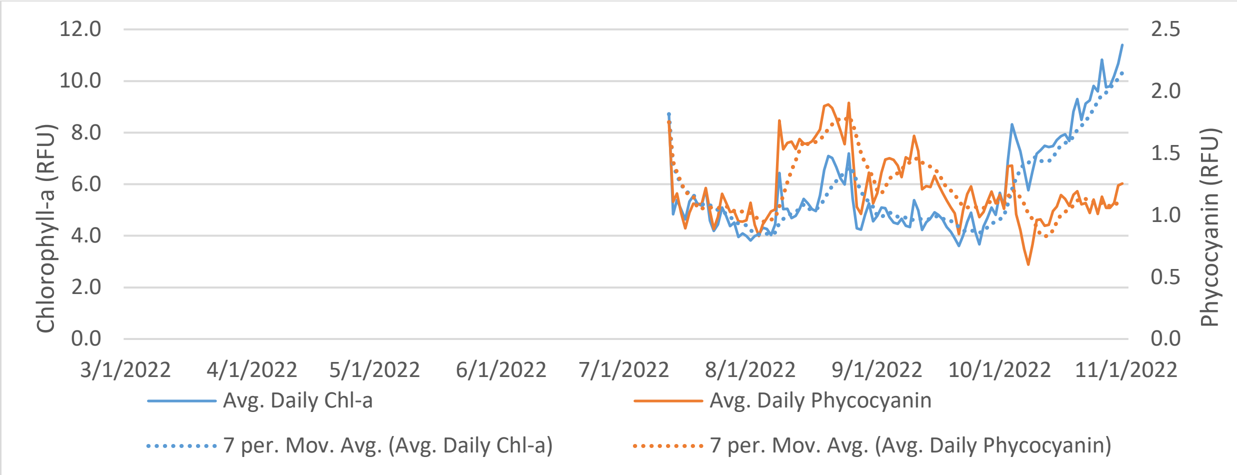

Figure 11. Daily average and moving 7-day average YSI EXO2 chlorophyll-a and phycocyanin fluorescence (RFU) at S-326 in Clouds Creek arm of Lake Murray. The record chlorophyll-a and phycocyanin initiated on July 12, 2022.

Fluorometer-Based Chlorophyll-a

Total chlorophyll-a was highest at RL-19154 in 2022 consistent with 2021 (Table 7). This station also demosntrated the highest year over year increase in average concentration. Average total chlorophyll-a concentrations at S-326 and S-309 showed little change year over year. Median concentrations were generally lower in 2021 at the three primary stations (Figure 13). The lower medians may be influenced partially by a high total concentration outlier present in each 2021 primary station dataset (data points accompanied by black dots; Figure 13). In 2021, 33.3% (5 of 15) of total chlorophyll-a measurements exceeded the State 40 µg/L ecoregional standard for chlorophyll-a at RL-19154. In 2022, the percentage of observations exceeding the standard increased to 53.3% (8 of 15) at this site. One sample excceded the State standard at S-326 in 2021, while two exceedances were recorded in 2022. At S-309, four of 15 samples (26.7%) exceeded 40 µg/L in 2021. In 2022, six of 15 (40.0%) samples exceeded the State standard for S-309.

Table 7. Surface (0.3 m) total chlorophyll-a summary statistics for each lake station in 2022. T. Chl-a results from the 2021 field program are listed below each 2022 site for reference. Average is presented as ± 1σ. All total chlorophyll-a units in µg/L.

Station	Avg. T. Chl-a			Minimum	Maximum	n
RL-19154	44.3	±	21.3	7.0	84.8	15
RL-19154-2021	36.6	±	18.4	18.0	83.1	15
S-326	28.8	±	10.5	13.7	48.9	15
S-326-2021	29.9	±	15.3	13.3	77.5	15
S-309	35.4	±	16.0	7.3	60.3	15
S-309-2021	35.9	±	14.3	15.0	71.9	15
S-222	20.2	±	6.4	11.2	25.9	4
S-222-2021	16.8	±	2.3	13.1	18.5	5
S-279	12.2	±	9.5	6.7	26.4	4
S-279-2021	10.0	±	1.6	7.2	10.9	5

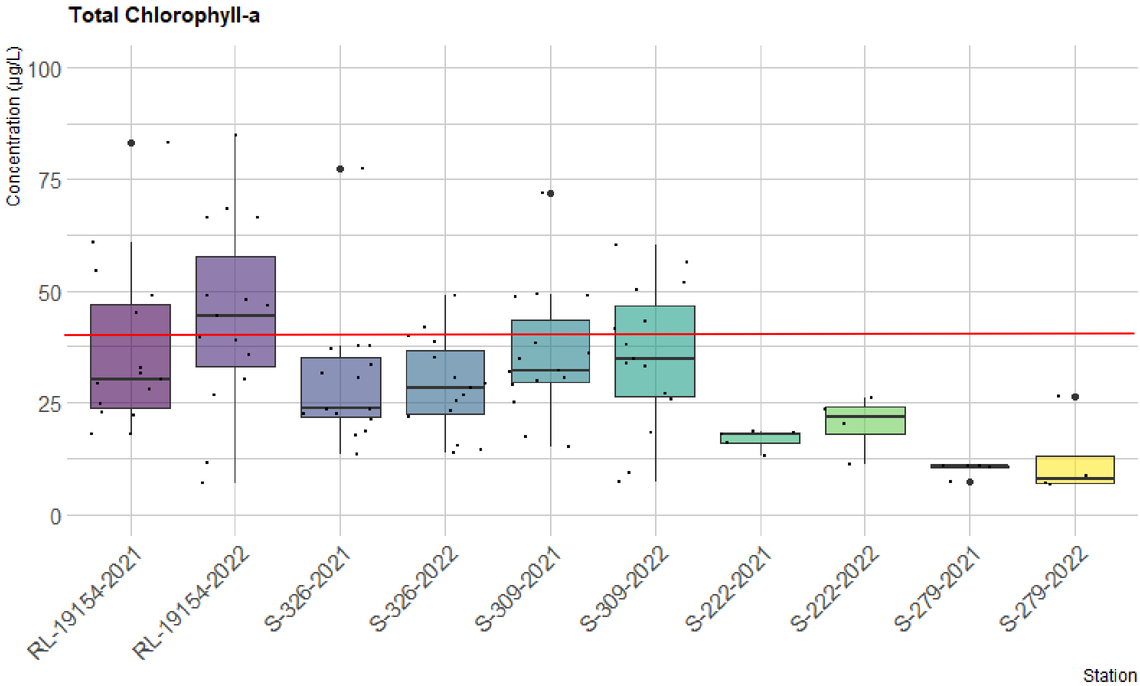

Figure 12. Box plot summary of surface (0.3 m) total chlorophyll-a concentrations (µg/L) for each lake station in 2021 and 2022. Box plots include median, first (lower) and third (upper) quartiles, and ranges (minimum and maximum) for the data. Data points accompanied by a black dot are deemed outliers. The red line denotes the 40 µg/L ecoregional total chlorophyll-a standard.

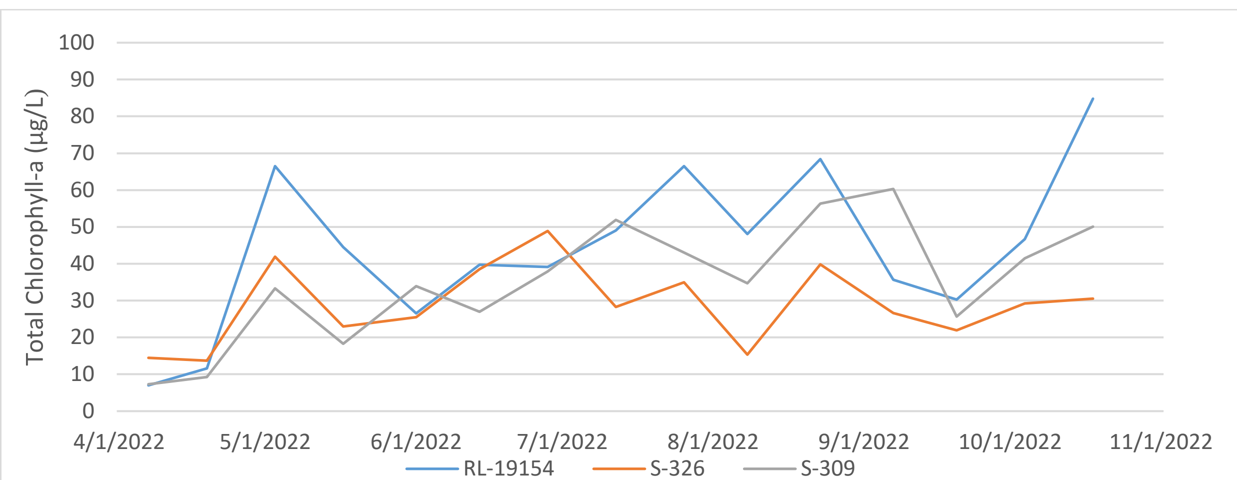

Figure 13. Total chlorophyll-a measurements (µg/L) at the three biweekly lake stations.

Cyanotoxins

In 2021 and 2022, microcystins concentrations at the upper Lake Murray stations were generally low and below the United States Environmental Protection Agency recreational health advisory value and DHEC recreational standard of 8 µg/L.[9,10] Station by station, average microcystins concentrations were slightly higher in 2021 compared to 2022; however, standard deviations are high relative to the averages. These sites are located away from shores and coves and were selected to capture features of the lake arms. Cyanotoxin concentrations are typically higher within blooms of toxin producing cyanobacteria and in coves or nearshore environments where macrophyte algae tend to accumulate. For more information related to cyanotoxin distributions within South Carolina waters, refer to DHEC Bureau of Water Technical Report No. 001-2021.[11]

Table 8. Surface (0.3 m) microcystins cyanotoxin summary statistics for each lake station in 2022. Microcystins results from the 2021 field program are listed below each 2022 site for reference. Average is presented as ± 1σ. Dashes (-) indicate a concentration below analytical detection limit. Given the relatively low microcystins concentrations, values below detection limit are assumed zero in summary statistic calculations. All total microcystins concentrations in µg/L.

Station	Avg. Microcystins	Minimum	Maximum	n
RL-19154	0.133 ± 0.101	-	0.296	15
RL-19154-2021	0.159 ± 0.118	0.008	0.323	14
S-326	0.159 ± 0.083	0.071	0.298	15
S-326-2021	0.164 ± 0.133	0.008	0.500	15
S-309	0.057 ± 0.040	-	0.133	14
S-309-2021	0.089 ± 0.054	0.016	0.215	15
S-222	0.128 ± 0.096	0.046	0.267	4
S-222-2021	0.184 ± 0.111	0.092	0.367	5
S-279	0.102 ± 0.045	0.050	0.131	3
S-279-2021	0.129 ± 0.045	0.064	0.185	5

Algal Growth Potential Testing

The algal growth potential test, or AGPT, measures the bioavailability of nutrients in water bodies. Specifically, the test is used to estimate, under ideal growth conditions, the maximum possible standing crop of algal biomass and to assess nutrient limitation. The method, which uses primary productivity of the freshwater green alga *Selenastrum capricornutum*, is based on Liebig's Law of the Minimum which states that the maximum yield is proportional to the nutrient or combination of nutrients present in lower quantity with respect to the growth requirements for *S. capricornutum*. The measurements are designed to establish baseline data, nutrient growth limiting factors, and the influence of growth promoting nutrients. The AGPT analysis may not reflect natural conditions but provides meaningful insights into nutrient limitation which can guide nutrient management strategies.

As with 2021, surface (0.3 m) AGPT samples from five locations were analyzed four times over the course of the program. The samples were spaced by approximately two months to capture seasonal changes in

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9 U.S. Environmental Protection Agency. 2019. Recommended Human Health Recreational Ambient Water Quality Criteria or Swimming Advisories for Microcystins and Cylindrospermopsin. U.S. Environmental Protection Agency, Office of Water, EPA- 822-R-19-001.

10 South Carolina Department of Health and Environmental Control. Regulations 61-68 Water Classifications and Standards.

11 South Carolina Department of Health and Environmental Control. 2021. 2019 South Carolina Cyanotoxin Distribution Project. Bureau of Water Technical Report No. 001-2021. March 2021.

nutrient limitation. All stations demonstrated nitrogen-limited algal growth in each of the four sampling events in 2022 (Table 9). In contrast, station S-279, an open-lake station in main channel of Lake Murray, demonstrated phosphorus limitation early in the 2021 growing season before shifting to co-limitation in July. By late summer, S-279 became nitrogen limited. All other 2021 sites demonstrated nitrogen limitation for each sampling event.

Table 9. Limiting nutrient to phytoplankton as determined by algal growth potential testing on surface (0.3 m) grab samples.

Station	4/19/2022	6/14/2022	8/8/2022	10/4/2022
RL-19154	Nitrogen	Nitrogen	Nitrogen	Nitrogen
S-326	Nitrogen	Nitrogen	Nitrogen	Nitrogen
S-309	Nitrogen	Nitrogen	Nitrogen	Nitrogen
S-222	Nitrogen	Nitrogen	Nitrogen	Nitrogen
S-279	Nitrogen	Nitrogen	Nitrogen	Nitrogen

Phytoplankton Community Structure

The abundances of specific phytoplankton groups were estimated from indicator pigment concentrations relative to total chlorophyll-a using the CHEMTAX program.[12] CHEMTAX estimates the contribution of algal taxa by iteratively modifying user-specified pigment: chlorophyll-a ratios (initial matrix) using a steepest descent algorithm to successively reduce the root mean square of the residuals. The initial matrix was adapted from Schluter et al. (2006) as part of the DHEC 2019 Lower Catawba River Basin nutrient study (DHEC Tech. Report. No. 009-2020).[13,14] Phytoplankton groups included in the present analysis are cyanobacteria, chlorophytes, diatoms, cryptophytes, dinoflagellates, and euglenophytes.

Simple regression analysis of the 2021 and 2022 Lake Murray fluorometer-based total chlorophyll-a and HPLC-based total chlorophyll-a data indicates a relatively strong relationship between the two analytical techniques ($R^2 = 0.68$; Figure 14). The slope of the Lake Murray data regression (m = 0.81) is similar to the reservoirs of the Lower Catawba River Basin (m = 0.81; DHEC Tech. Report. No. 009-2020).

As with 2021, total chlorophyll-a was variable through the growing season (Figure 13). Despite different seasonal progressions in total chlorophyll-a in 2022 compared to 2021, average concentrations were similar year over year (Table 7). HPLC pigment data largely reflect the progression in fluorometer-based total chlorophyll-a for at the three primary lake sites (Figure 15, Appendix C). Cyanobacteria were generally not present in early April based on CHEMTAX and supported by low concentrations of zeaxanthin and absence of myxoxanthophyll. This feature was also observed in 2021. Cyanobacteria were present from early May through end of the field program largely consistent with 2021. On average cyanobacteria represented a larger percentage of total chlorophyll-a in 2022 compared to 2021. In 2021, cyanobacteria

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[12] Mackey, M.D., Mackey, D.J., Higgins, H.W. and S.W. Wright. 1996. CHEMTAX – A program for estimating class abundances from chemical markers: Application to HPLC measurements of phytoplankton. Marine Ecology Progress Series, 144(1-3), 265-283.

[13] Schluter, L., Lauridsen, T.L., Krogh, G. and T. Jorgensen. 2006. Identification and quantification of phytoplankton groups in lakes using new pigment ratios – a comparison between pigment analysis by HPLC and microscopy. *Freshwater Biology*, 51, 1474-1485.

[14] Baumann, M.S. 2020. Lower Catawba River Basin – Stream and Lake Nutrient Water Quality Study; Final Report of the 2019 Study. SC DHEC Technical Report No. 009-2020.

represented on average 21 – 28% of chlorophyll-a at the three primary lake sites. In 2022, average cyanobacteria represented 44 – 49% of chlorophyll-a for these sites (Figure 16, Appendix C). Chlorophytes represented 31 – 36 % (overall average: 33%) of chlorophyll-a in 2022 as compared to 53% of chlorophyll-a in 2021. In 2021, diatoms represented 9 – 10% of chlorophyll-a with large relative contributions in the spring and fall. In 2022, diatoms represented 6 – 9% of chlorophyll-a also with larger relative contributions in spring and fall.

As noted above, relatively high phycocyanin reflectance was observed in early to mid-June in vertical profile data at S-326 (Figure 6). This feature is supported by the highest measured absolute cyanobacterial chlorophyll-a at S-326 on 6/14/2022 for this site. In addition, late season increases in both chlorophyll-a and phycocyanin reflectance was observed in the continuous data records for S-309 and RL-19154 (Appendix B). These sensor-based observations are reflected in increasing fluorometer- and HPLC-based total chlorophyll-a (Figure 13, Appendix C) along with increasing cyanobacterial-chlorophyll-a (Appendix C) from early to mid-October at these sites. These observations suggest that sensor-based data are capturing features observed in laboratory-based datasets.

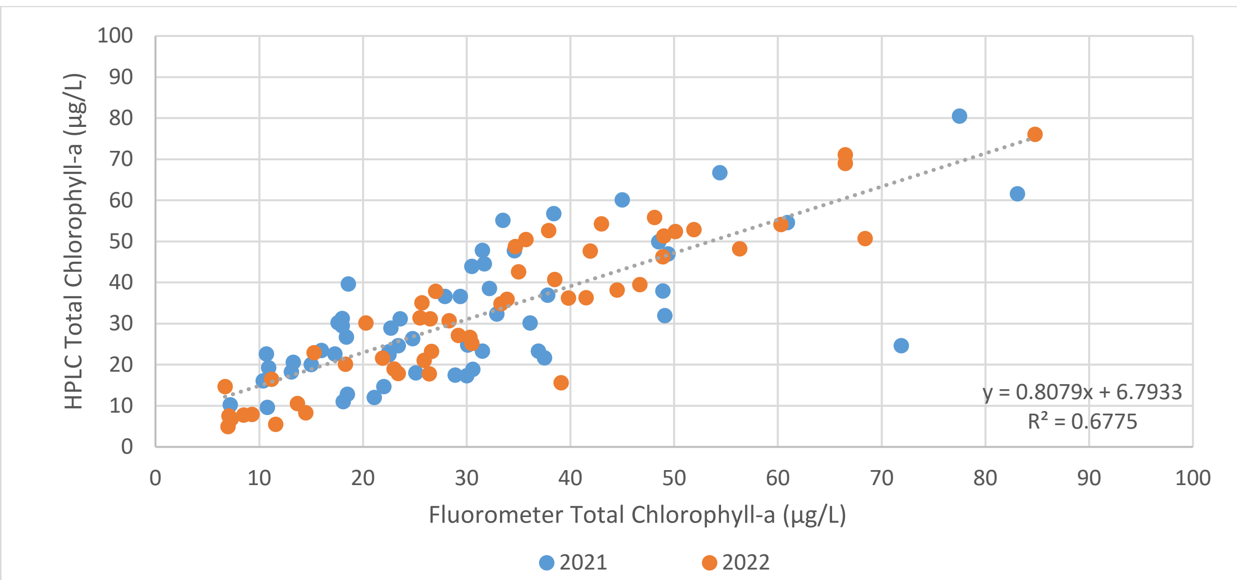


Figure 14. Comparison of total chlorophyll-a concentrations (µg/L) determined using fluorometer and HPLC techniques.

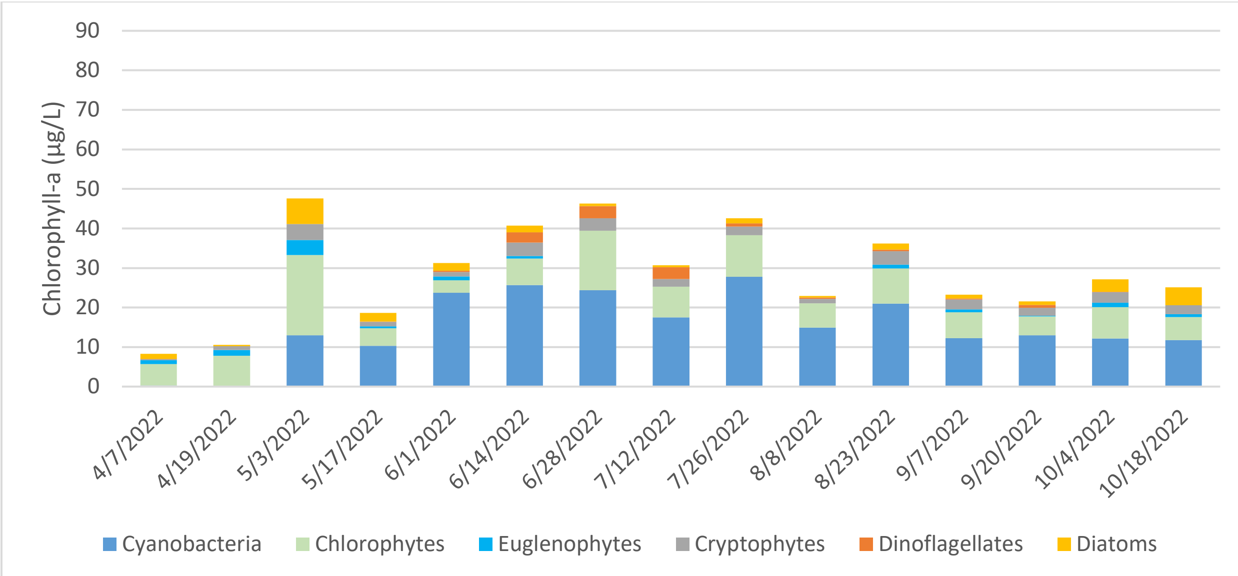


Figure 15. Absolute contribution of primary phytoplankton groups to HPLC-based chlorophyll-a as determined by CHEMTAX at S-326 in Clouds Creek arm of Lake Murray in 2022. All samples were collected at the surface (0.3 m). Scale based on 2021 data.

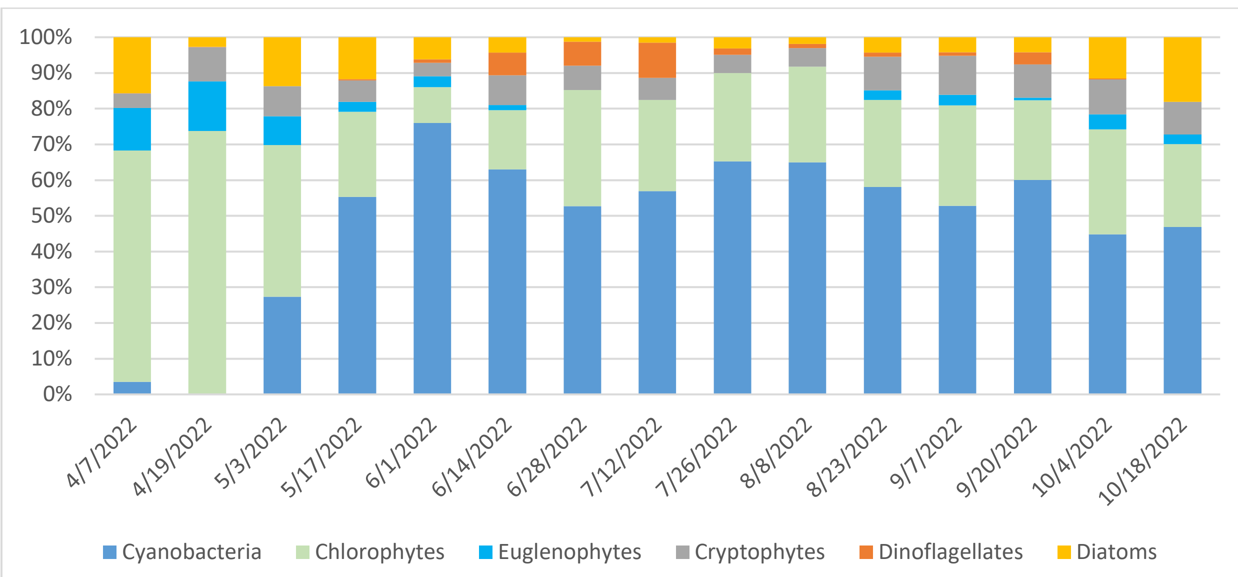


Figure 16. Relative contribution of primary phytoplankton groups to HPLC-based chlorophyll-a as determined by CHEMTAX at S-326 in Clouds Creek arm of Lake Murray in 2022. All samples were collected at the surface (0.3 m).

Water Quality - Nutrients

The water quality data collected in 2022 provide important year-over-year variability in the nutrient conditions in the upper Lake Murray lake arms. The comprehensive water quality data set collected as part of this study, the 2021 lake arm program, wet-weather synoptic watershed project, and routine ambient monitoring will be used to support various components of TMDL development for priority restoration areas in upper Lake Murray including watershed loading and lake water quality models. The following discussion summarizes surface grab sample (0.3 m) results for total phosphorus (TP) and total nitrogen (TN), two nutrient parameters regulated in lakes by the State, as well as total organic carbon (TOC). Note that TN is not explicitly measured but reported as the sum of Total Kjeldahl Nitrogen (TKN, sum of ammonia/ammonium and organic nitrogen) and nitrate/nitrite.

Total phosphorus and total nitrogen concentrations were on average higher in 2022 than 2021 at all stations (Tables 10 and 11). The 2022 averages are influenced by relatively high concentrations for the 4/7 and 4/19/2022 samples (outlier points in Figures 17 and 18). These early season samples followed heavy rainfall events in the area (~10 cm precipitation [4”] prior to 4/7/2022 and 3.8 cm precipitation [1.5”] prior to 4/19/2022). High turbidity, elevated lake levels, and debris were noted in the field logbook. High turbidity was also evident in vertical profiling (Appendix A) and in laboratory grab sample analysis. Further, total organic carbon was also elevated during the April sampling events with concentrations 1.5 to 3x higher than were observed from May through October on a site-by-site basis (outlier points in Figure 19).

In 2022, six of 15 (40.0%) total phosphorus measurements exceeded the State ecoregional TP standard (0.06 mg/L) at RL-19154 compared to four exceedances (26.7%) in 2021. No total phosphorus concentrations exceeded the State standard at S-326 in 2021, while three of 15 (20.0%) samples were higher than 0.06 mg/L in 2022. At S-309, 40.0% (six of 15) of total phosphorus values exceeded the State standard; an increase from 2021 in which two exceedances (13.3%) were observed. No measurements exceeded the 1.5 mg/L ecoregional TN standard in 2021. In 2022, two measurements were higher than 1.5 mg/L (one at S-309 and one at S-222 during an AGPT sampling event).

Table 10. Total phosphorus summary statistics for surface (0.3 m) samples 2022. Concentrations from 2021 are included for comparison of the data. For concentrations below the analytical detection limit (0.02 mg/L), a value of one-half the detection limit was substituted (0.01 mg/L). All units in mg/L.

Station	Avg. Total Phosphorus	Minimum	Maximum	n
RL-19154	0.07 ± 0.06	0.02	0.22	15
RL-19154-2021	0.05 ± 0.02	0.01	0.09	15
S-326	0.04 ± 0.03	0.01	0.12	15
S-326-2021	0.02 ± 0.01	0.01	0.04	15
S-309	0.09 ± 0.10	0.03	0.38	15
S-309-2021	0.04 ± 0.01	0.03	0.08	15
S-222	0.05 ± 0.07	0.01	0.15	4
S-222-2021	0.02 ± 0.01	0.01	0.03	5
S-279	0.02 ± 0.01	0.01	0.04	4
S-279-2021	0.01 ± 0	0.01	0.01	5

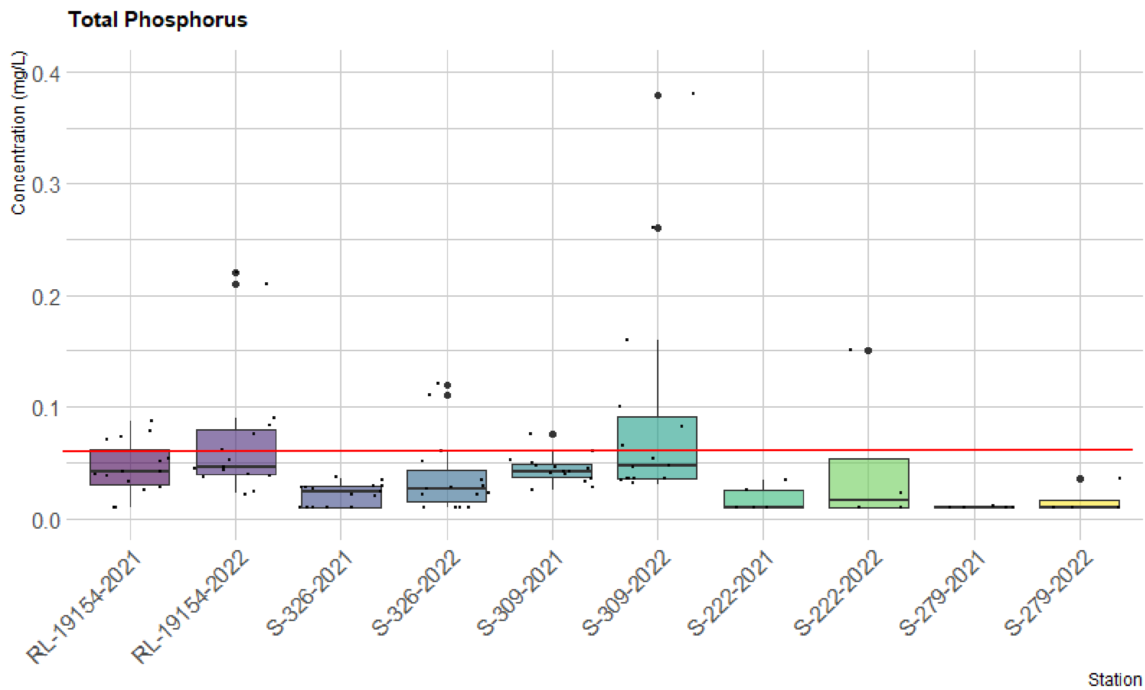


Figure 17. Box plot summary of total phosphorus concentrations (mg/L) measured at each lake station (surface, 0.3 m) in 2021 and 2022. For concentrations below the analytical detection limit (0.02 mg/L), a value of one-half the detection limit was substituted (0.01 mg/L). Box plots include median, first (lower) and third (upper) quartiles, and ranges (minimum and maximum) for the data. The red line denotes the 0.06 mg/L lake ecoregional total phosphorus standard.

Table 11. Total nitrogen summary statistics for surface (0.3 m) samples 2022. Concentrations from 2021 are included for comparison of the data. For concentrations below the analytical detection limit (0.1 mg/L for TKN and 0.02 mg/L for nitrate/nitrite), a value of one-half the detection limit was substituted (0.05 mg/L for TKN and 0.01 mg/L for nitrate-nitrite). All units in mg/L.

Station	Avg. Total Nitrogen	Minimum	Maximum	n
RL-19154	0.75 ± 0.26	0.29	1.21	14
RL-19154-2021	0.68 ± 0.27	0.26	1.21	15
S-326	0.50 ± 0.25	0.06	0.95	15
S-326-2021	0.57 ± 0.30	0.23	1.41	15
S-309	0.69 ± 0.49	0.06	1.71	15
S-309-2021	0.64 ± 0.29	0.24	1.19	15
S-222	0.79 ± 0.50	0.35	1.51	4
S-222-2021	0.52 ± 0.21	0.21	0.78	5
S-279	0.48 ± 0.24	0.24	0.80	4
S-279-2021	0.41 ± 0.23	0.06	0.67	5

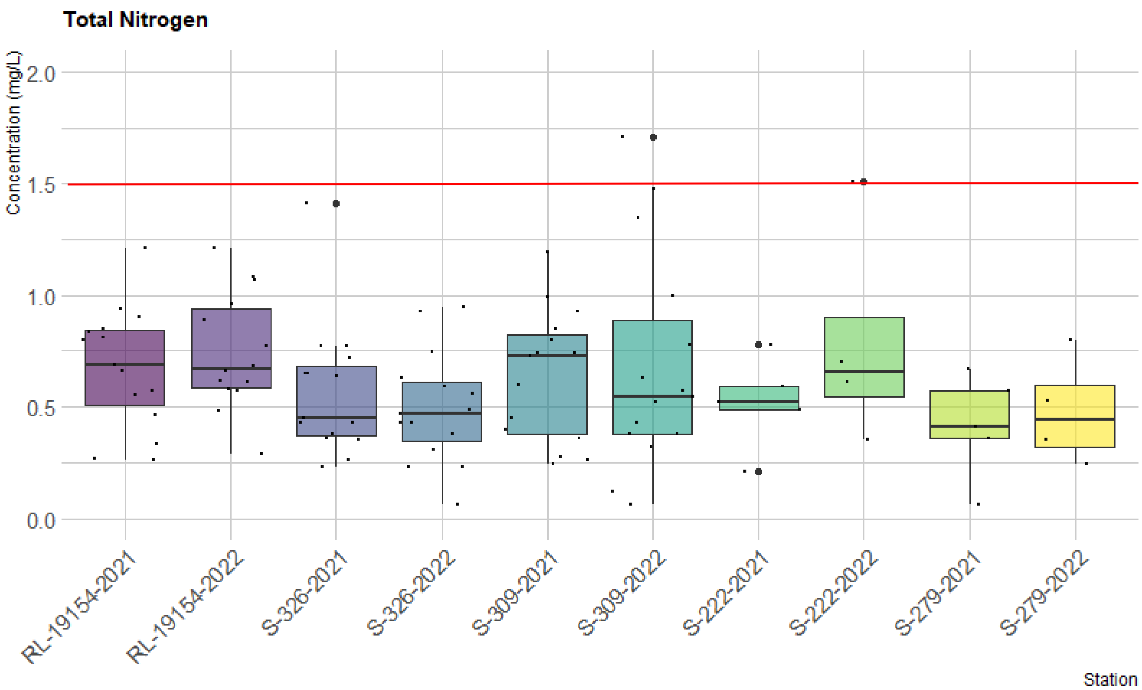


Figure 18. Box plot summary of total nitrogen concentrations (mg/L) measured at each lake station (surface, 0.3 m) in 2021 and 2022. Total nitrogen is reported as the sum of Total Kjeldahl Nitrogen and nitrate-nitrite. For concentrations below the analytical detection limit (0.1 mg/L for TKN and 0.02 mg/L for nitrate/nitrite), a value of one-half the detection limit was substituted (0.05 mg/L for TKN and 0.01 mg/L for nitrate-nitrite). Box plots include median, first (lower) and third (upper) quartiles, and ranges (minimum and maximum) for the data. The red line denotes the 1.5 mg/L lake ecoregional total nitrogen standard.

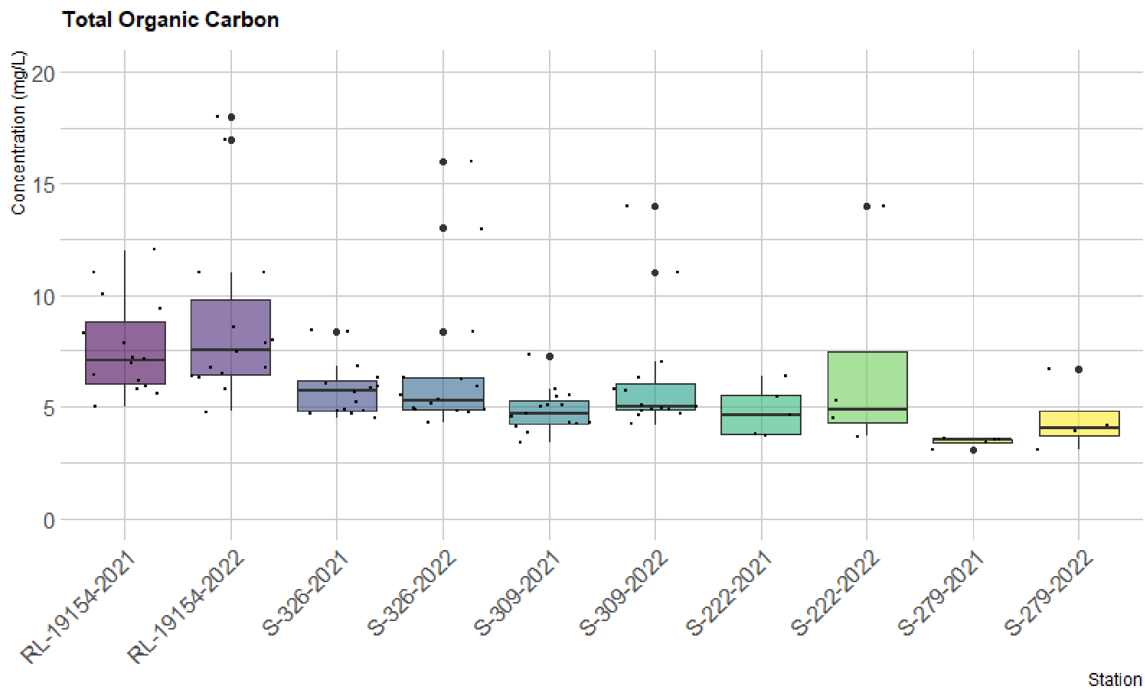


Figure 19. Box plot summary of total organic carbon concentrations (mg/L) measured at each lake station in 2021 and 2022. Box plots include median, first (lower) and third (upper) quartiles, and ranges (minimum and maximum) for the data.

Conclusion

The 2021 and 2022 upper Lake Murray programs are part of a comprehensive effort to resolve the relationship between physical and chemical conditions and ecological responses in designated priority restoration areas of upper Lake Murray. The results collected as part of these programs fill important data gaps and provided insights into year-over-year variability of this system.

In 2022, early (April) and late (late September) weather systems were evident in several components of the project. The April rainfall events produced high turbidity, cooler April temperatures compared to 2021, and mixed the water columns at the three routine lake sites. These events also produced elevated April nutrient concentrations which contributed to higher on average total phosphorus and total nitrogen compared to 2021. However, only RL-19154 showed a marked increase in average total chlorophyll-a among the three primary lake sites. Average total chlorophyll-a at S-326 and S-309 was similar to 2021.

Following the remnants of Hurricane Ian in late September, the primary lake sites demonstrated unique responses in chlorophyll-a and phycocyanin based on continuous monitoring. While it is not possible to compare these data to 2021 because of differences in monitoring equipment, comparisons can be made using laboratory total chlorophyll-a and phytoplankton community composition data. In the continuous monitoring record, chlorophyll-a increased gradually while phycocyanin remained relatively constant which is possibly attributed to a shift to a more diverse, fall phytoplankton assemblage at S-326. At RL-19154 and S-309 both chlorophyll-a and phycocyanin increased from the middle of October until the end of the month. The responses at both sites may represent late season sustained phytoplankton production with relatively high contributions of cyanobacteria. These features were also observed in laboratory-based data sets. Importantly, these observations suggest that sensor-based observations may be reasonably capturing physical and ecological progressions at these sites.

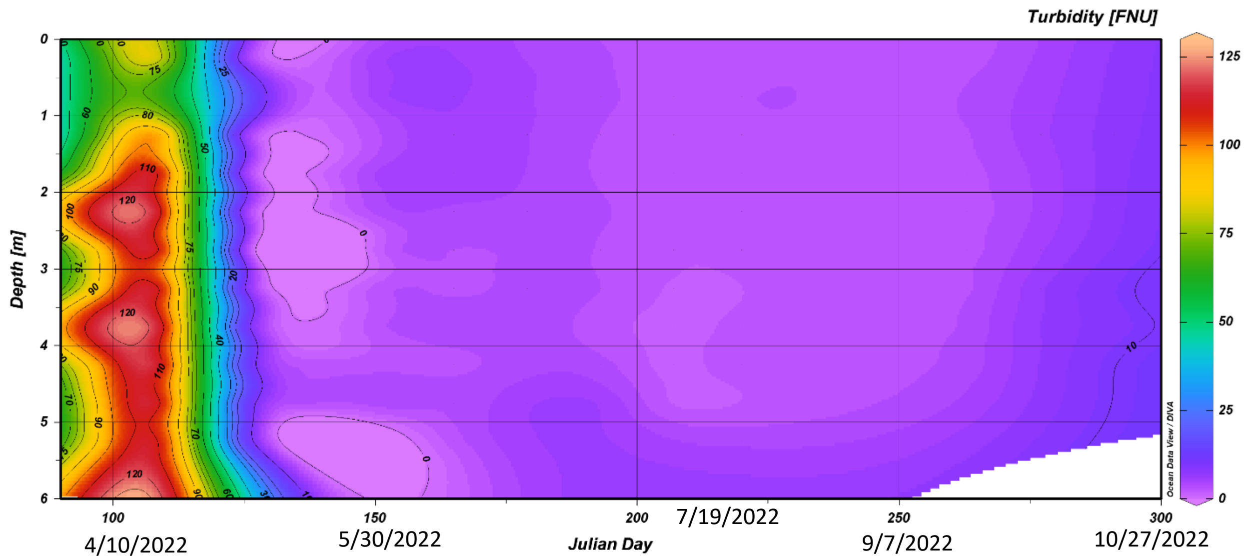
The 2022 upper Lake Murray program will provide a year over year characterization of the system and possibly illustrate lake responses to different environmental and climatological forcing which will enhance interpretation of ecological responses. The aggregated results of these lake programs and accompanying watershed nutrient loading studies will provide a robust data set to develop, calibrate, and validate coupled watershed loading and lake water quality models to inform TMDLs for these priority restoration areas.

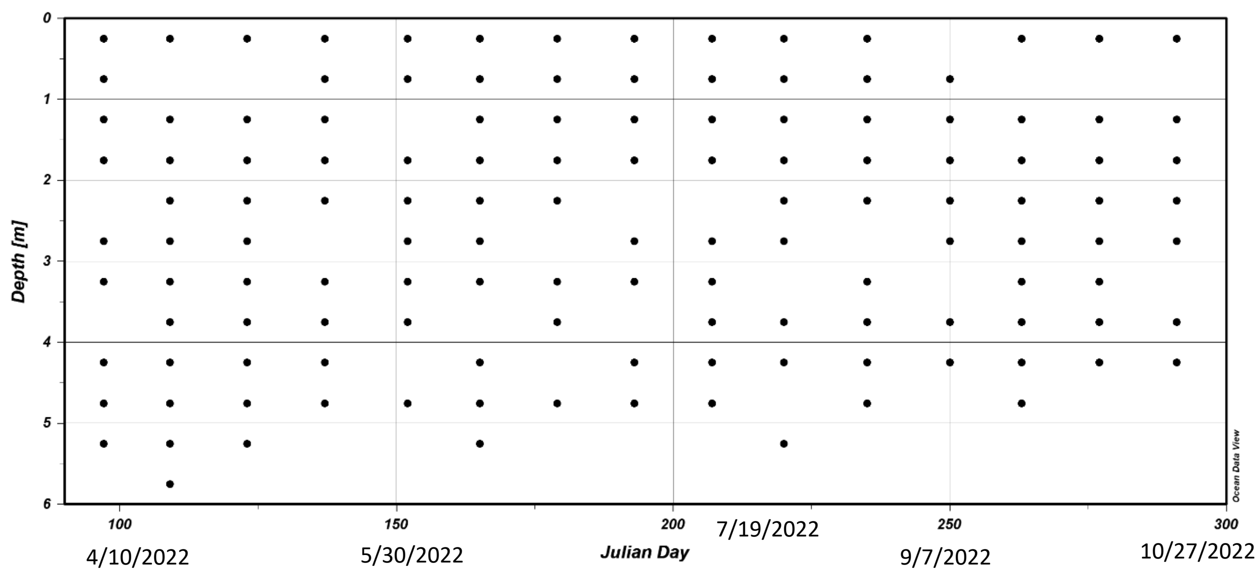
Acknowledgments

This project was made possible through support from DHEC Bureau of Water (BOW) TMDL group as well as Quality Assurance programs from the DHEC BOW and Bureau of Environmental Health Services (BEHS). The BEHS laboratory processed and analyzed water quality samples. Total chlorophyll-a and cyanotoxin samples were processed and analyzed by the BOW Aquatic Science Programs (ASP). Phytoplankton photosynthetic pigments samples were analyzed by the University of South Carolina Estuarine Ecology Laboratory. Field sampling was conducted by personnel from the BOW TMDL and ASP groups.

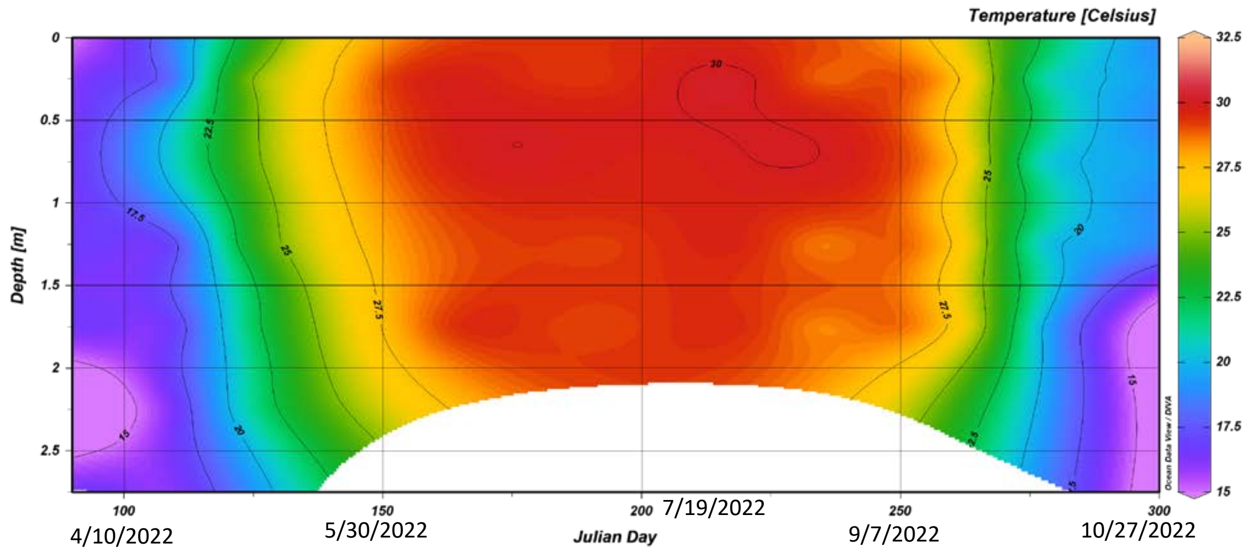
Appendix A – Vertical Profile Section Graphs

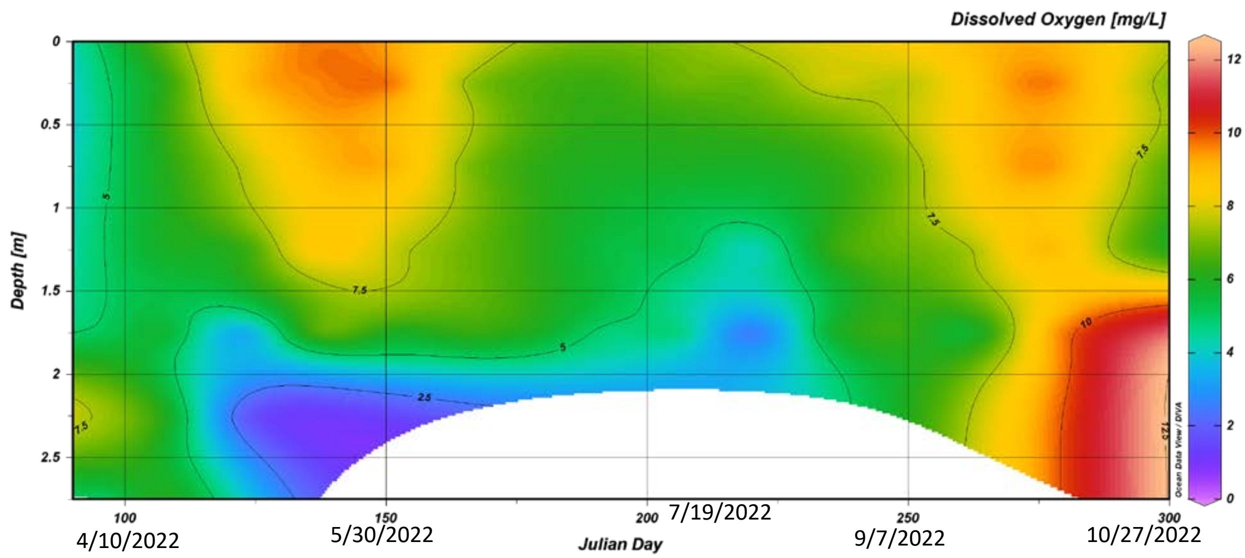
S-326 – Clouds Creek arm (additional section plots, average total depth = 5.1 m)

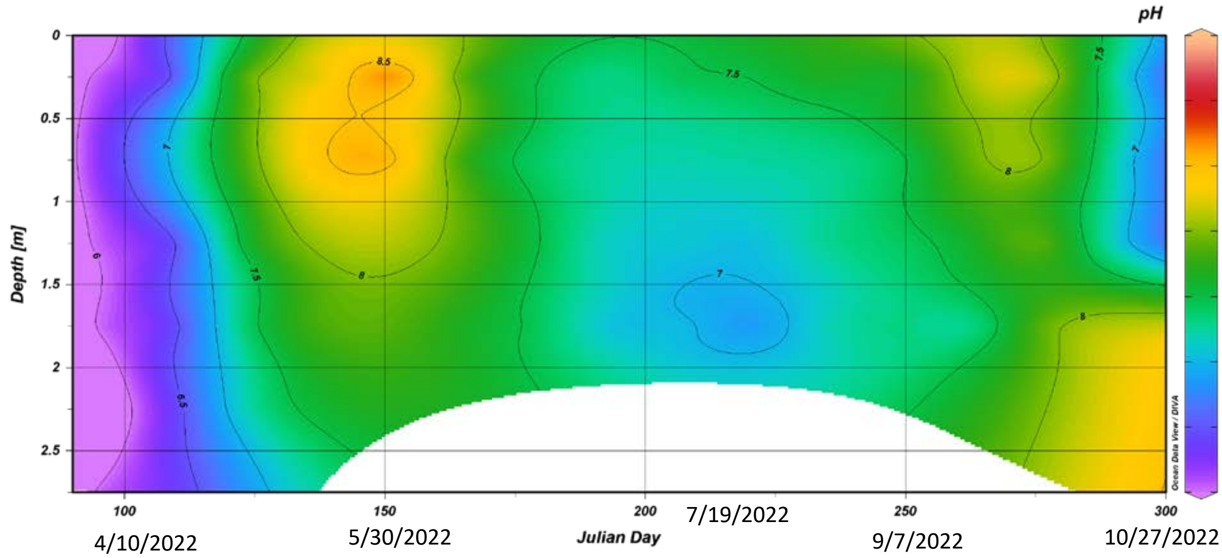


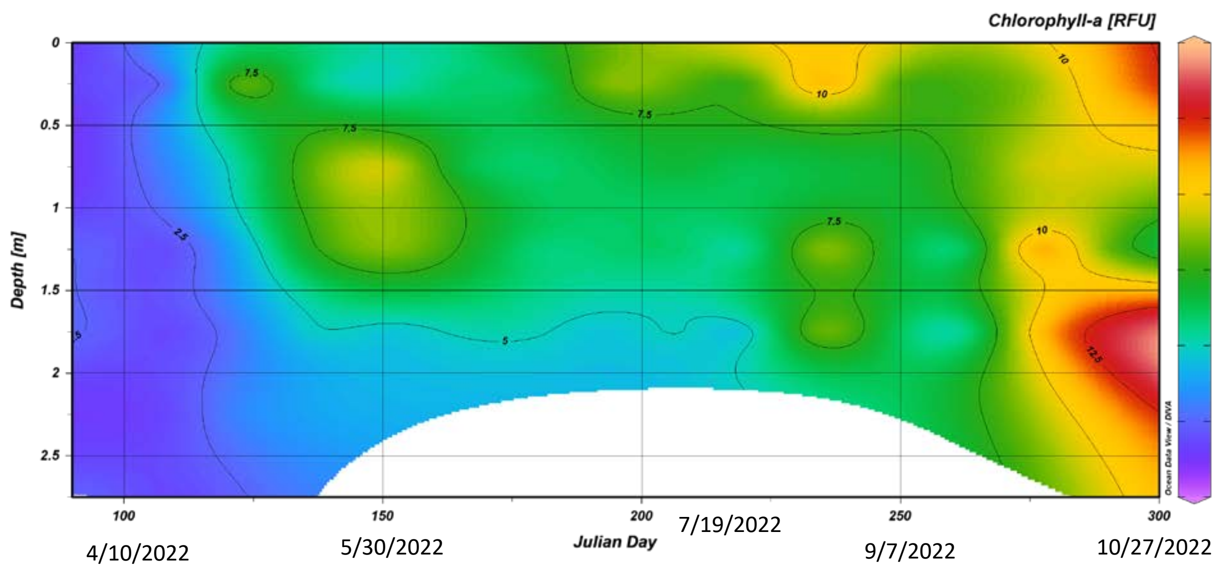


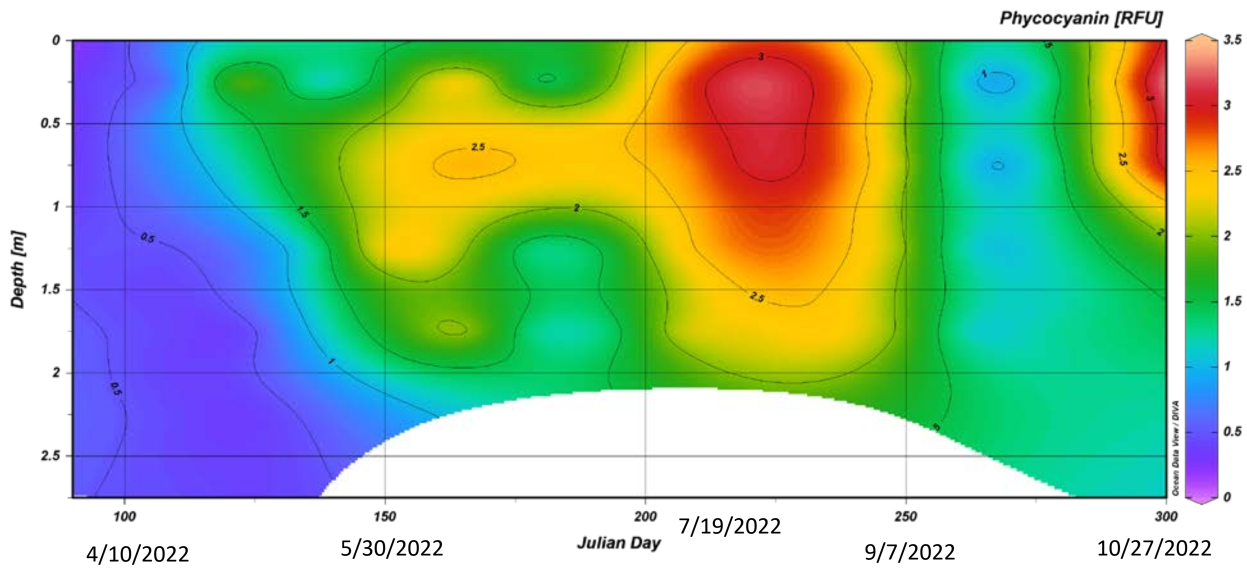
RL-19154 – Little Saluda River arm (average total depth = 2.3 m)

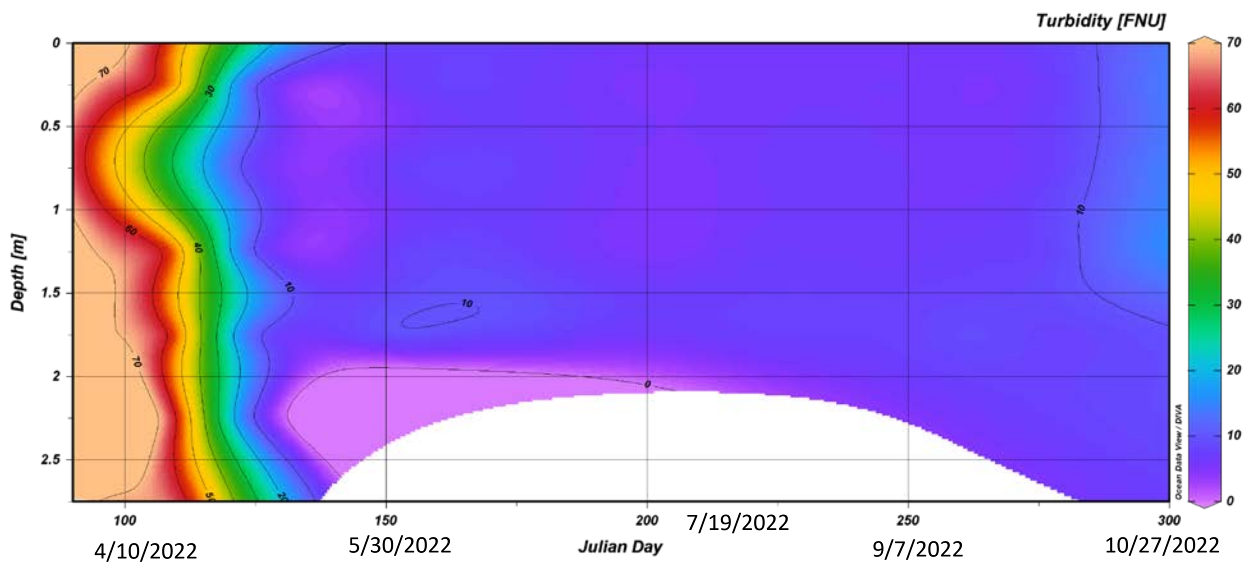


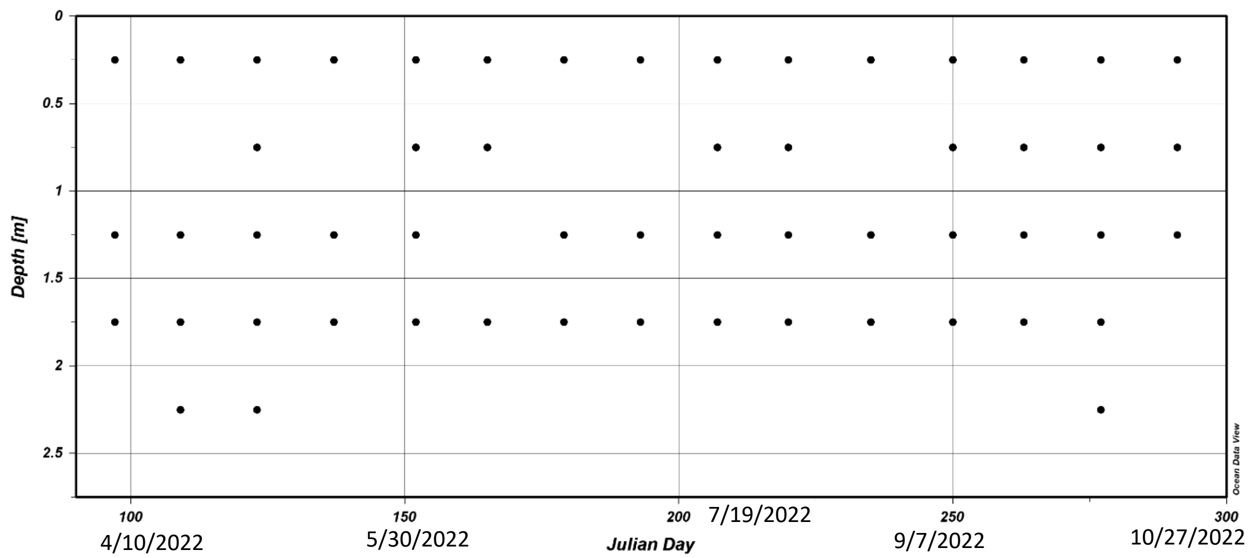



pH
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA


Chlorophyll-a [RFU]
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA

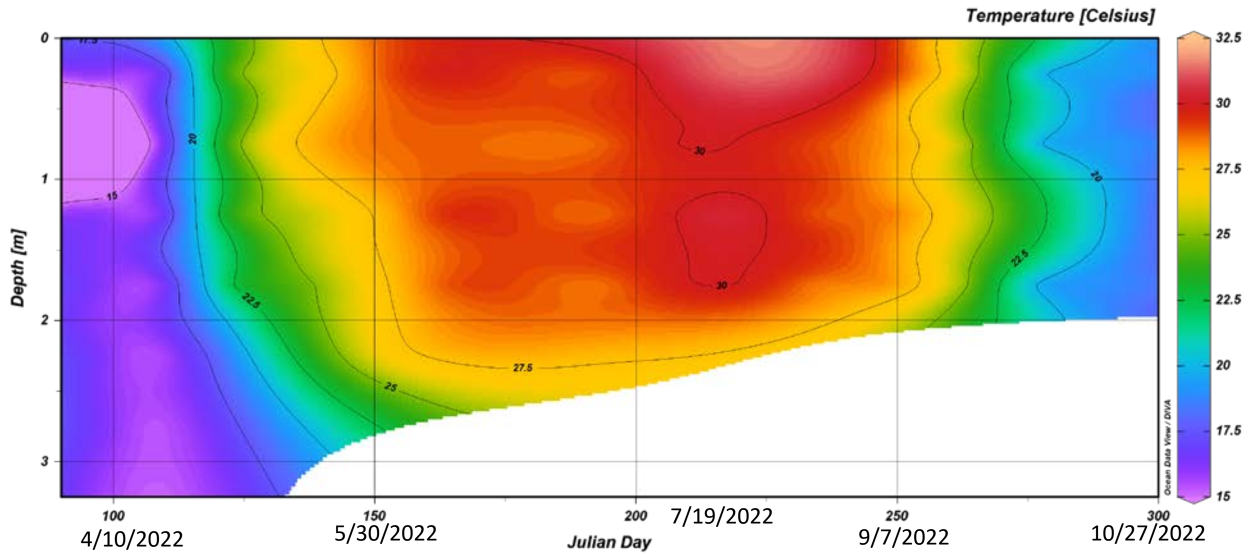

Phycocyanin [RFU]
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA

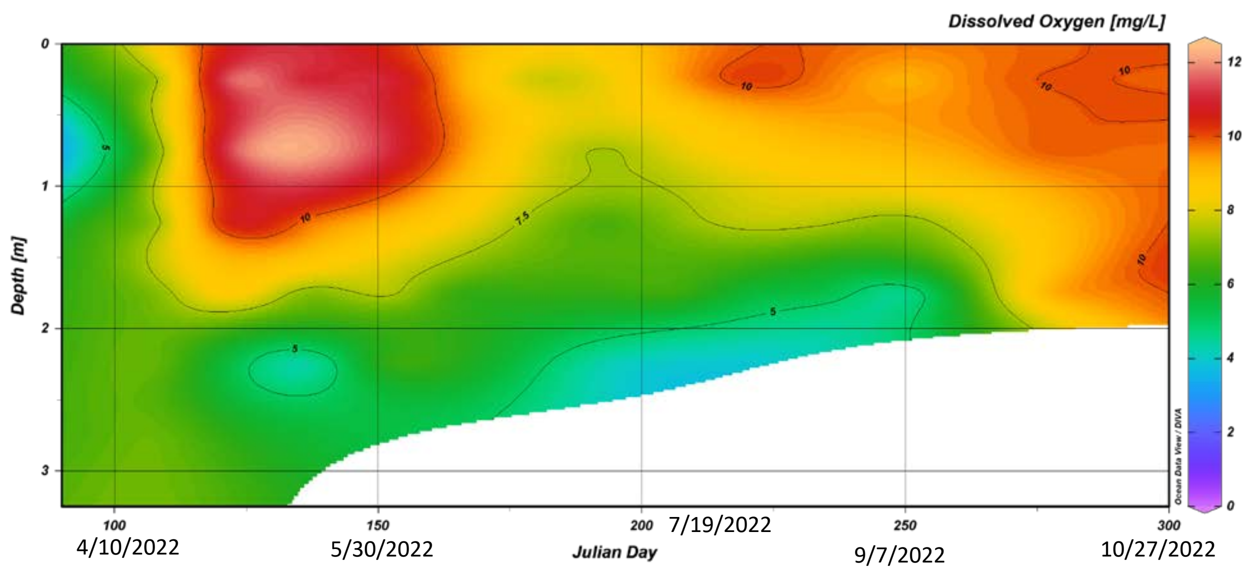

Turbidity [FNU]
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA

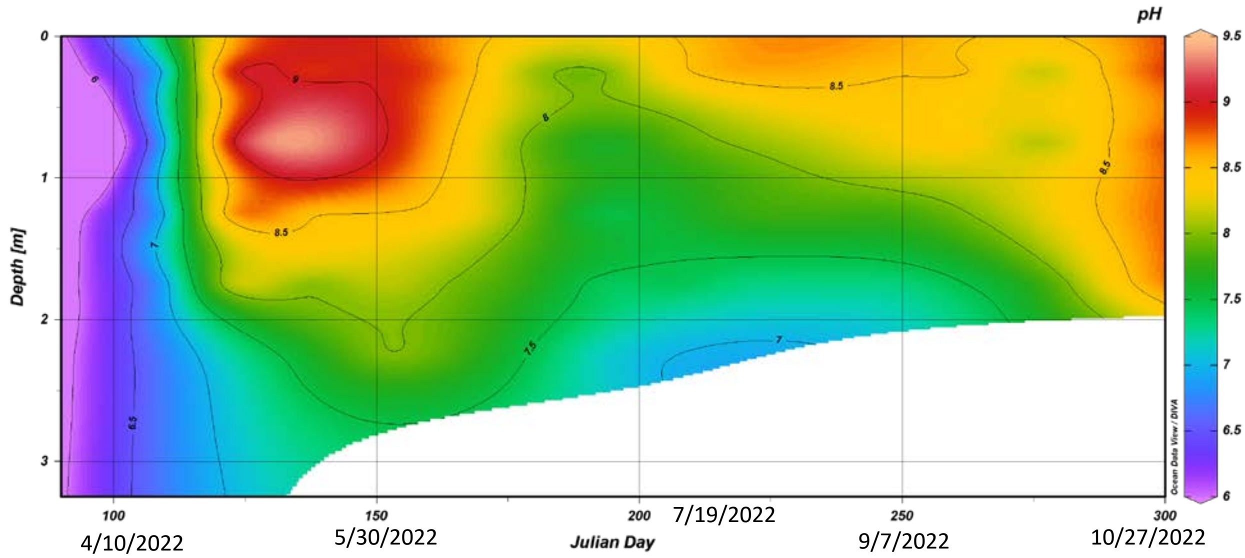


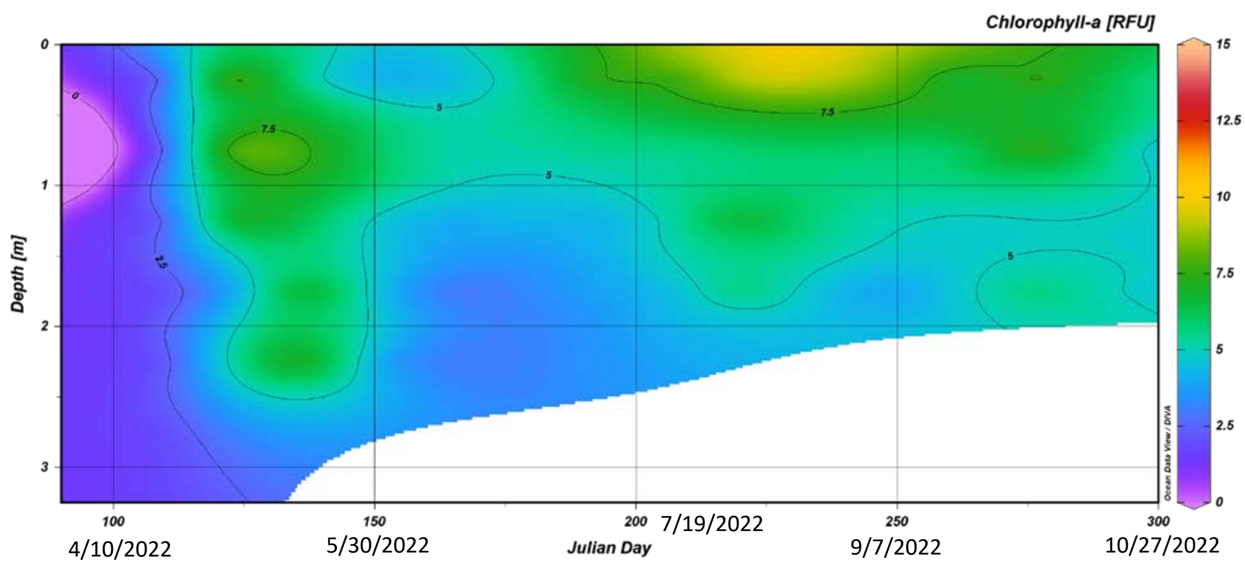
0
0.5
1
1.5
2
2.5
Depth [m]
100
150
200
250
300
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Julian Day
Ocean Data View

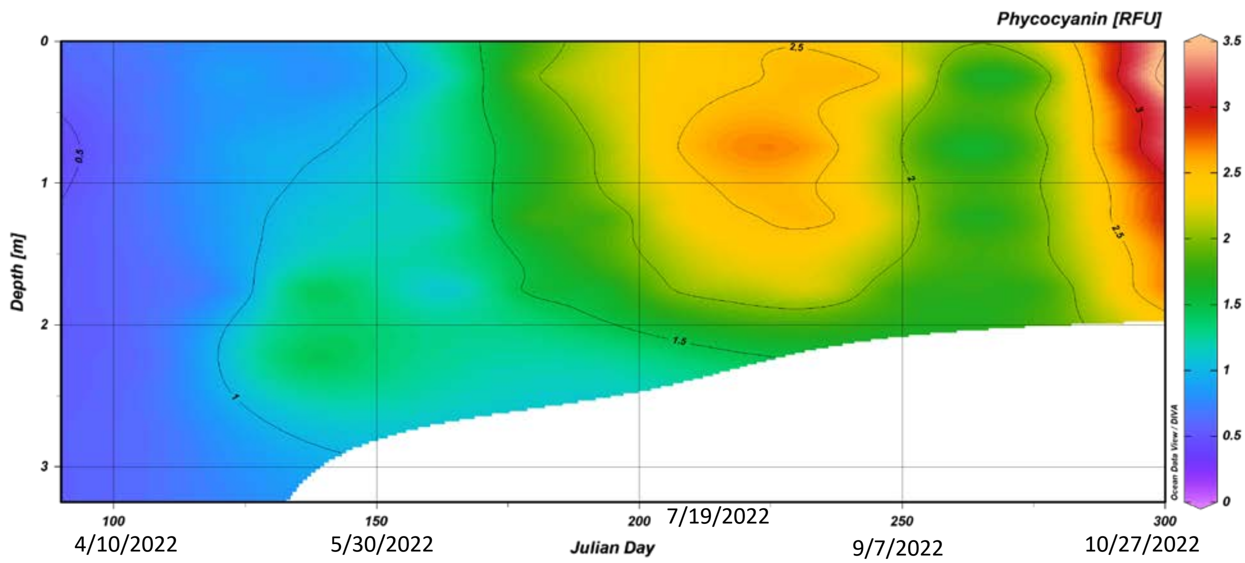
S-309 – Bush River arm (average total depth = 2.6 m)



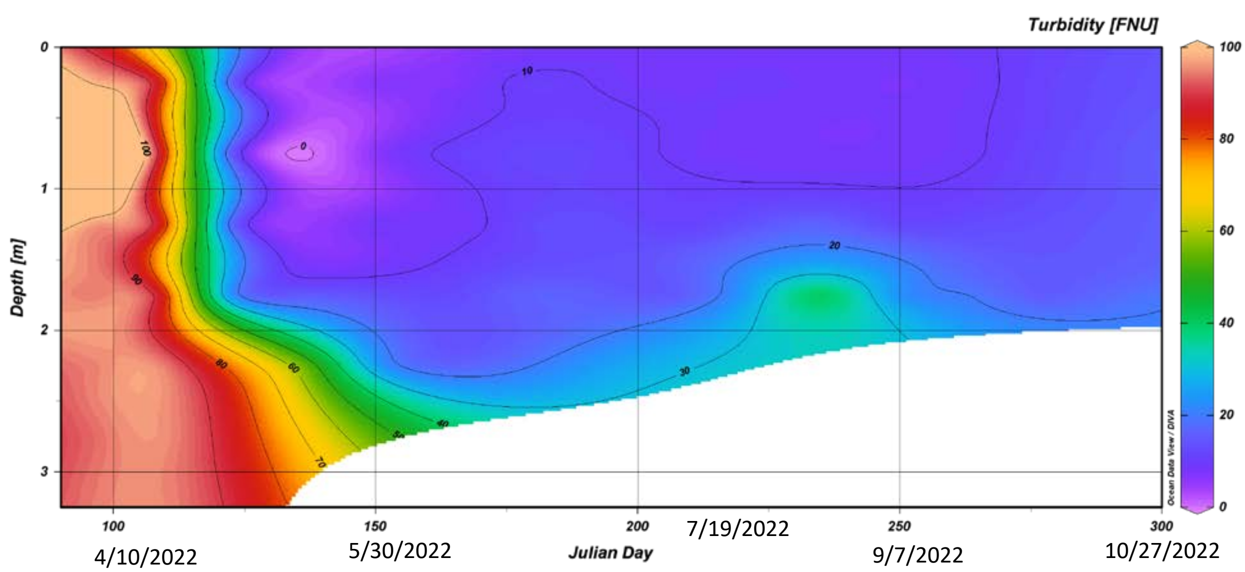



pH
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA

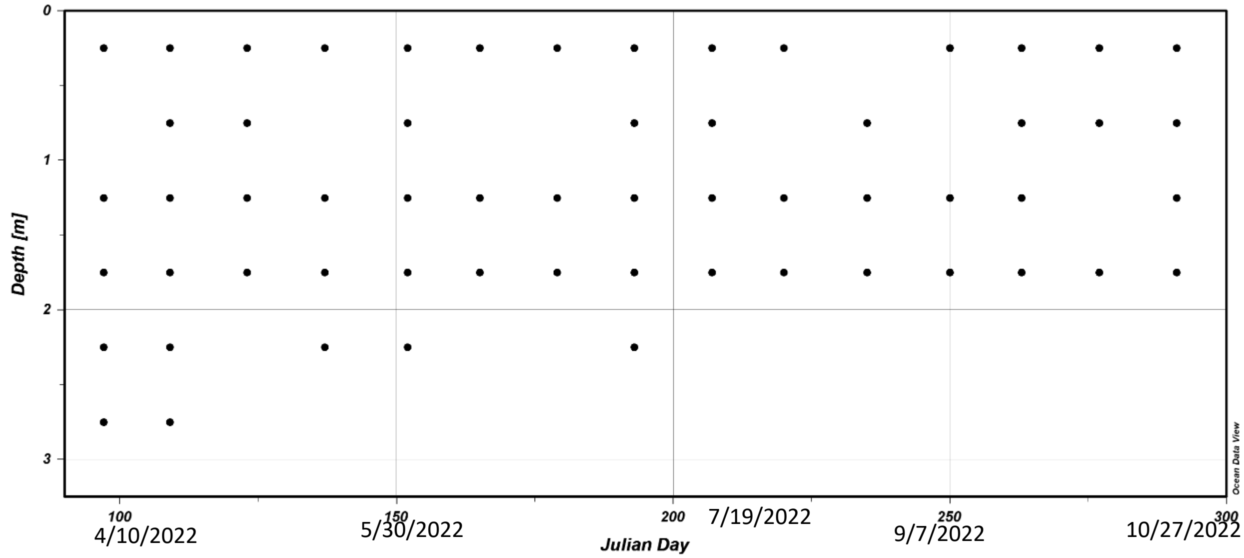

Chlorophyll-a [RFU]
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA



Phycocyanin [RFU]
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA

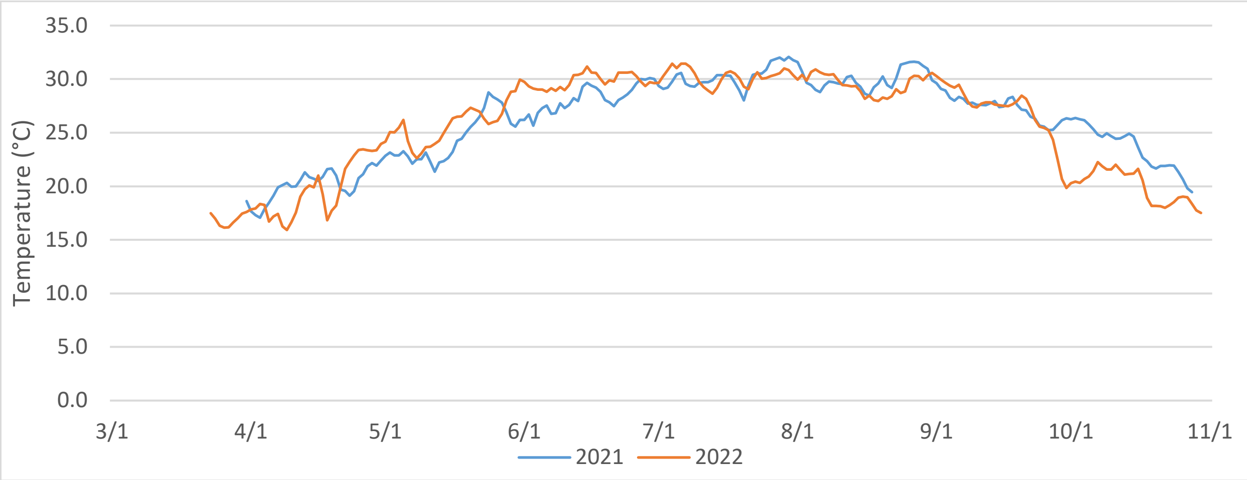


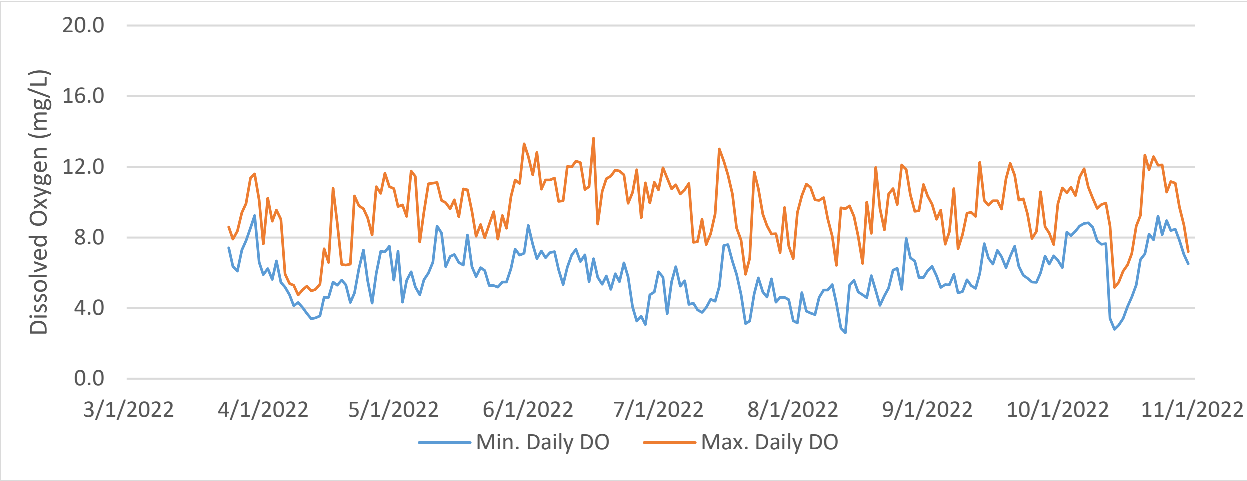
Turbidity [FNU]
Depth [m]
Julian Day
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Ocean Data View / DIVA

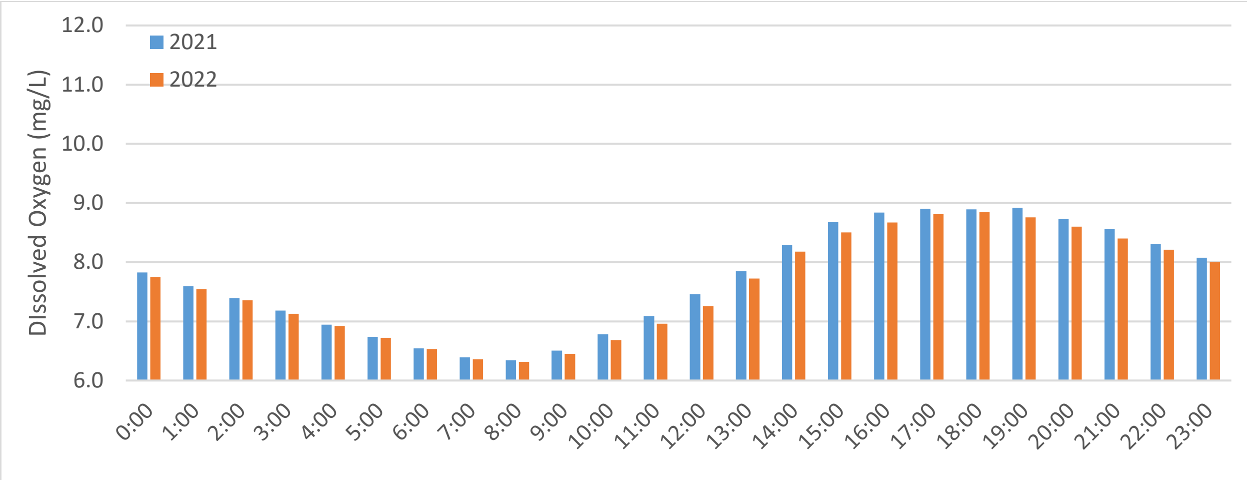

0
1
2
3
Depth [m]
100
150
200
250
300
4/10/2022
5/30/2022
7/19/2022
9/7/2022
10/27/2022
Julian Day
Ocean Data View

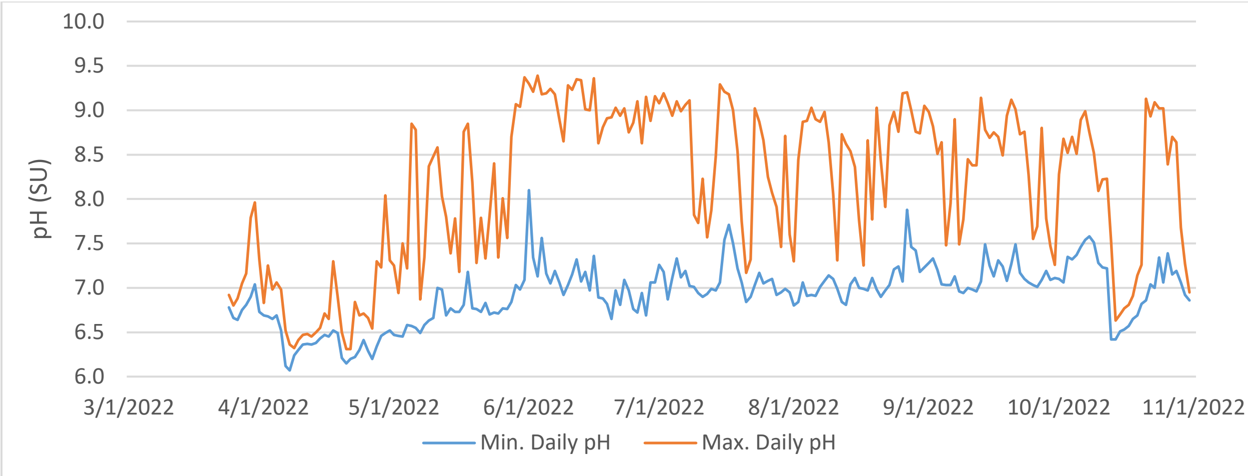
Appendix B – Surface Continuous Monitoring Time-series Plots

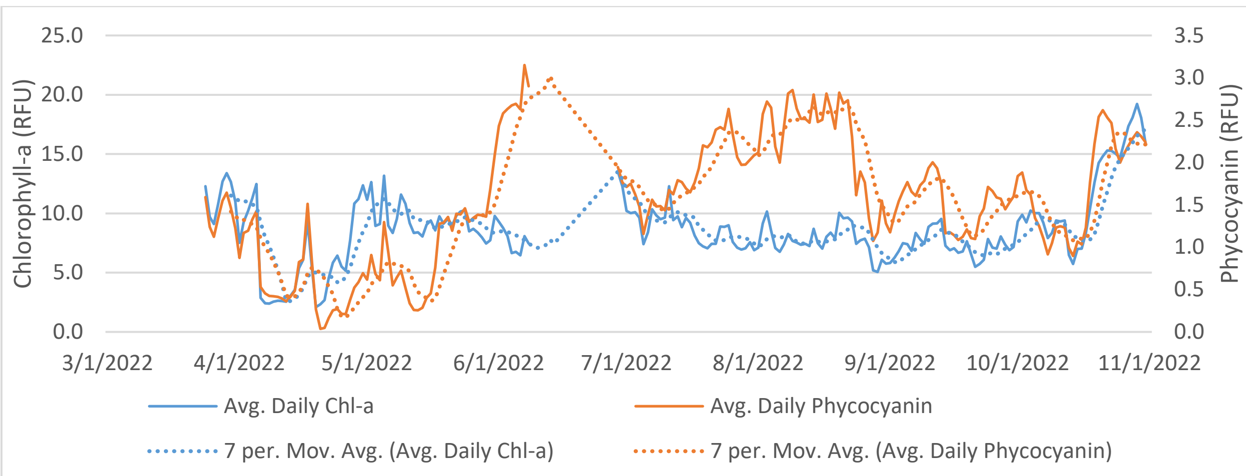
RL-19154 – Little Saluda River arm



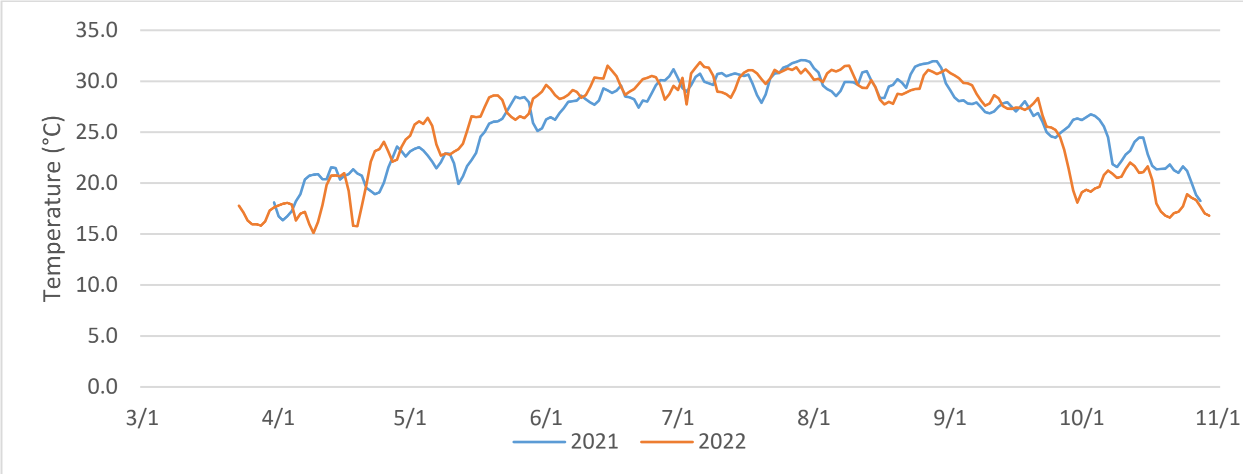


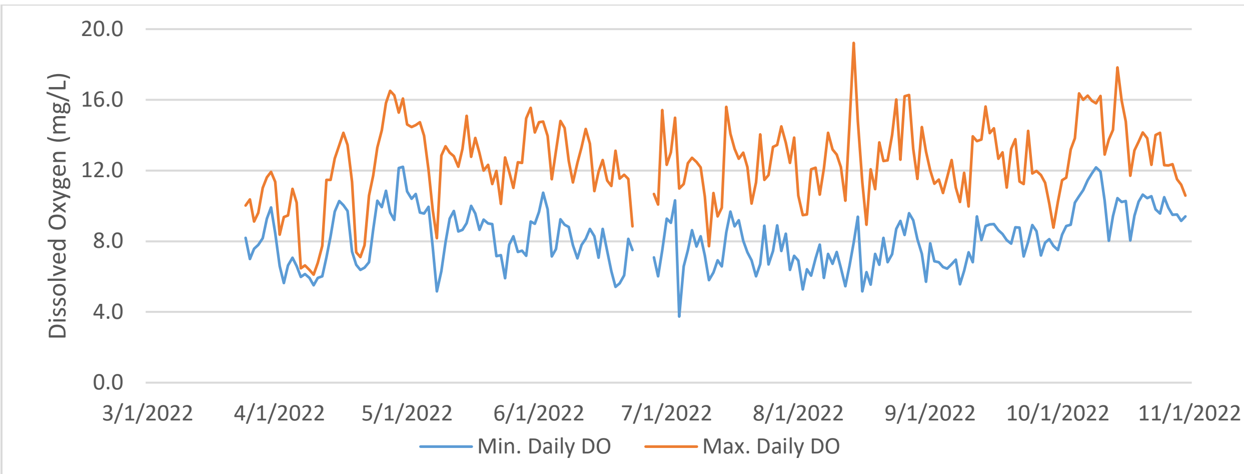


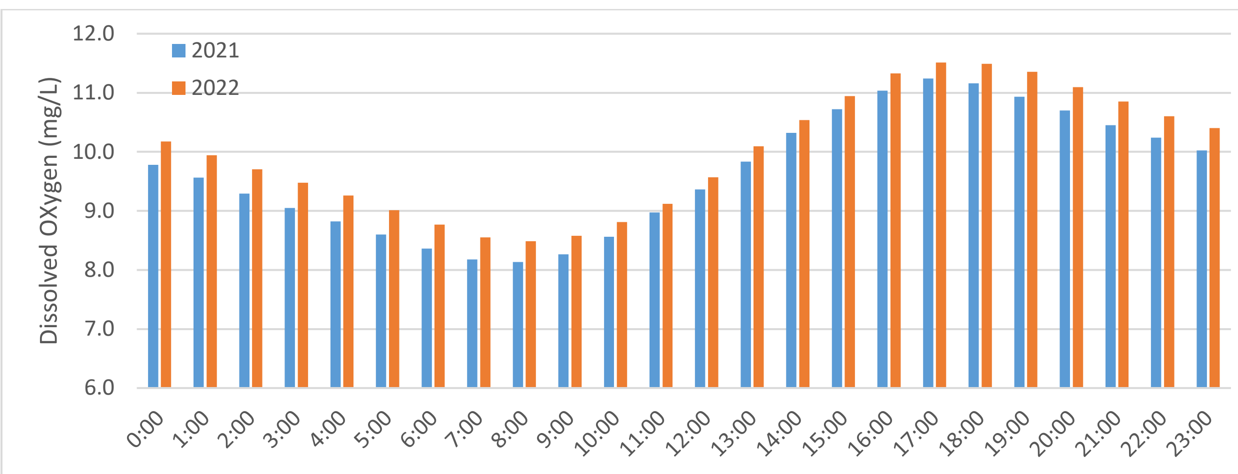

10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
pH (SU)
3/1/2022
4/1/2022
5/1/2022
6/1/2022
7/1/2022
8/1/2022
9/1/2022
10/1/2022
11/1/2022
Min. Daily pH
Max. Daily pH

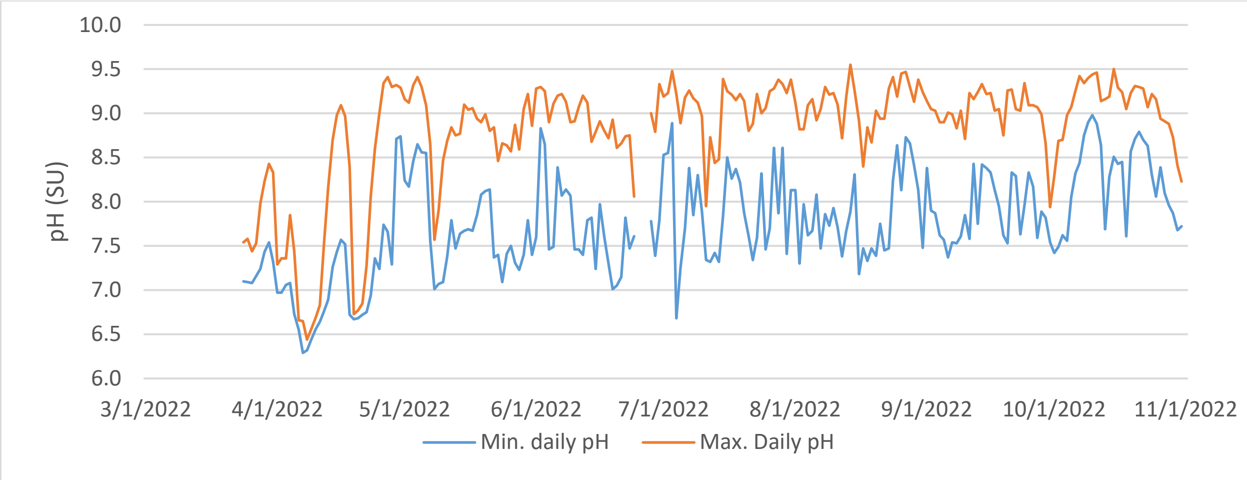

25.0
20.0
15.0
10.0
5.0
0.0
Chlorophyll-a (RFU)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Phycocyanin (RFU)
3/1/2022
4/1/2022
5/1/2022
6/1/2022
7/1/2022
8/1/2022
9/1/2022
10/1/2022
11/1/2022
Avg. Daily Chl-a
Avg. Daily Phycocyanin
7 per. Mov. Avg. (Avg. Daily Chl-a)
7 per. Mov. Avg. (Avg. Daily Phycocyanin)

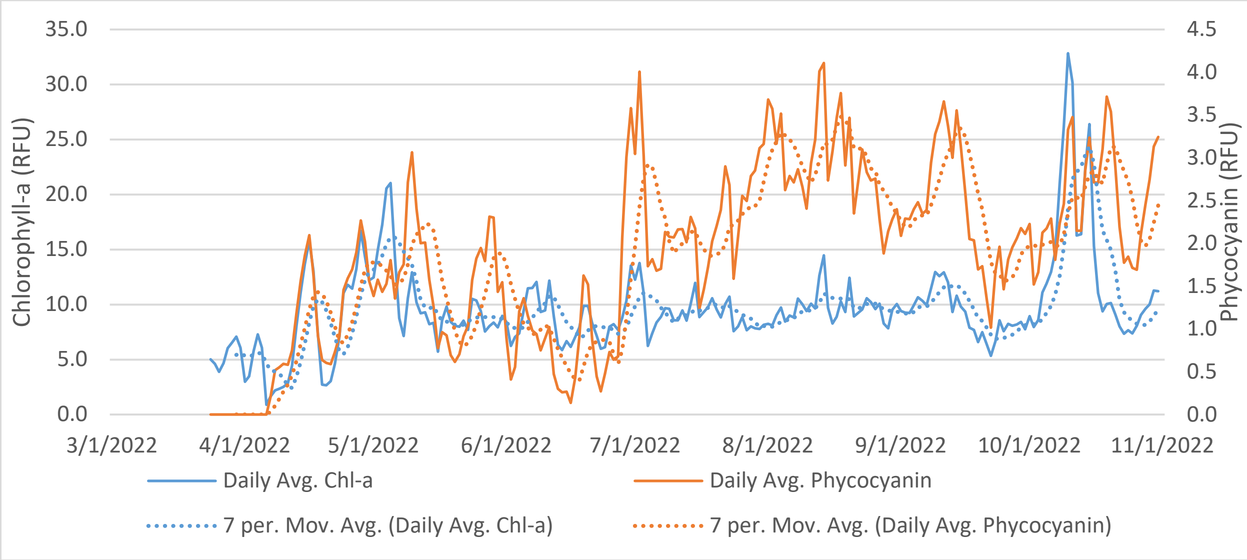
S-309 – Bush River arm







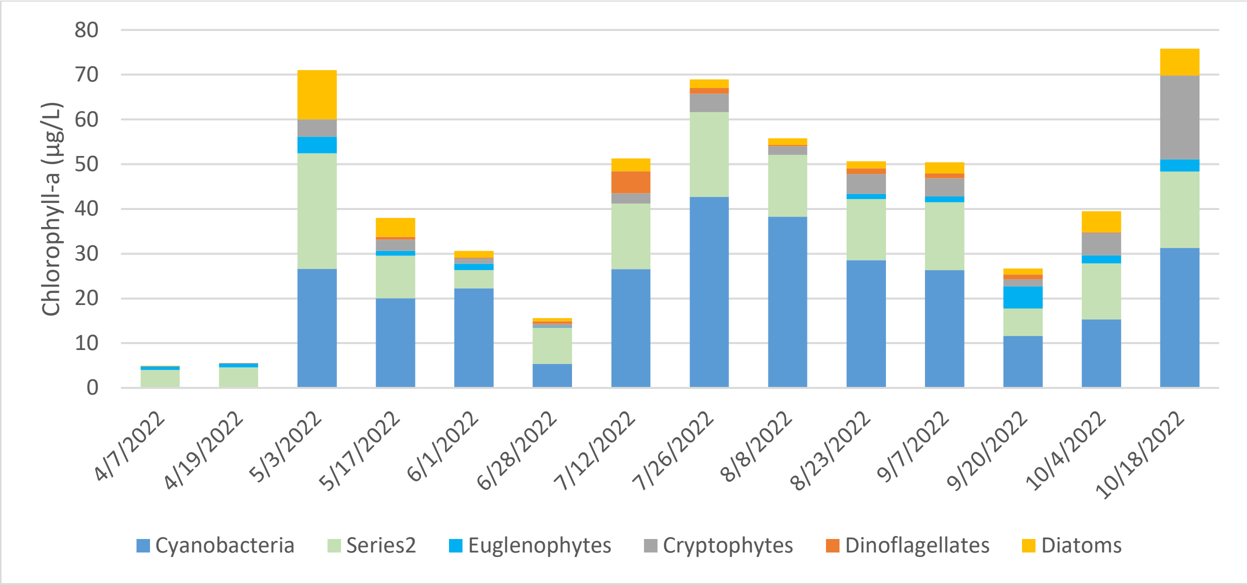

10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
pH (SU)
3/1/2022
4/1/2022
5/1/2022
6/1/2022
7/1/2022
8/1/2022
9/1/2022
10/1/2022
11/1/2022
Min. daily pH
Max. Daily pH


35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Chlorophyll-a (RFU)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Phycocyanin (RFU)
3/1/2022
4/1/2022
5/1/2022
6/1/2022
7/1/2022
8/1/2022
9/1/2022
10/1/2022
11/1/2022
Daily Avg. Chl-a
Daily Avg. Phycocyanin
7 per. Mov. Avg. (Daily Avg. Chl-a)
7 per. Mov. Avg. (Daily Avg. Phycocyanin)

Appendix C – Phytoplankton Community Structure

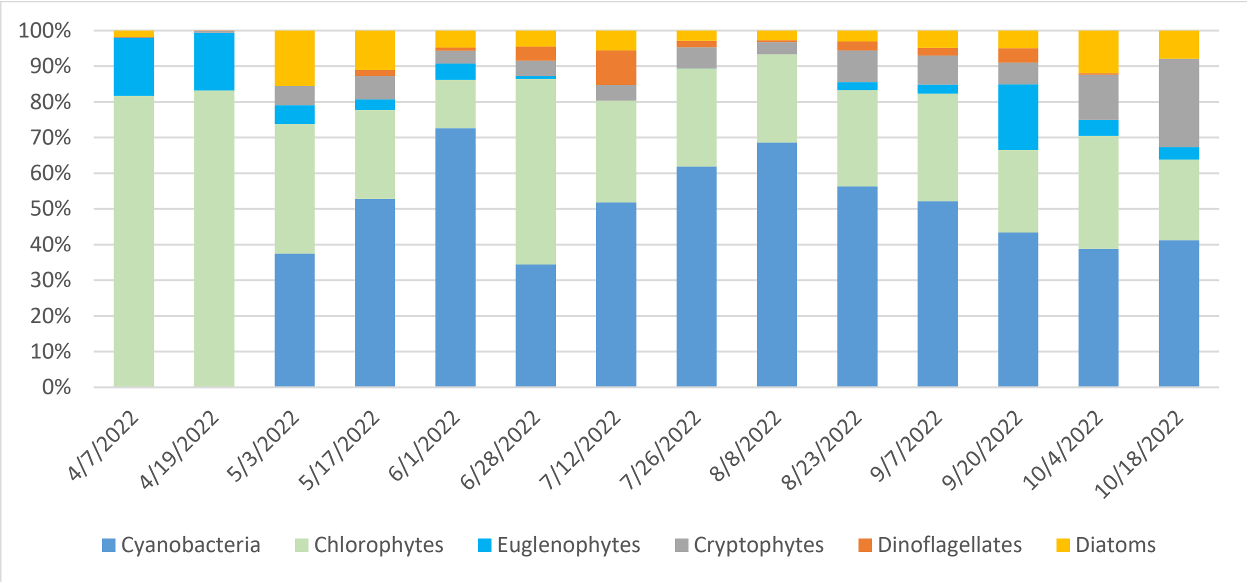
RL-19154 – Little Saluda River arm (average total depth = 2.4 m)

Group specific contribution to chlorophyll-a (absolute)



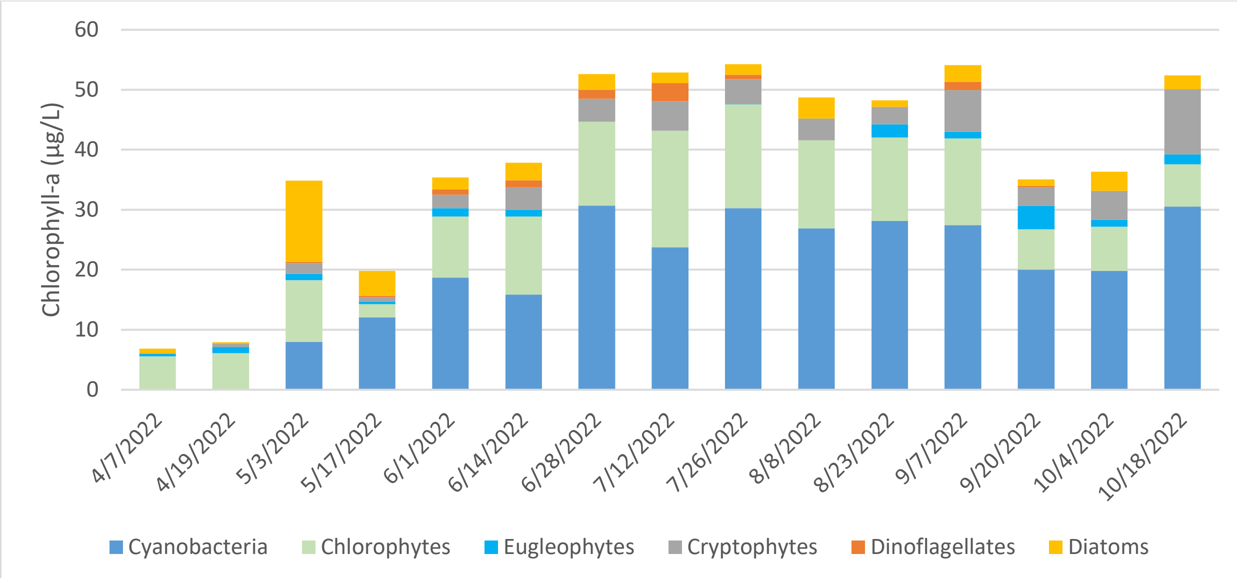
Sample from 6/14/2022 lost.

Group specific contribution to chlorophyll-a (relative)

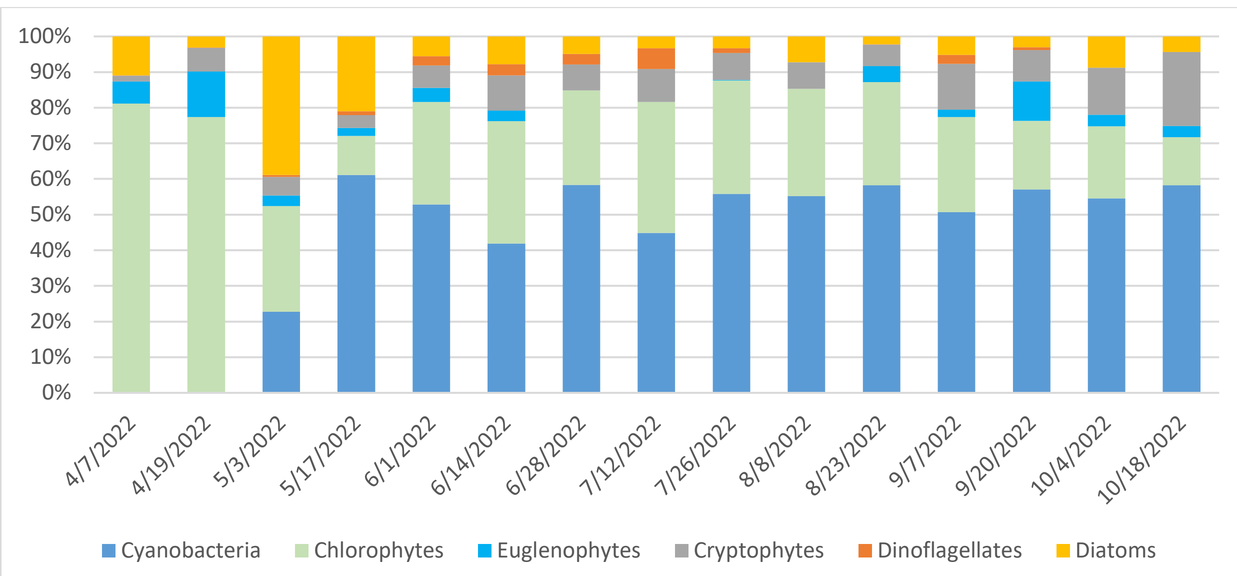


S-309 – Bush River arm (average total depth = 2.5 m)

Group specific contribution to chlorophyll-a (absolute)

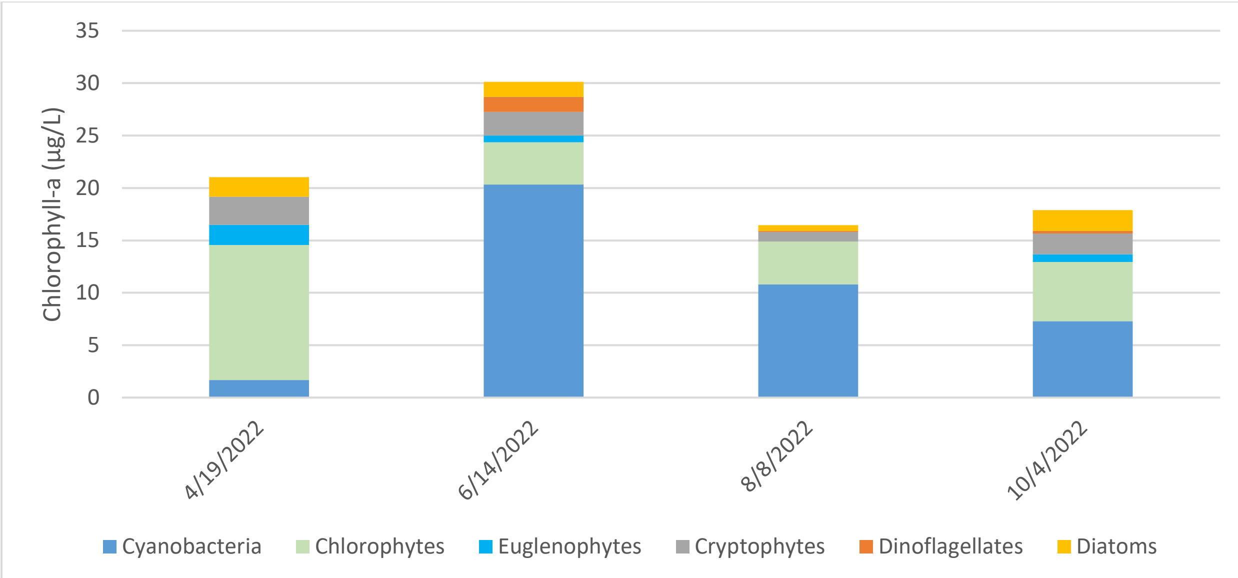


Group specific contribution to chlorophyll-a (relative)

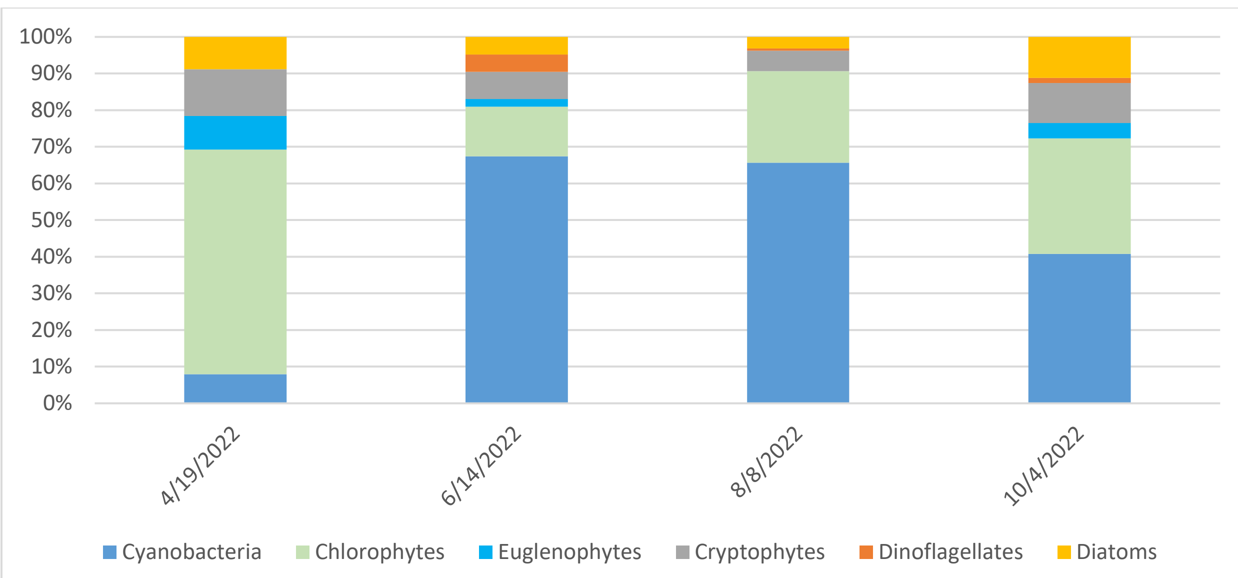


S-222 – Little Saluda River arm below RL-19154 and S-326 (average total depth = 7.0 m)

Group specific contribution to chlorophyll-a (absolute)

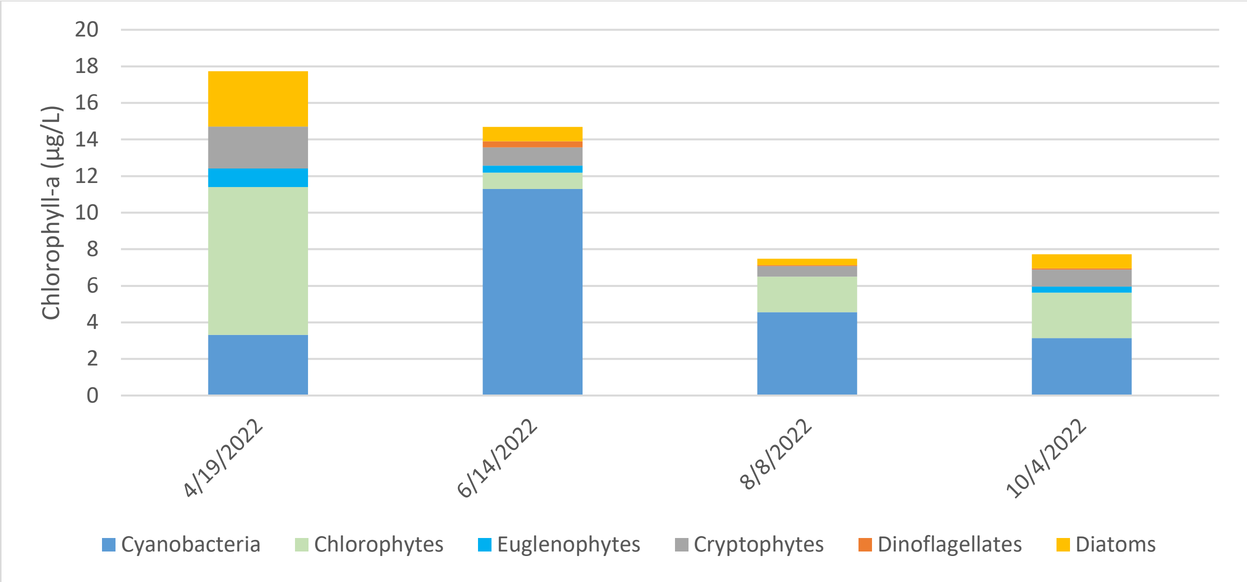


Group specific contribution to chlorophyll-a (relative)



S-279 – Lake Murray at Mark 63 (average total depth = 15.3 m)

Group specific contribution to chlorophyll-a (absolute)



Group specific contribution to chlorophyll-a (relative)