Lake Murray Little Saluda River and Bush River Arms 2021 Nutrient Study

Final Report of the Field Program

April 2022

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Executive Summary

During 2021, South Carolina Department of Health and Environmental Control Bureau of Water collected water quality data from three lake sites routinely and two additional sites approximately bimonthly in upper Lake Murray. The field sampling program, spanning April through October, targeted priority restoration areas in the upper reaches of the lake. Specifically, the study focused on providing important 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.

The 2021 Lake Murray program objectives were achieved using a series of three monitoring systems in these lake arms to continuously record physical/hydrographic parameters and biological responses coupled with biweekly (every other week) water quality sampling and vertical profiling at these lake sites. In addition, 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 regular sampling of phytoplankton photosynthetic pigments, the data collected as part of this study provided insights into the mechanistic 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 continuous monitoring and biweekly grab sample project components. Generally, all field program objectives were achieved as nearly all targeted data were successfully collected.

Summary of observations:

- Surface temperature patterns at the continuous monitoring stations in Little Saluda River, Clouds Creek, and Bush River arms were similar over the course of the field program. In early April, surface temperatures were 17-18°C and progressively rose to >30°C in mid-July and peaking at ~32°C in early August before a gradual cooling to 18°C at the end of October.
- Temperature stratification was apparent in Clouds Creek arm (5.5 m total depth) from April through September when the water column vertically mixed.
- Average total chlorophyll-a concentrations based on biweekly grab sampling were higher in the Little Saluda River and Bush River arms than in Clouds Creek.
- Sensor-based chlorophyll-a was on average highest in April for the Little Saluda River and Bush River arms while June was the highest month in the Clouds Creek arm.
- Phytoplankton growth in the lake arms was nitrogen limited throughout the season based on algal growth potential assays.
- The phytoplankton community was composed primarily of chlorophytes and diatoms in early April. Cyanobacteria maintained approximately 30% of the chlorophyll-a from late May through the end of the study. Chlorophytes represented most of the sample chlorophyll-a (average: 53%). Diatoms were a smaller component averaging 9.3% of chlorophyll-a.
- Total phosphorus concentrations were similar in Little Saluda River and Bush River arms. Variability was considerably higher at the Little Saluda River site, however. These average values were nearly twice the average in Clouds Creek arm. Total nitrogen was on average highest in Little Saluda River arm followed by Bush River and Clouds Creek. Average total organic carbon was highest in the Little Saluda River followed by the Clouds Creek and Bush River arms.

Overview of the 2021 Upper Lake Murray Study

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

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[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]

Following a three-year planning and discussion phase, South Carolina Department of Health and Environmental Control (DHEC) Bureau of Water (BOW) issued wasteload allocations to the Saluda County Water and Sewer Authority and the Saluda Commission of Public Works which would increase the permitted wastewater discharge to the Little Saluda River from 0.465 MGD to up to 5 MGD. The discharge limits to the Little Saluda River provided in the wasteload allocations approach technological limits and are designed to prevent any further impairment of the stream and downstream lake related to dissolved oxygen and nutrients. Discharge limits for this facility are subject to modification as needed based on the results of a completed TMDL for the watershed.

As a precursor to a watershed nutrient loading study in 2022, and in coordination with a separate effort by BOW Aquatic Science Programs (ASP) and DHEC Bureau of Environmental Health Services (BEHS) to reactivate seven lake sites as special request ambient monitoring sites, DHEC BOW completed a 2021 lake arm study at key lake locations in the Little Saluda River arm, Clouds Creek arm, and Bush River arm in upper Lake Murray. The objectives of the 2021 study were to:

- 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.

Taken together, these objectives provided 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 this study provided guidance for the 2022 study and will inform forthcoming system modeling/TMDL development.

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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.

Nutrient Study Project/Task Description

Field Logistics

The 2021 Upper Lake Murray Program spanned 31 weeks from April through the end of October 2021. 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

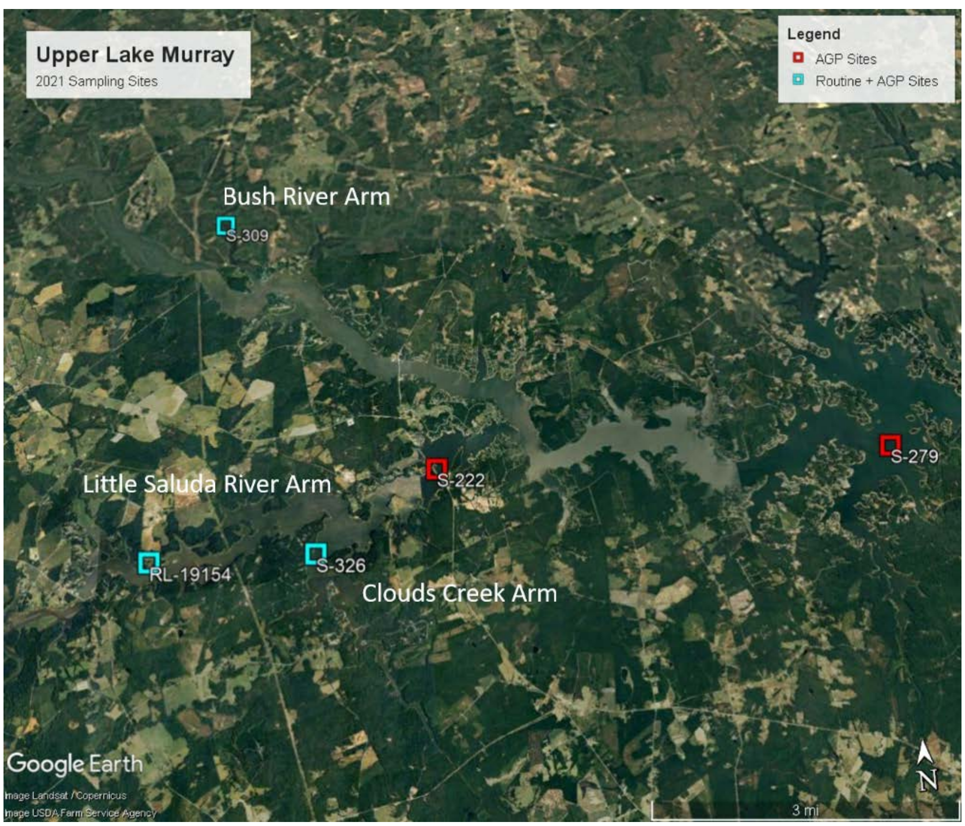


Figure 1. Site locations in upper Lake Murray. Blue squares indicate routine sampling sites and red squares indicate additional sites sampled as part of the algal growth potential test component.

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 three sites as well. Continuous monitoring systems were serviced every other week. Stations S-222 and S-279 were sampled five 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 (4/20, 6/29, 8/10, and 10/5/2021). The shipping service lost the 6/29/2021 AGPT samples en route to US Environmental Protection Agency (EPA) in Athens, GA, and a repeat sampling was conducted on 7/13/2021. The 8/10/2021 AGPT event was shifted to 8/24/2021. 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, lake site only, approximately monthly)

Field surface sensor measurements were recorded at each grab sample site along with vertical profiles using a YSI-EXO2 and photosynthetically active radiation penetration:

- 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 and In-Situ Aqua Troll 600s (phycocyanin only) were used instead of the YSI EXO2. Technical issues related to calibration, verification, and manufacturer failings of the In-Situ Aqua Troll 600 phycocyanin sensors limited the usefulness of these continuous measurements and will not be presented here.

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. 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).

Table 2. Range (surface minimum and surface maximum) for each primary field parameter over the 4/6/2021 – 10/19/2021 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 five times during routine field sampling events. 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	7.12 - 8.95	5.85 - 10.2	18.24 - 32.30	75.9 - 100	3.94 - 10.74
S-326	6.97 - 9.69	6.08 - 13.1	19.57 - 31.51	70.7 - 94.9	1.99 - 12.29
S-309	7.38 - 9.04	7.45 - 14.1	17.98 - 32.01	103.0 - 172	4.12 - 11.58
S-222	7.72 - 8.82	8.16 - 10.4	21.42 - 30.55	73.1 - 83.1	1.76 - 3.71
S-279	7.58 - 8.46	7.64 - 10.2	20.58 - 30.22	70.6 - 80.1	0.93 - 2.61

An expanded suite of surface measurements was 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 maximum depth or vertical band where pigment fluorescence was highest. Calibration protocols for the EXO Total Algae sensors were changed to be more consistent with manufacturer recommendations prior to the 5/5/2021 sampling event. As such the records for chlorophyll-a and phycocyanin measurements range from 5/5/2021 through 10/19/2021 (n = 13).

Table 3. Range (minimum and maximum) for additional field parameters at the lake sites over the 4/6/2021 – 10/19/2021 study period. Generally, each range consists of 15 sampling events. Note that stations S-222 and S-279 were sampled five times during routine field sampling events. 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	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	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	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	1.55 - 3.26	0.3 - 1.5	0.25 - 1.00	0.3 - 1.5	2.6 - 3.9	0.90 - 1.30
S-279	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 the 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 created 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. The program then averaged 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, 55 vertical profiles were collected as part of the 2020 Lake Program. Fifteen biweekly profiles were targeted at each of the routine sites (RL-19154, S-326, and S-309). Five profiles were collected at stations S-222 and S-279 as they were periodically sampled as part of the algal growth potential test project component. 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, but do not capture diel variability.

Continuous Monitoring

Continuous monitoring systems were deployed at RL-19154, S-326, and S-309 from 4/1/2021 through 10/29/2021. Each deployment was approximately two weeks in duration and data were recorded at 30-minutes intervals.

End of deployment verifications for the primary variables (DO, pH, specific conductivity, and chlorophyll-a) were largely successful (Table 4). A complete end of deployment verification record is stored in the SharePoint Field Log.

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: 25% criterion for phycocyanin is not an approved accuracy rating but is used to provide basic interpretation of sensor performance.

Station	Dissolved Oxygen (0.2 mg/L)	pH (0.2 SU)	Specific Conductivity (10%)	Chlorophyll-a (10%)	Phycocyanin (25%)	Turbidity (10%)
RL-19154	100%	87%	100%	93%	60%	80%
S-326	93%	93%	93%	93%	67%	74%
S-309	100%	87%	100%	93%	73%	67%

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

- The Hydrolab DS5X thermistor failed on the 9/14-9/28/2021 deployment at S-326 which led to the one verification fail for dissolved oxygen and specific conductivity.
- Four pH sensors failed end of deployment verification to within 0.2 SU; however, the readings were within 0.2 to 0.4 SU of the standard and considered good. These data were not rejected.
- The In-Situ phycocyanin sensors demonstrated considerable drift on several deployments based on end of deployment verifications. Care was taken to calibrate and verify these sensors in the laboratory under stable conditions. The sensors are possibly highly temperature dependent despite efforts to control conditions. Early in the program sensors failed due to condensation accumulation under the sensor glass.
- Turbidity verifications were largely successful despite several end of deployment verification fails. In total 11 deployments failed verification. Six of the 11 may be related to a turbidity calibration standard that failed in September.

- The configuration of the turbidity sensor on the Hydrolab DS5X instrument likely leads to issues during long-term deployments. The turbidity record on several deployments drifted upward to improbable levels likely to due to overgrowth of algae on the sensor that could not be cleared by the small central wiper on the system.

Fluorometer-Based Chlorophyll-a

A total of 55 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. No samples were lost.

Cyanotoxins

Samples for microcystins analysis were collected at the surface along with each total chlorophyll-a sample. A total of 55 samples were collected. One sample at RL-19154 on 10/5/2021 was lost.

Algal Growth Potential Testing

Algal growth potential testing (AGPT) was initially scheduled to occur on 4/20, 6/29, 8/10, and 10/5/2021. The courier service lost the 6/29/2021 sample shipment to EPA in Athens, GA. AGPT samples were collected on 7/13/2021 and the 8/10/2021 scheduled sampling was shifted to 8/24/2021 to space out the events. Overall completeness for this activity is 100% as all 20 planned samples (four at each site) were collected and successfully analyzed.

Photosynthetic Pigments

A total of 55 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. No samples were lost.

Water Quality

Grab samples for water quality occurred biweekly from 4/6/2020-10/19/2021. 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 five times as part of the AGPT component. Overall completeness is determined to be 100% as no sample event was omitted due to field team decision or error. 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 three filtered total organic carbon samples on 7/27/2021 due to misplaced filter cartridges.

Summary of Findings

The following summary presents a brief discussion of high-level observations of key parameters investigated as part of the 2021 Upper Lake Murray field program. It is not meant to be exhaustive of all data collected during the study. 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.

Vertical Profile

Section plots for temperature, dissolved oxygen, pH, chlorophyll-a reflectance for station S-326 are presented in Figures 2-5. Section graphs for temperature, dissolved oxygen, pH, and chlorophyll-a for

RL-19154 and S-309 are presented in Appendix A. The 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, week over week, evolution of the water column at each site for physical and biological parameters.

Surface water temperature at S-326 was approximately 19°C during the first vertical cast in early April. The water column reached a maximum of 32.1°C in late July (Figure 2). 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). Thermal stratification appeared to lessen in later September as temperature and dissolved oxygen levels vertically homogenized. A strong sulfur odor was noted on 9/28/2021 during regular buoy servicing possibly indicating a turnover of the lake associated with recent storm conditions. 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. In the deeper part of the water column, pH was consistently between 6.0 and 7.5 with lower dissolved oxygen concentrations. At this station, the chlorophyll-a maximum was typically between 1 and 1.5 m. Maximum reflectance of 7.5 RFUs was recorded on 8/24/2021 (Figure 5).

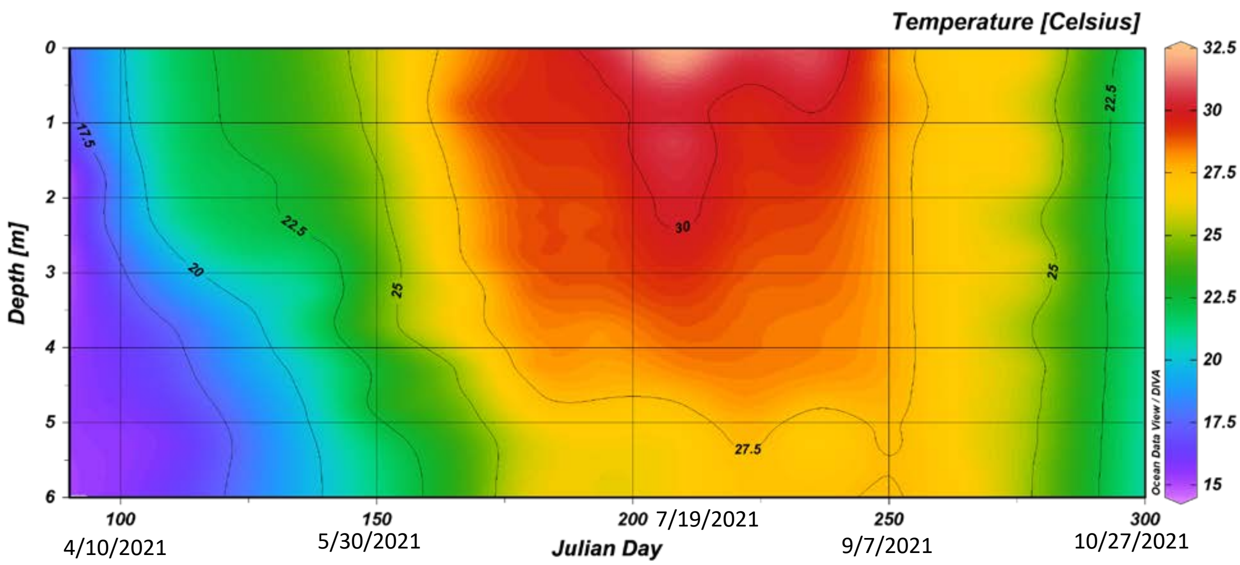


Figure 2. Temperature (°C) section plot for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

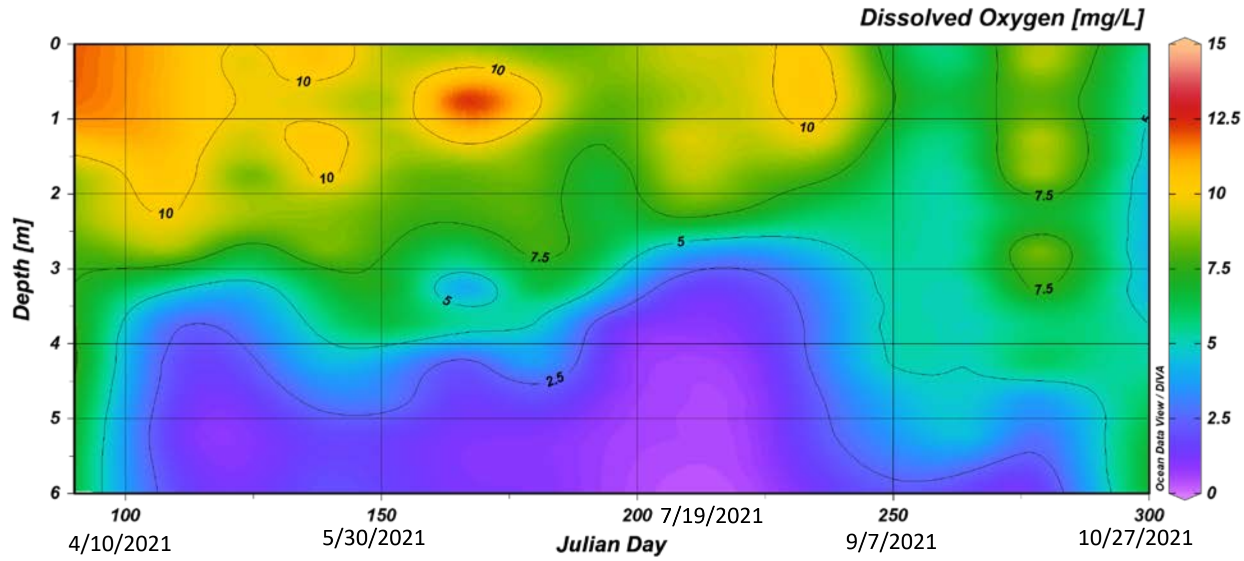


Figure 3. Dissolved oxygen (mg/L) section plot for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

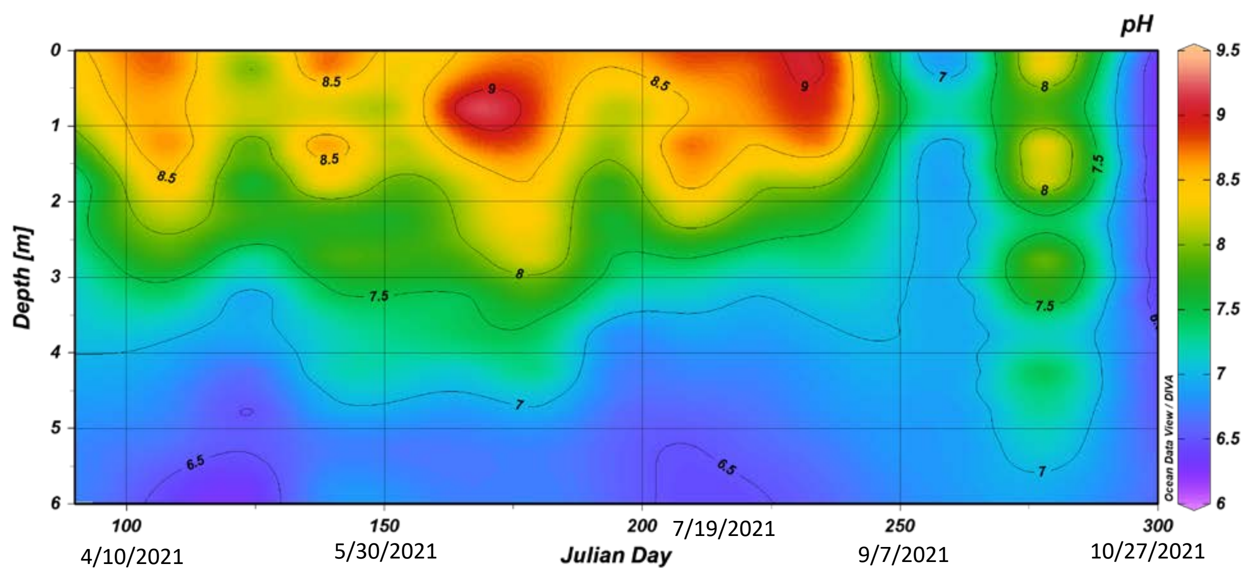


Figure 4. pH section plot for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

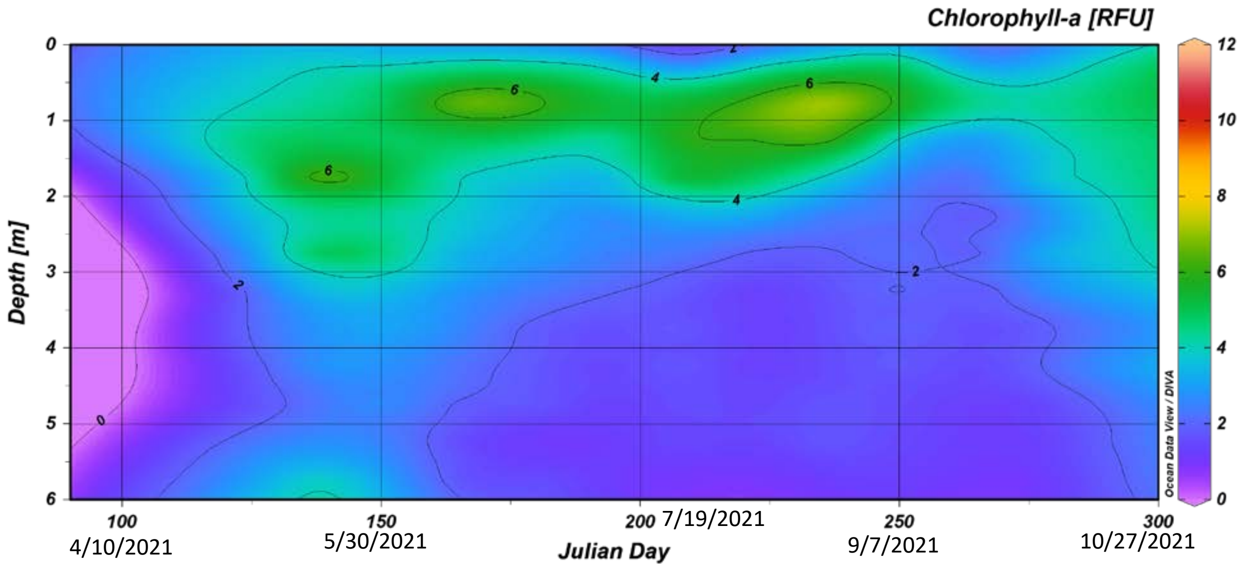


Figure 5. Chlorophyll-a reflectance (RFU) for S-326 in the Clouds Creek arm of Lake Murray. Corresponding calendar dates are listed next to Julian Day labels.

Continuous Monitoring

Daily time-series plots and hourly histograms of temperature, dissolved oxygen, pH, and chlorophyll-a for S-326 are presented in Figures 6-9. Time-series plots for RL-19154 and S-309 are presented in Appendix B. As with the vertical profile data, continuous monitoring of surface temperature showed a gradual rise from April through late July to a maximum daily average of 31.1°C on July 31, 2021 at S-326 (Figure 6). Daily average temperatures near or above 30°C were recorded until September before progressively decreasing to a monitoring period minimum of 20.3°C on 10/29/2021 when the buoys were retrieved.

Daily minimum and maximum dissolved oxygen concentrations at the surface were highly variable day over day (Figure 7). Relatively high average concentrations were observed in April and May with a seasonal peak in June (Table 5). On average, June demonstrated the largest difference between daily maximum and minimum dissolved oxygen concentrations. After June, average dissolved oxygen levels (minimum and maximum) decreased from July through September. For the April through October monitoring period, dissolved oxygen appeared to mirror the pattern of daytime photosynthesis and overnight respiration (Figure 8). On average, the 0700 and 0800 hours demonstrated the lowest dissolved oxygen concentration (7.9 mg/L) and 1700 and 1900 hours produced the highest concentration (10.1 to 10.2 mg/L).

As with dissolved oxygen, pH was highly variable day to day (Figure 9). However, on average pH increased from April to maximum in June and then decreased from July through October (Table 6). This pattern is similar to dissolved oxygen (Table 5). At least half of the daily maximum recorded pH values exceeded the State standard for pH of 8.5 in April through August. In June and July ~90% of the daily maximum pH values exceeded 8.5.

Sensor-based chlorophyll-a may explain, in part, the dissolved oxygen and pH features noted above. The highest average daily chlorophyll-a occurred in June consistent with seasonal maximums for dissolved oxygen and pH (Tables 4,5). A possible phytoplankton bloom occurred on approximately 6/10-6/12/2021 (Figure 10). The possible bloom condition skews month over month comparisons of average chlorophyll-a; however, this feature underscores the importance of periodic pulses of algal growth in lake settings. Both dissolved oxygen and pH increased in the days following the spike in chlorophyll-a (Figures 7,9) followed by a sharp decline in dissolved oxygen approximately a week later (6/20-6/22/2021). The daily pattern in chlorophyll-a concentrations was offset from dissolved oxygen by three hours (Figure 11). Daily minimum chlorophyll-a concentrations occurred from 0400 to 0500 (26.5 µg/L) and maximum occurred around 1300 (31.2 µg/L). Note that these chlorophyll-a values were recorded using an Ott Hydrolab DS5X are not directly comparable to the chlorophyll-a reflectance values in Figure 5 which were measured with a YSI EXO2.

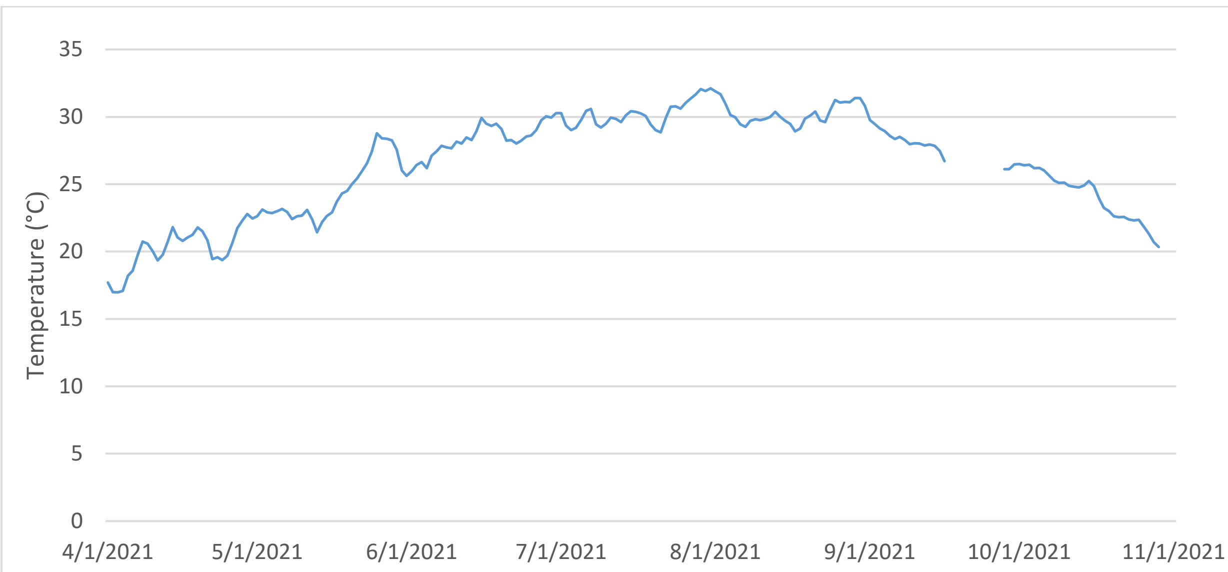


Figure 6. Average daily temperature at S-326 in Clouds Creek arm of Lake Murray. Data loss occurred due to a thermistor failure for September 17-27, 2021.

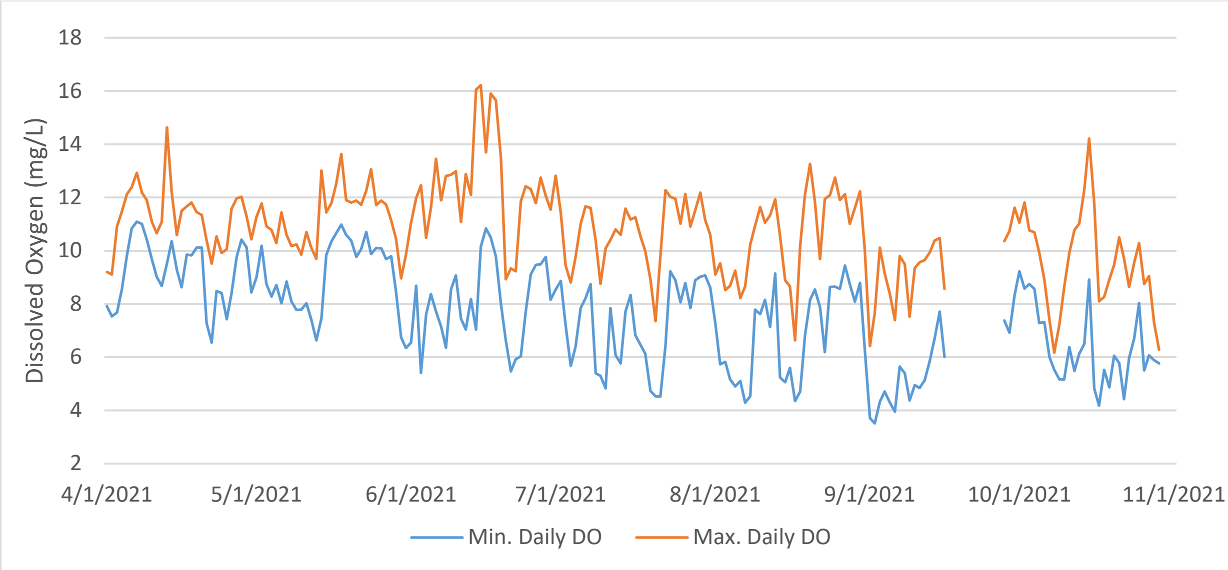


Figure 7. Daily minimum and maximum recorded dissolved oxygen concentrations (mg/L) at S-326 in Clouds Creek arm of Lake Murray. Data loss occurred due to a thermistor failure for September 17-27, 2021.

Table 5. Month by month average minimum and maximum dissolved oxygen concentration along with average daily range in recorded values. Data loss occurred due to a thermistor 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	9.17	11.26	2.09	30
May	9.01	11.24	2.23	31
June	8.02	12.45	4.43	30
July	7.17	10.68	3.51	31
August	6.85	10.53	3.68	31
September	5.46	9.29	3.83	19
October	6.36	9.56	3.20	29

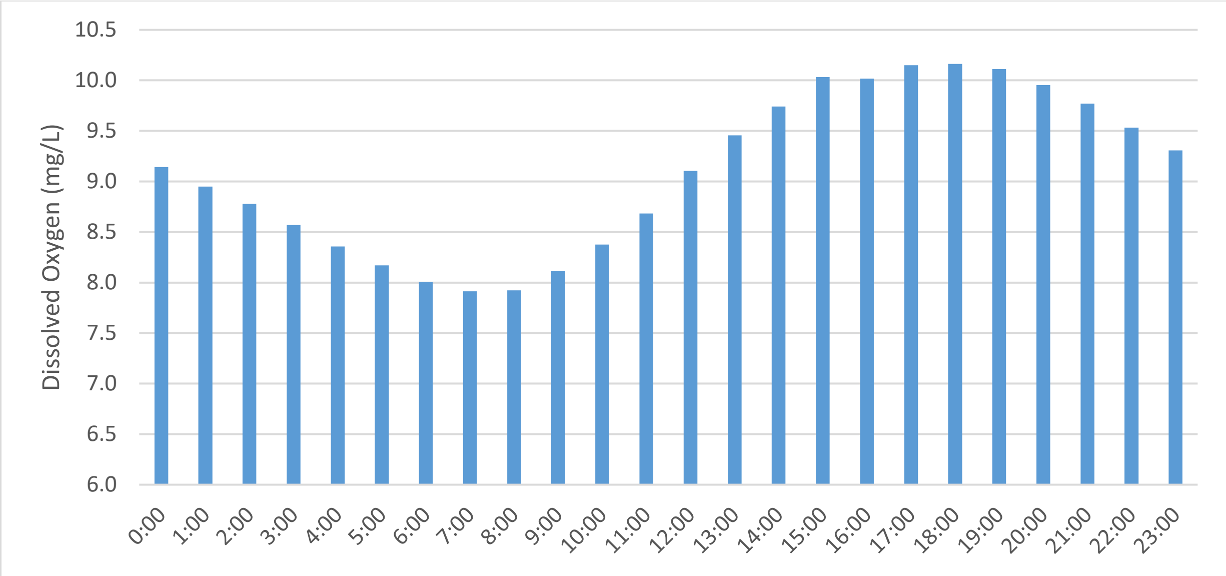


Figure 8. Hourly average dissolved oxygen concentrations (mg/L) for the April 11 through October 29, 2021, continuous monitoring record at S-326 in Clouds Creek arm of Lake Murray. Data loss occurred due to a thermistor failure for September 17-27, 2021.

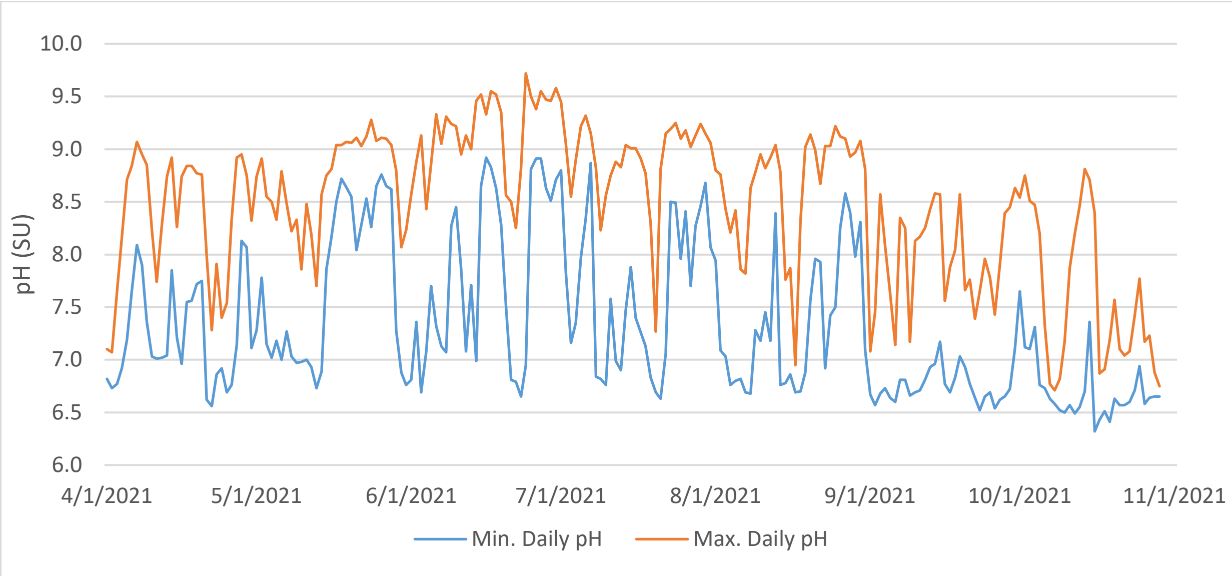


Figure 9. Daily minimum and maximum recorded dissolved pH values at S-326 in Clouds Creek arm of Lake Murray.

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.

Month	Avg. Daily Minimum pH	Avg. Daily Maximum pH	Avg. Δ pH	Max. > 8.5	n
April	7.23	8.33	1.10	15	30
May	7.69	8.69	1.00	20	31
June	7.80	9.15	1.35	27	30
July	7.65	8.91	1.26	28	31
August	7.35	8.65	1.30	22	31
September	6.75	7.96	1.21	5	30
October	6.72	7.61	0.89	5	29

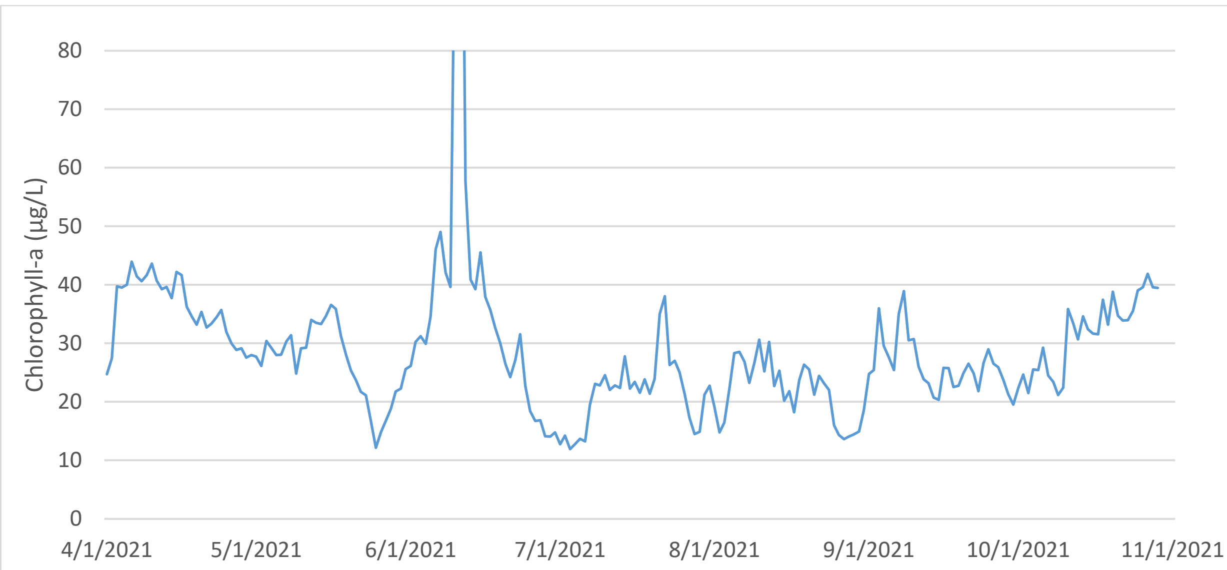


Figure 10. Daily average Hydrolab DS5X chlorophyll-a concentration (µg/L) at S-326 in Clouds Creek arm of Lake Murray. These data are not directly comparable to the YSI EXO2 chlorophyll-a reflectance field data ranges listed above in (Table 3) and presented in Figure 5 of the vertical profile discussion. Two days, 6/10 and 6/11/2021 are off axis with average concentrations of 113.8 µg/L and 153.1 µg/L, respectively.

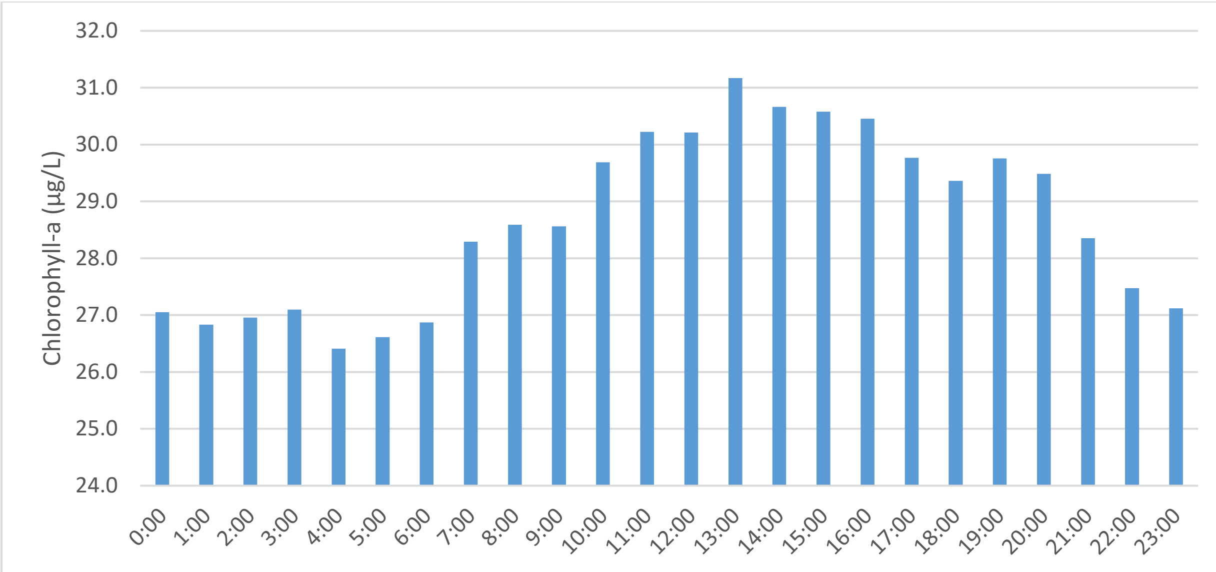


Figure 11. Hourly average Hydrolab DS5X chlorophyll-a concentration (µg/L) for the April 11 through October 29, 2021, continuous monitoring record at S-326 in Clouds Creek arm of Lake Murray. As stated in the Figure 10 caption, these data are not directly comparable to the YSI EXO2 chlorophyll-a reflectance values but illustrate seasonal, daily, and hourly trends.

Fluorometer-Based Chlorophyll-a

Biweekly grab sample total chlorophyll-a was highest in the Little Saluda River arm (RL-19154) with an average 36.6 µg/L, followed by the Bush River arm at S-309 (35.9 µg/L) and Clouds Creek arm at S-326 (29.9 µg/L). Variability was high across the system and throughout the program was high as indicated by the high standard deviations and wide ranges associated with the average total chlorophyll-a concentrations (Tabe 7). Five of the fifteen total chlorophyll-a concentrations measured in the Little Saluda River (RL-19154) arm exceeded the State 40 µg/L standard while four exceeded the standard in the Bush River arm and only once exceedance was observed in the Clouds Creek arm (Figure 12). The highest grab total chlorophyll-a values for Little Saluda River and Clouds Creek occurred during the mid-June field event on 6/15/2021 (Figure 13) consistent with the vertical profile and continuous monitoring data described above for the Clouds Creek arm.

Table 7. Surface (0.3 m) total chlorophyll-a summary statistics for each lake station. Average is presented as ± 1σ. All total chlorophyll units in µg/L.

Station	Avg. T. Chl-a	Minimum	Maximum	n
RL-19154	36.6 ± 18.4	18.0	83.1	15
S-326	29.9 ± 15.3	13.3	77.5	15
S-309	35.9 ± 14.3	15.0	71.9	15
S-222	16.8 ± 2.3	13.1	18.5	5
S-279	10.0 ± 1.6	7.2	10.9	5

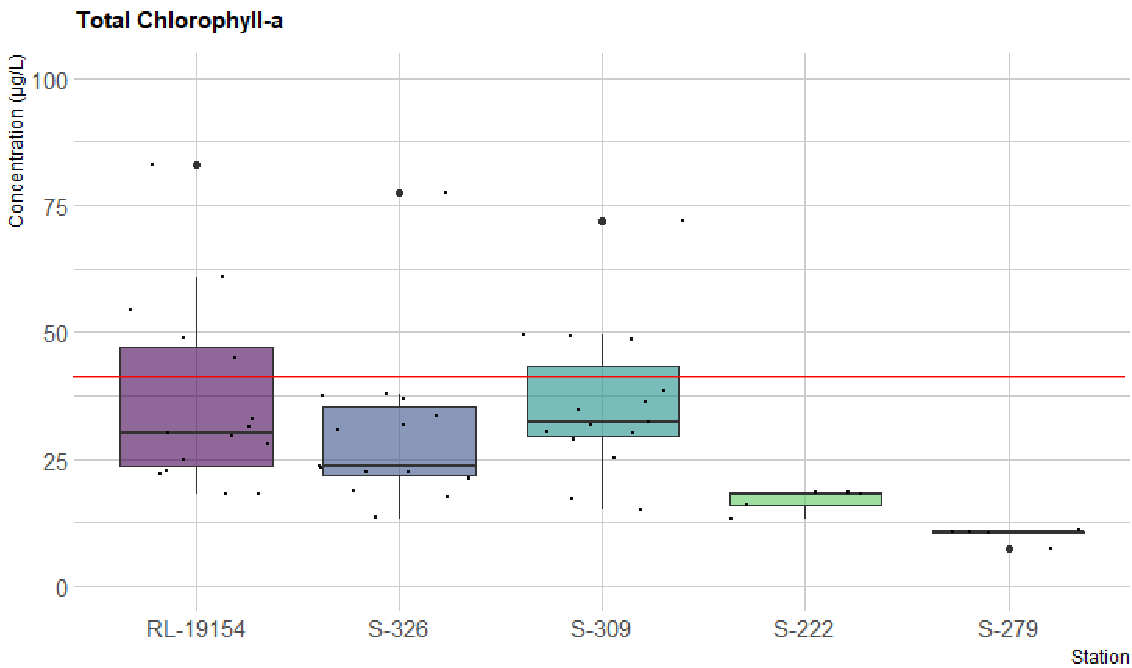


Figure 12. Box plot summary of surface (0.3 m) total chlorophyll-a concentrations (µg/L) for each lake station (n = 15). The red line denotes the 40 µg/L ecoregional total chlorophyll-a standard.

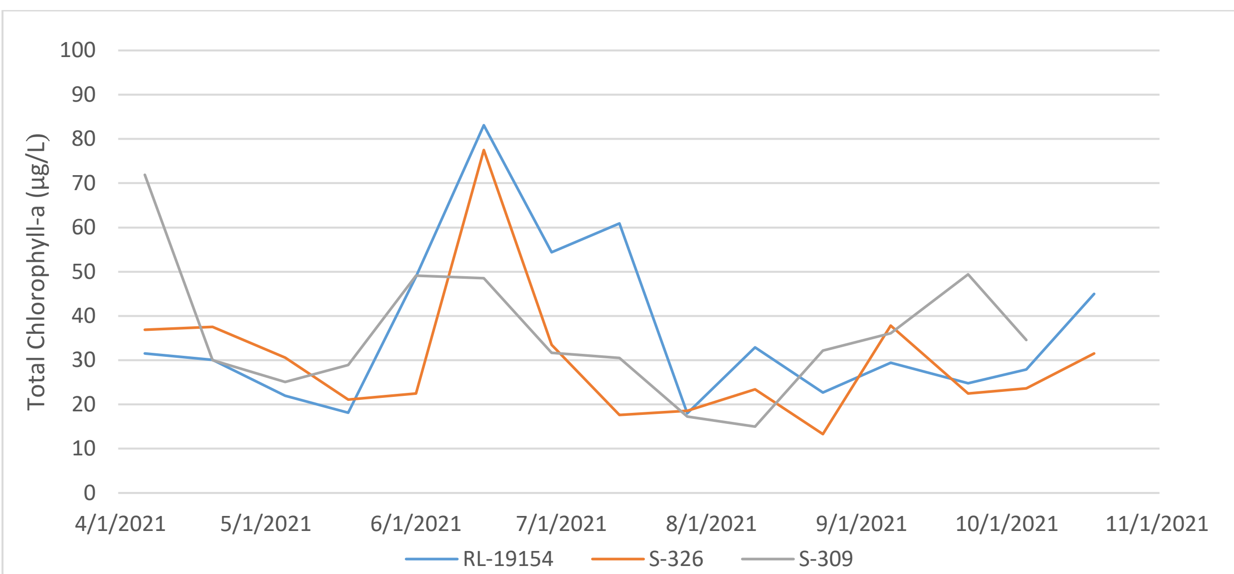


Figure 13. Total chlorophyll-a measurements (µg/L) at the three biweekly lake stations.

Cyanotoxins

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.[7,8] 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.[9]

Table 8. Surface (0.3 m) microcystins cyanotoxin summary statistics for each lake station. Average is presented as ± 1σ. All total microcystins concentrations in µg/L.

Station	Avg. Microcystins	Minimum	Maximum	n
RL-19154	0.159 ± 0.118	0.008	0.323	14
S-326	0.164 ± 0.133	0.008	0.500	15
S-309	0.089 ± 0.054	0.016	0.215	15
S-222	0.184 ± 0.111	0.092	0.367	5
S-279	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.

Surface 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 nutrient limitation. Station S-279 is an open-lake station in main channel of Lake Murray. Early in the growing season, this site demonstrated phosphorus limitation which shifted to co-limitation in July before becoming nitrogen limited in late summer and early fall. The remaining four sites are in lake arms of the main channel. Each lake arm site demonstrated nitrogen limitation throughout the study.

[7] 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.

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

[9] 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.

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

Station	4/20/2021	7/13/2021	8/24/2021	10/5/2021
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	Phosphorus	Nitrogen + Phosphorus	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.[10] 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 2019 Lower Catawba River Basin nutrient study (DHEC Tech. Report. No. 009-2020).[11,12] Phytoplankton groups included in the present analysis are cyanobacteria, chlorophytes, diatoms, cryptophytes, dinoflagellates, and euglenophytes.

As discussed above, total chlorophyll-a was variable across the system and over the course of the study. HPLC pigment data confirm the relatively high total chlorophyll-a concentrations observed at the three primary lake stations in June and in late September/October (Figure 14, Appendix C). Cyanobacteria were generally not present in early April based on CHEMTAX and supported by low concentrations of zeaxanthin and absence of myxoxanthophyll. At this point in the season, the phytoplankton community was composed primarily of chlorophytes and diatoms (Figure 14, Appendix C). Cyanobacteria were present from the April 20 sampling event through end of the field program. Cyanobacteria maximum relative contributions were observed between late May and June and maintained approximately 30% of the chlorophyll-a for the duration of the study (Figure 15, Appendix C). Overall, cyanobacteria comprised 0 – 65% (average 25%) of sample chlorophyll-a. Chlorophytes consistently represented most of the sample chlorophyll-a accounting for 20 – 80% (average: 53%) of phytoplankton biomass. Diatoms were a smaller, but usually present, component ranging from 0 – 35% (average: 9.3%). By comparison, cyanobacteria comprised, in general, a smaller share of chlorophyll-a in upper Lake Murray than in the Lower Catawba lakes as this phytoplankton group represented 50 – 70% of chlorophyll-a in the summer and early fall months.

[10] 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.
[11] 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.
[12] 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.

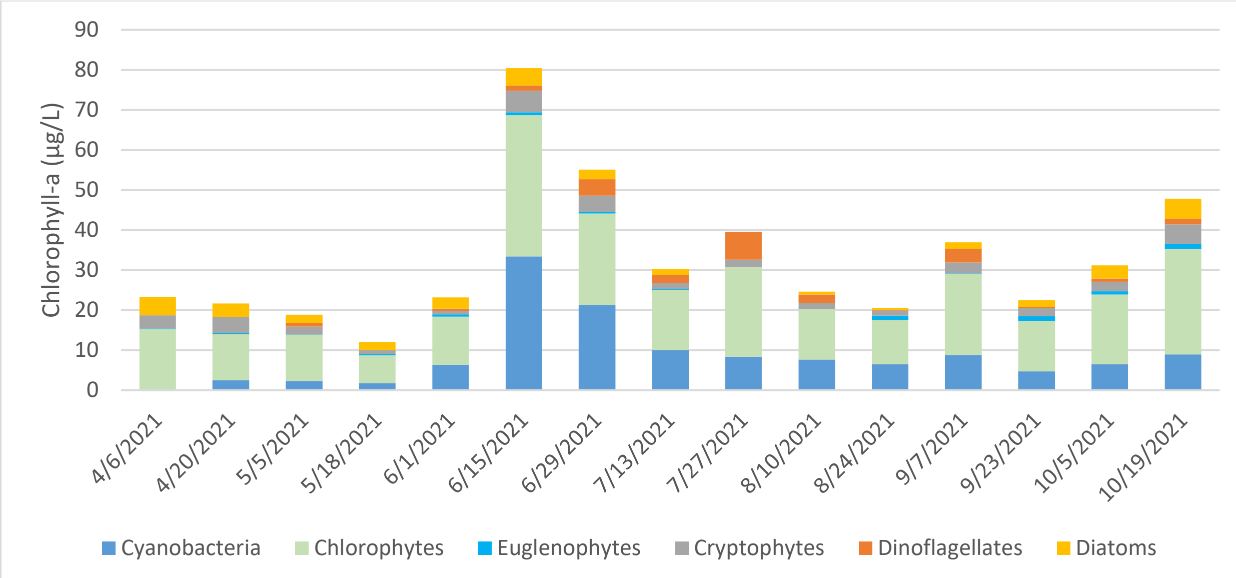


Figure 14. Absolute contribution of primary phytoplankton groups to HPLC-based chlorophyll-a as determined by CHEMTAX at S-326 in Clouds Creek arm of Lake Murray. All samples were collected at the surface (0.3 m).

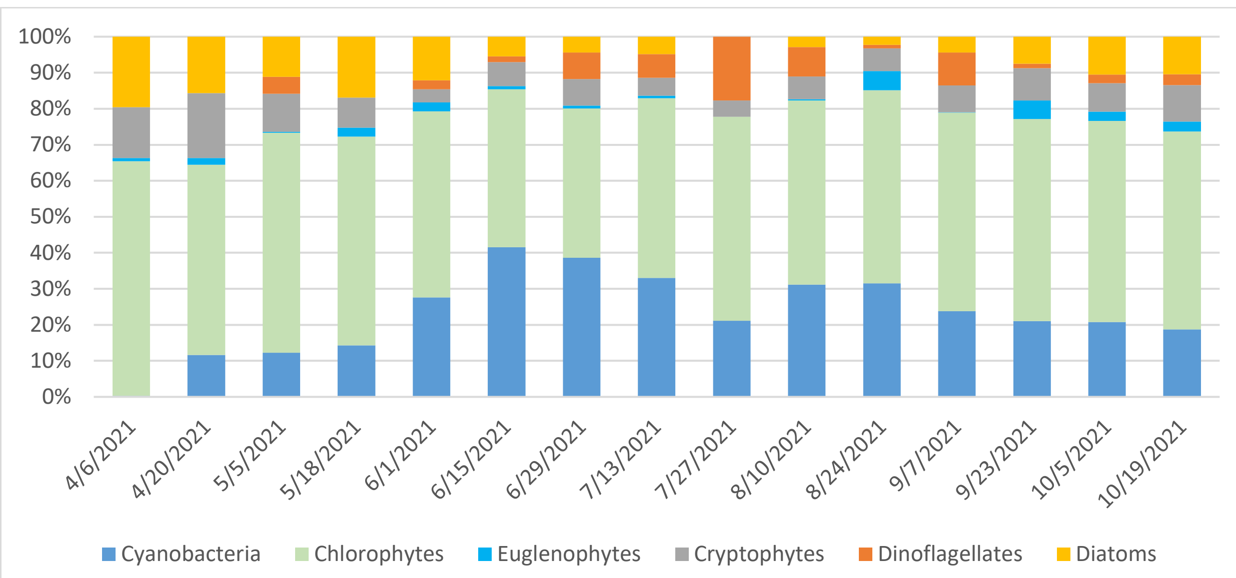


Figure 15. Relative contribution of primary phytoplankton groups to HPLC-based chlorophyll-a as determined by CHEMTAX at S-326 in Clouds Creek arm of Lake Murray. All samples were collected at the surface (0.3 m).

Water Quality

The water quality data collected as part of this study 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.

Average TP concentrations at RL-19154 and S-309 were similar at 0.045 mg/L and 0.044 mg/L, respectively. Variability was considerably higher at RL-19154 (Figure 14). These average values are twice that of S-326 with an average TP concentration of 0.022 mg/L. Four values exceeded the State ecoregional TP standard (0.06 mg/L) for RL-19154 while S-309 had one exceedance. No exceedances were observed for S-326 (Figure 14). RL-19154 also demonstrated the highest average TN concentration (0.676 mg/L) followed by S-309 (0.637 mg/L) and S-326 (0.567 mg/L). No measurements exceeded the 1.5 mg/L ecoregional TN standard (Figure 15). As with TP and TN, average TOC was highest at RL-19154 (7.65 mg/L) followed by S-326 (5.81 mg/L) and S-309 (4.83 mg/L) (Figure 16).

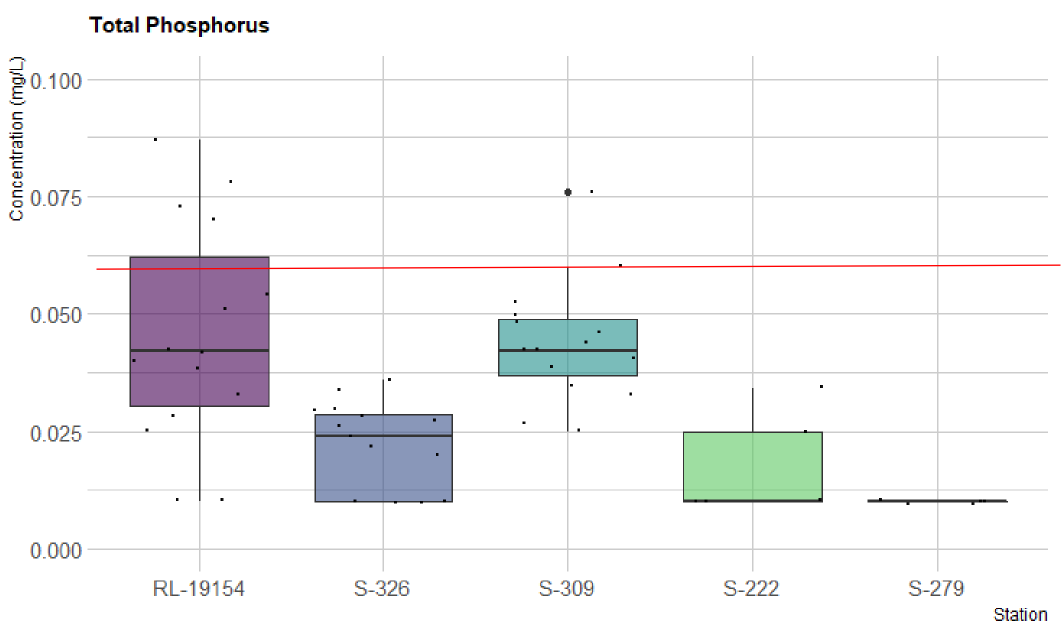


Figure 16. Box plot summary of total phosphorus concentrations (mg/L) measured at each lake station. The red line denotes the 0.06 mg/L lake ecoregional total phosphorus standard.

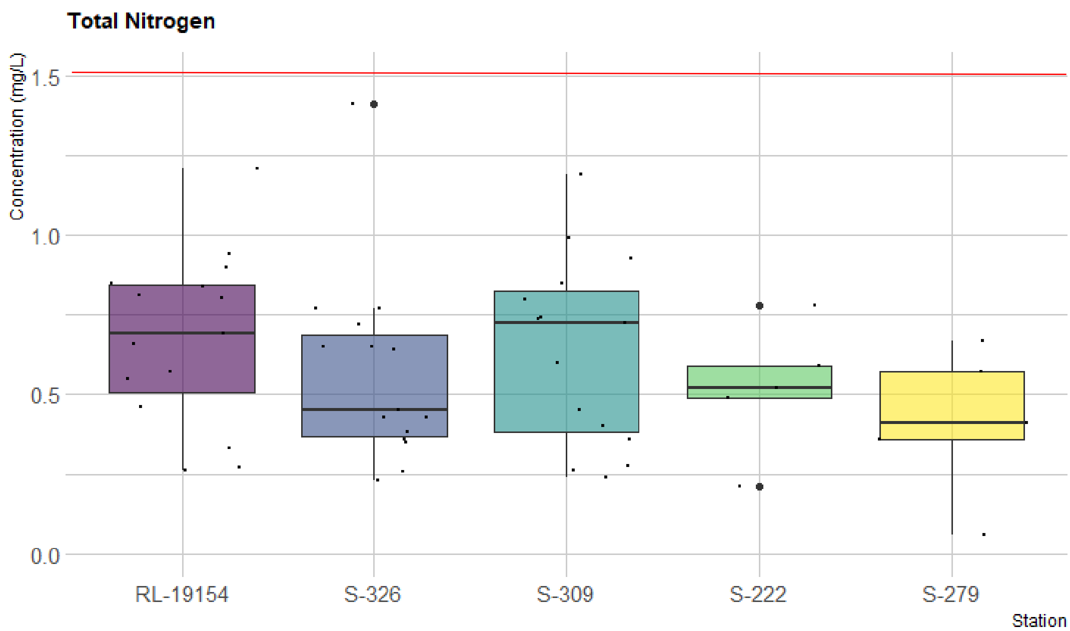


Figure 17. Box plot summary of total nitrogen concentrations (mg/L) measured at each lake station. The red line denotes the 1.5 mg/L lake ecoregional total nitrogen standard.

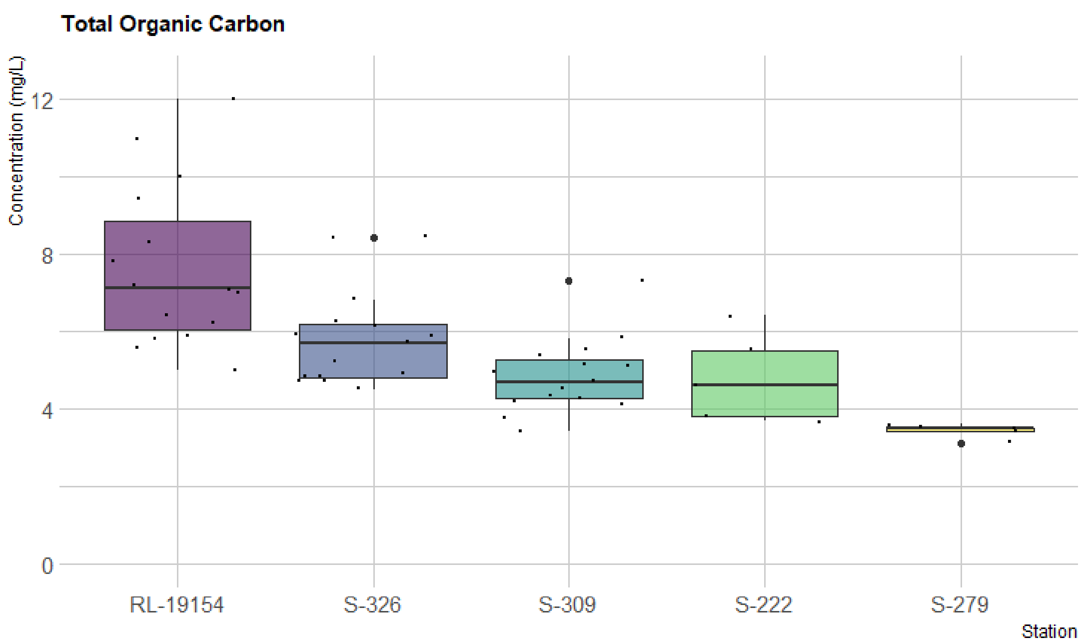


Figure 18. Box plot summary of total organic carbon concentrations (mg/L) measured at each lake station.

This disucssion is centered on S-326 as a case study within the project. Notable features observed at this station include:

- Surface water temperature reached of maximum of 31.1°C in late July. Thermal stratification was evident from spring through mid-summer. There was an apparent turnover event in September which mixed the water column.
- Enhanced dissolved oxygen concentrations and pH levels were observed in mid- to late June possibly in response to a phytoplankton bloom earlier in the month based on continuous monitoring data.
- Grab sample total chlorophyll-a concentrations were highest in June at S-326.
- A consistent feature of lower dissolved oxygen (<2.5 mg/L) below 3-4 m was present for most of the field season. Vertical mixing in September homogenized the water column.
- Total phosphorus and total nitrogen concentrations were on average lower at S-326 than RL-19154 and S-309.
- Nitrogen was determined to be the limiting nutrient to phytoplankton growth based on AGPT throughout the field program.
- Phytoplankton community composition was relatively homogenous and comprised mostly of chlorophytes (54%), cyanobacteria (23%), and diatoms (8.5%).

Conclusion

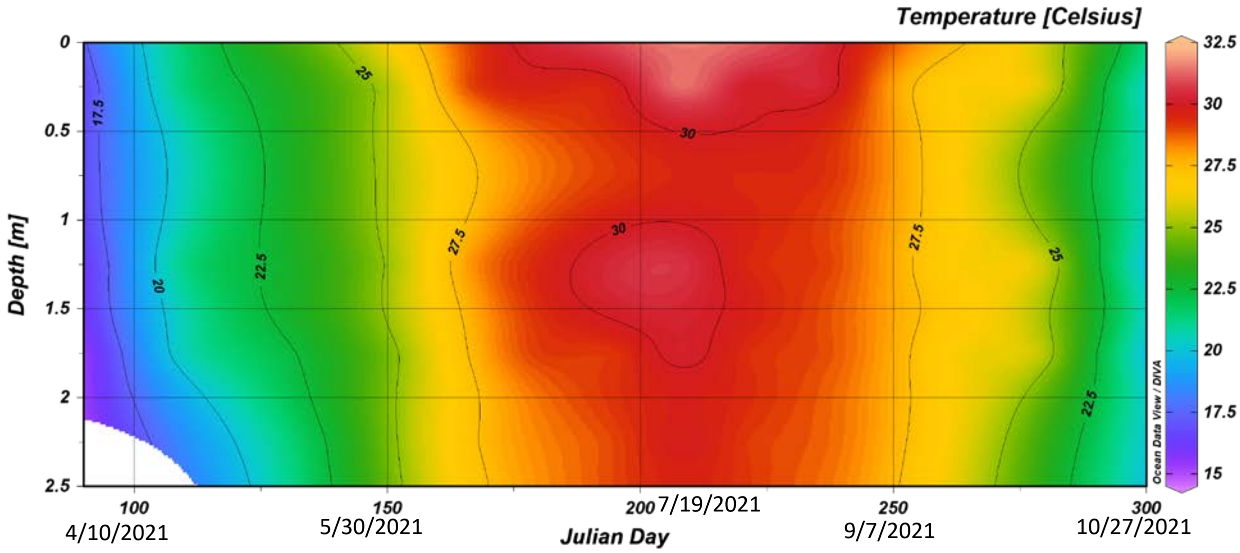
This 2021 upper Lake Murray project is part of a comprehensive effort to resolve the relationship between physical and chemical conditions and ecological responses in designated priority restoration areas of upper Lake Murray. Each of the objectives outlined in this study was successfully addressed. The results collected as part of this program fill important data gaps and provided insights into the seasonal succession of physical, chemical, and biological characteristics of the lake arms. 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.

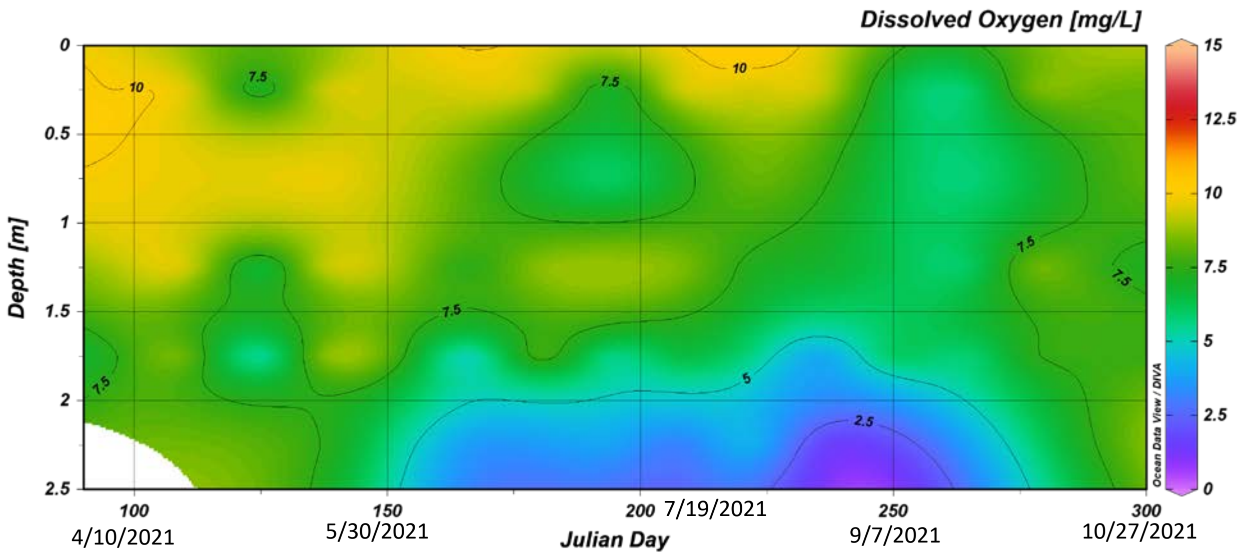
Acknowledgments

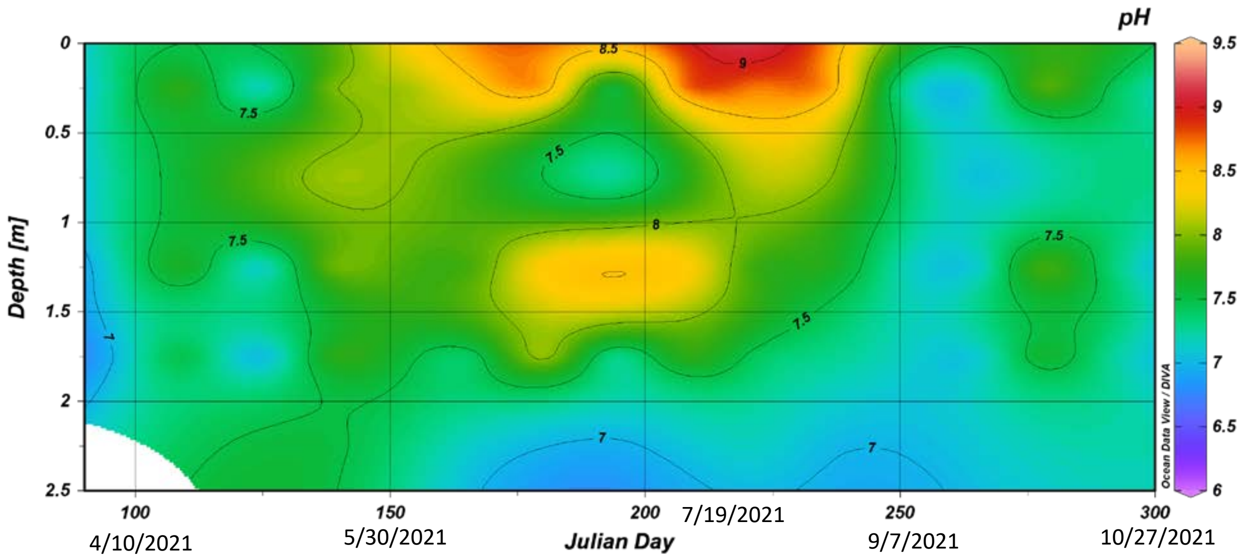
This project was made possible through support from DHEC Bureau of Water (BOW) TMDL group as well as Quality Assurance programs from the DHEC BOW and Bureau of Environmental Health Services (BEHS). The BEHS laboratory processed and analyzed water quality samples. Total chlorophyll-a and cyanotoxin samples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

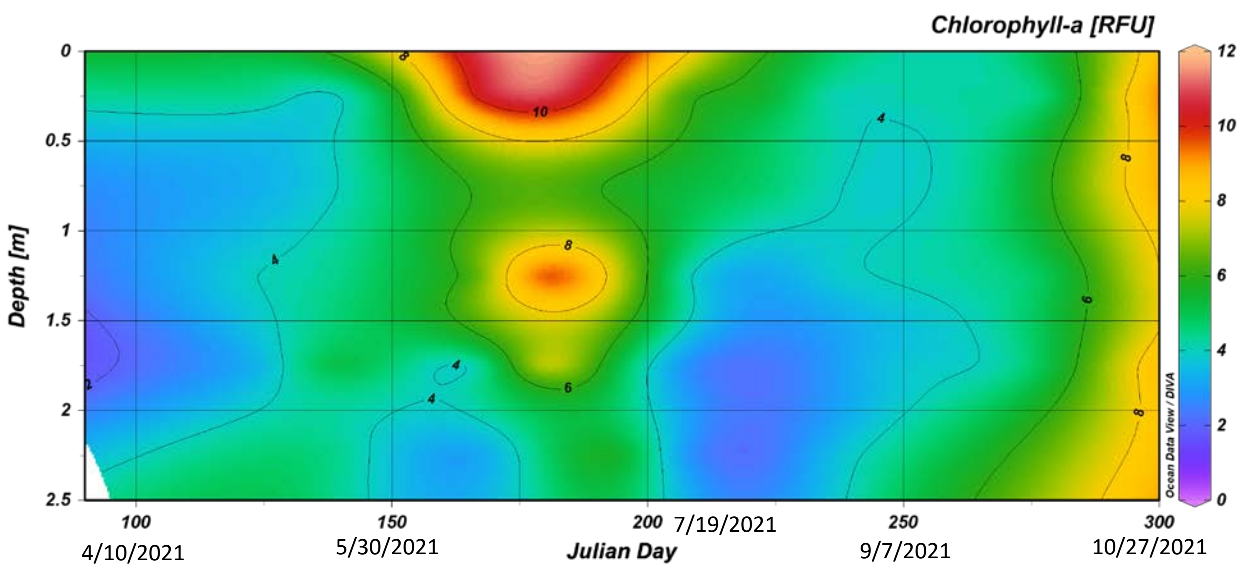
Appendix A – Vertical Profile Section Graphs

RL-19154 – Little Saluda River arm

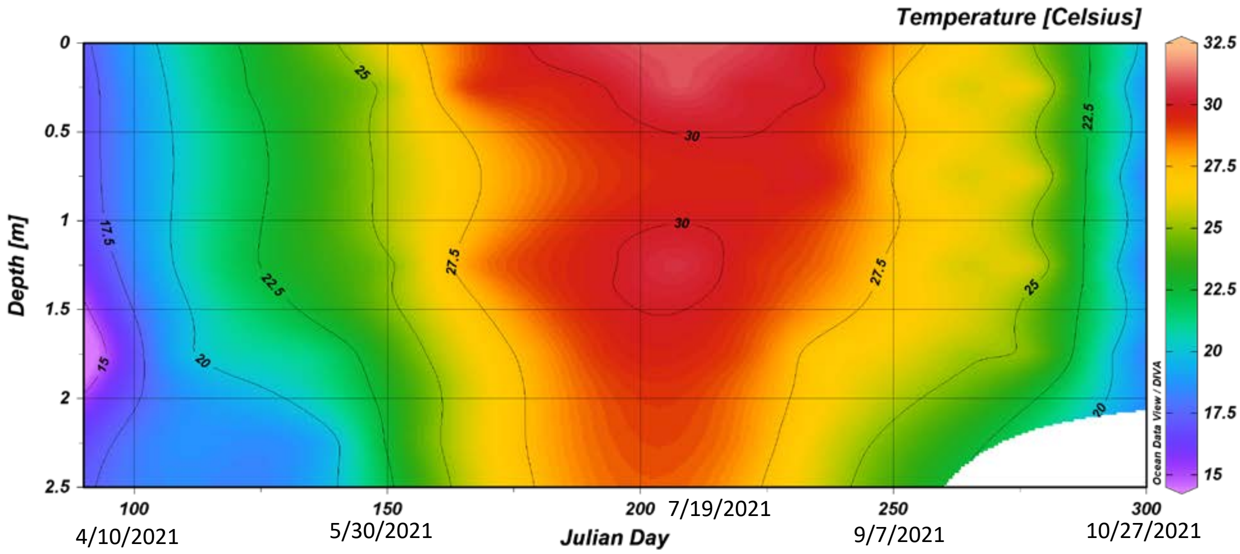


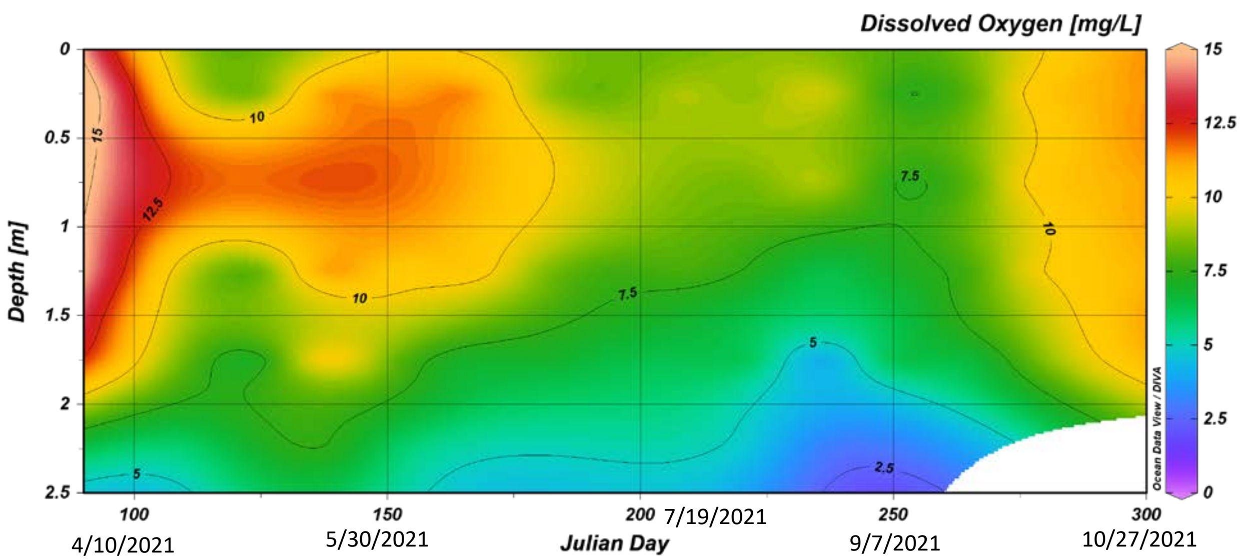


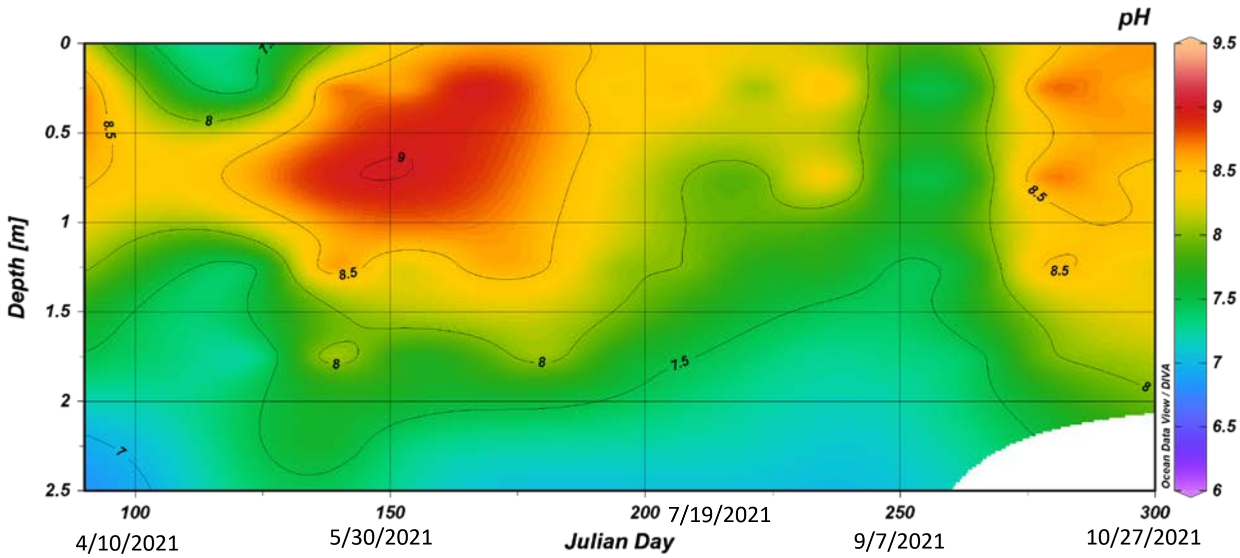

pH
Depth [m]
Julian Day
0
0.5
1
1.5
2
2.5
100
150
200
250
300
4/10/2021
5/30/2021
7/19/2021
9/7/2021
10/27/2021
9.5
9
8.5
8
7.5
7
6.5
6
Ocean Data View / DIVA


Chlorophyll-a [RFU]
Depth [m]
Julian Day
0
0.5
1
1.5
2
2.5
100
150
200
250
300
4/10/2021
5/30/2021
7/19/2021
9/7/2021
10/27/2021
12
10
8
6
4
2
0
Ocean Data View / DIVA

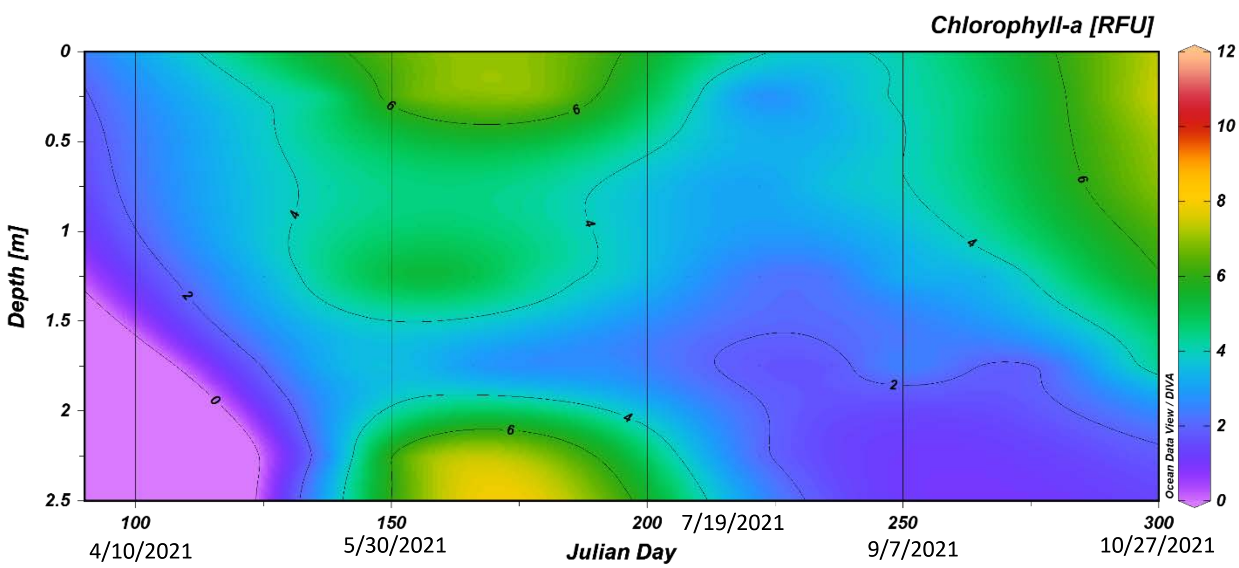
S-309 – Bush River arm







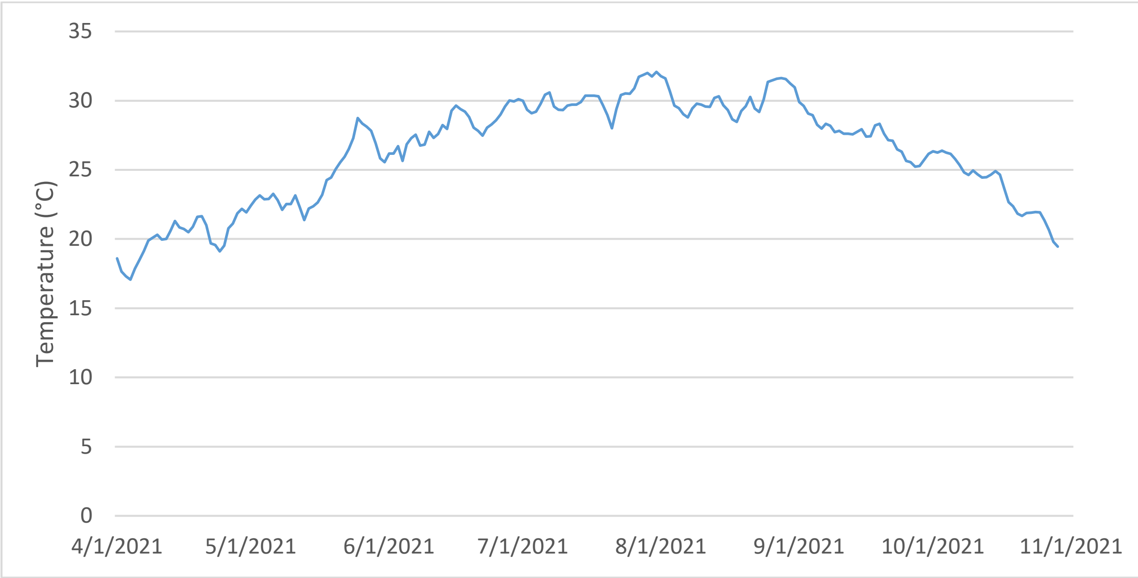
pH
Depth [m]
Julian Day
100
150
200
250
300
4/10/2021
5/30/2021
7/19/2021
9/7/2021
10/27/2021
Ocean Data View / DIVA

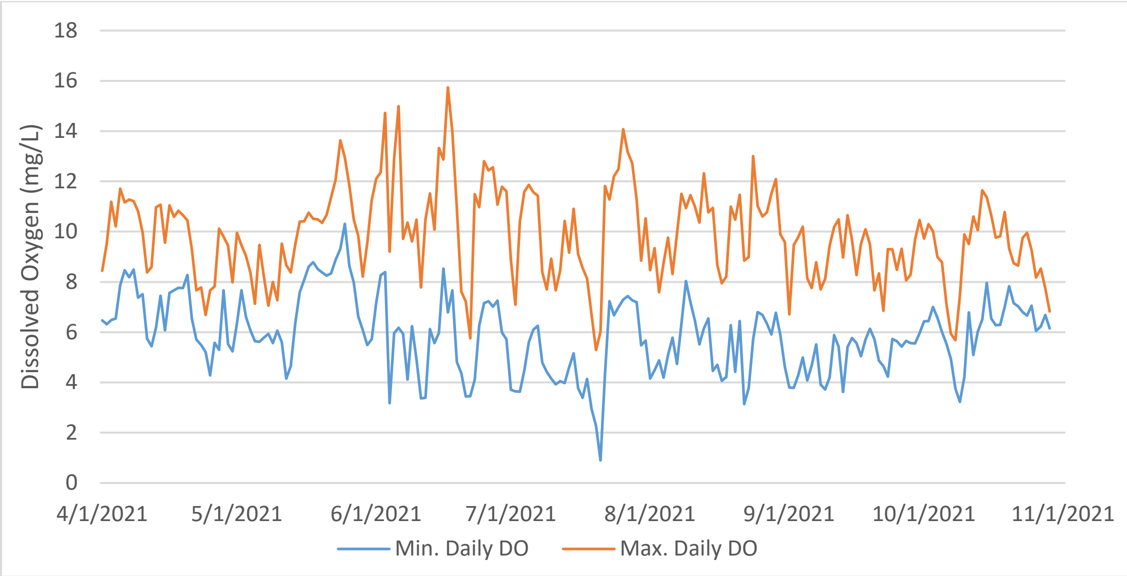


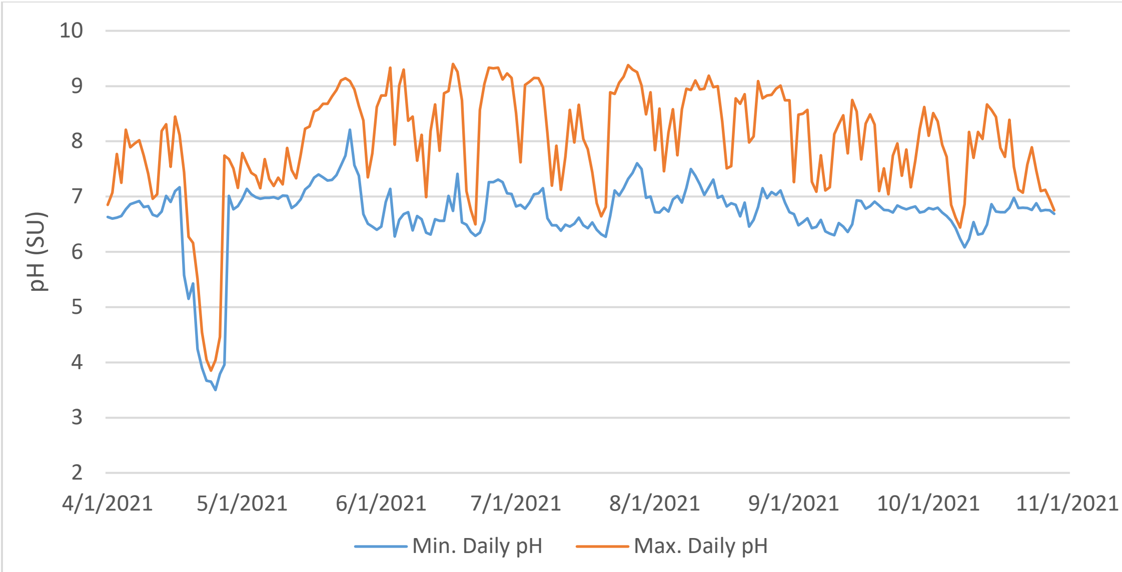
Chlorophyll-a [RFU]
Depth [m]
Julian Day
100
150
200
250
300
4/10/2021
5/30/2021
7/19/2021
9/7/2021
10/27/2021
Ocean Data View / DIVA

Appendix B – Surface Continuous Monitoring Time-series Plots

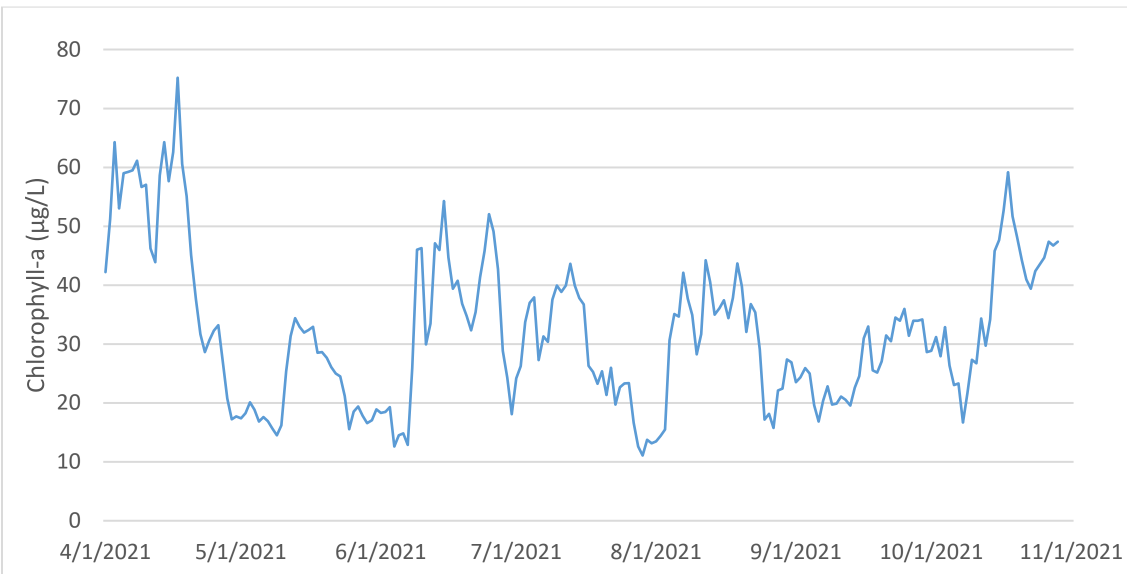
RL-19154 – Little Saluda River arm (average total depth = 2.4 m)





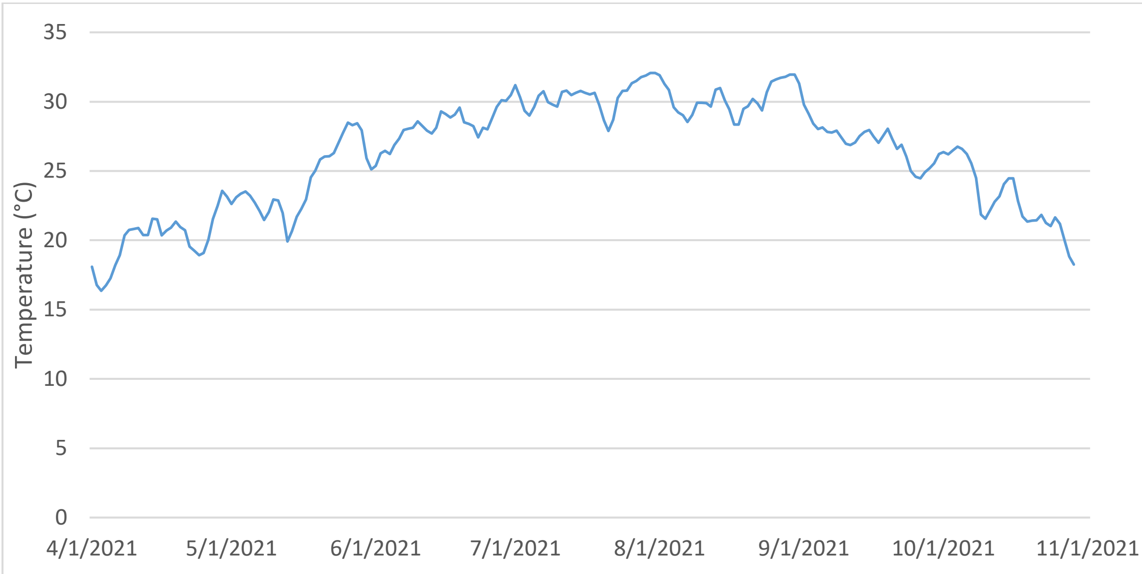


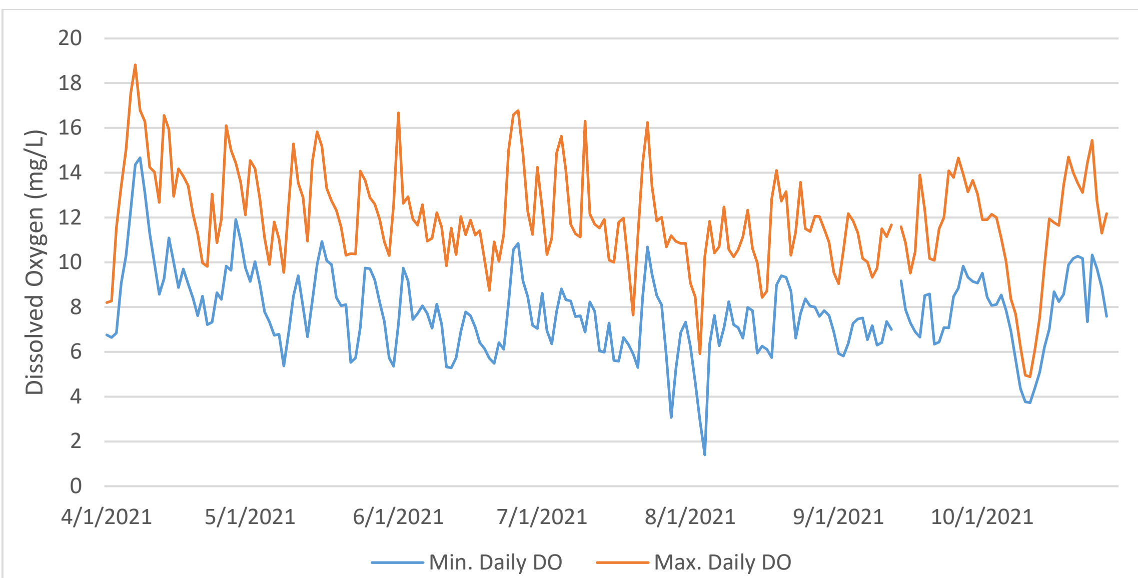
pH (SU)
10
9
8
7
6
5
4
3
2
4/1/2021
5/1/2021
6/1/2021
7/1/2021
8/1/2021
9/1/2021
10/1/2021
11/1/2021
Min. Daily pH
Max. Daily pH

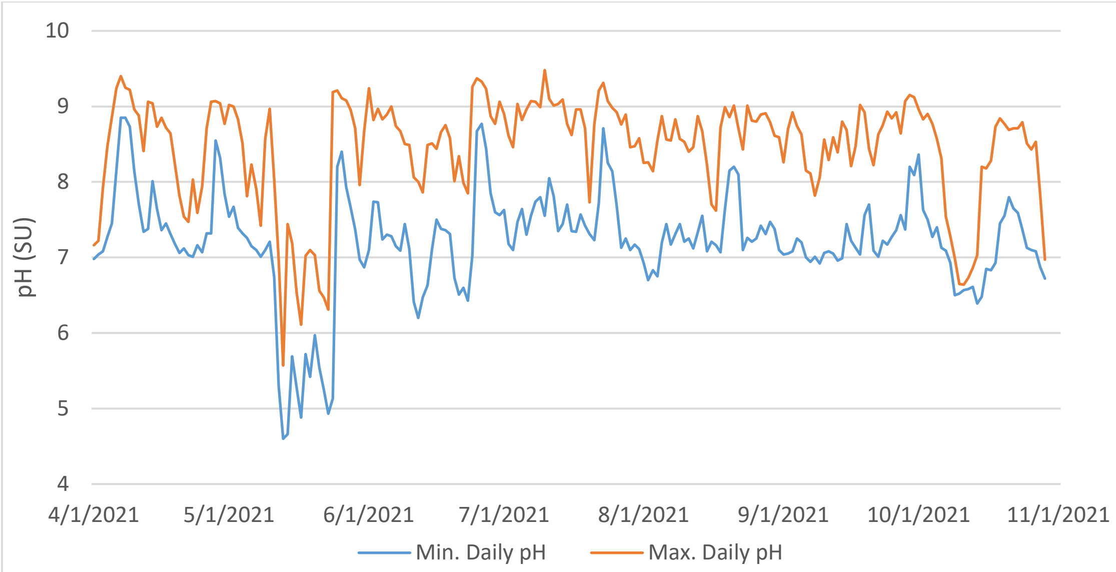


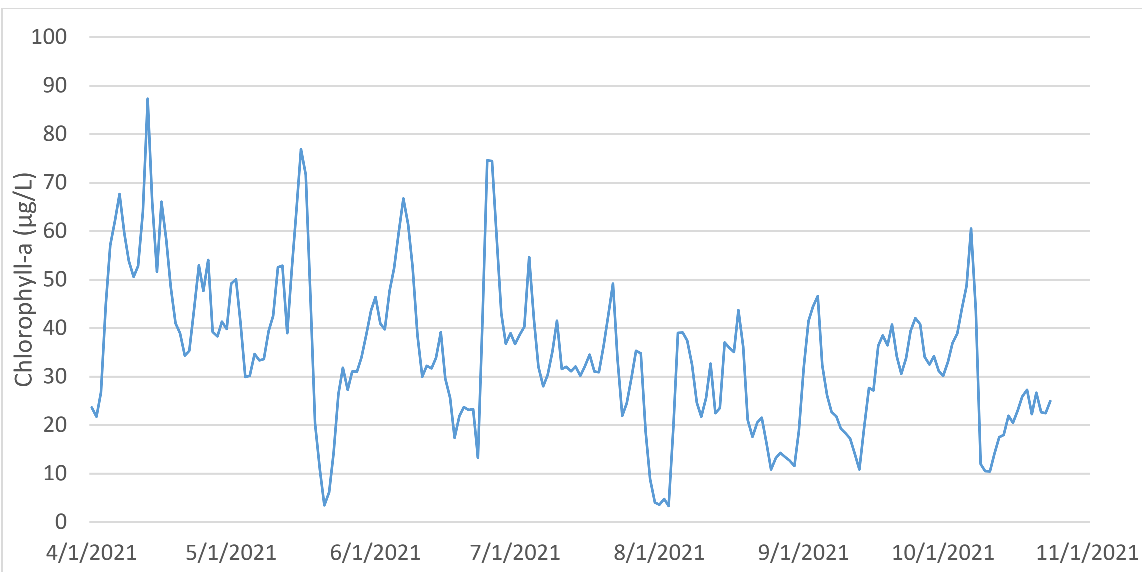
Chlorophyll-a (µg/L)
80
70
60
50
40
30
20
10
0
4/1/2021
5/1/2021
6/1/2021
7/1/2021
8/1/2021
9/1/2021
10/1/2021
11/1/2021

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





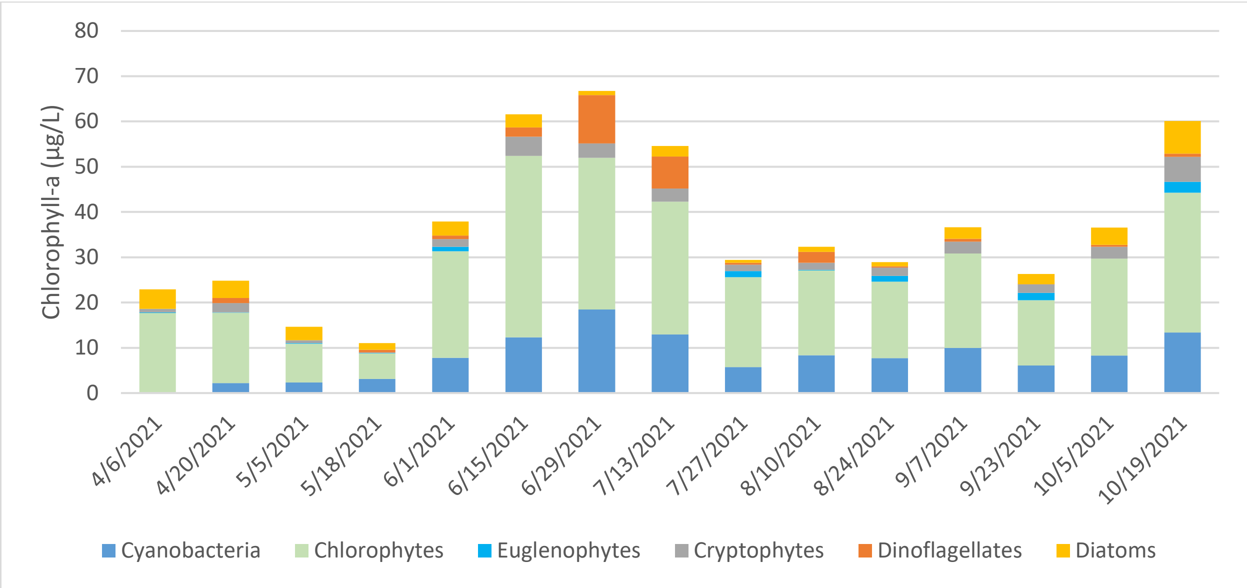

10
9
8
7
6
5
4
pH (SU)
4/1/2021
5/1/2021
6/1/2021
7/1/2021
8/1/2021
9/1/2021
10/1/2021
11/1/2021
Min. Daily pH
Max. Daily pH


100
90
80
70
60
50
40
30
20
10
0
Chlorophyll-a (µg/L)
4/1/2021
5/1/2021
6/1/2021
7/1/2021
8/1/2021
9/1/2021
10/1/2021
11/1/2021

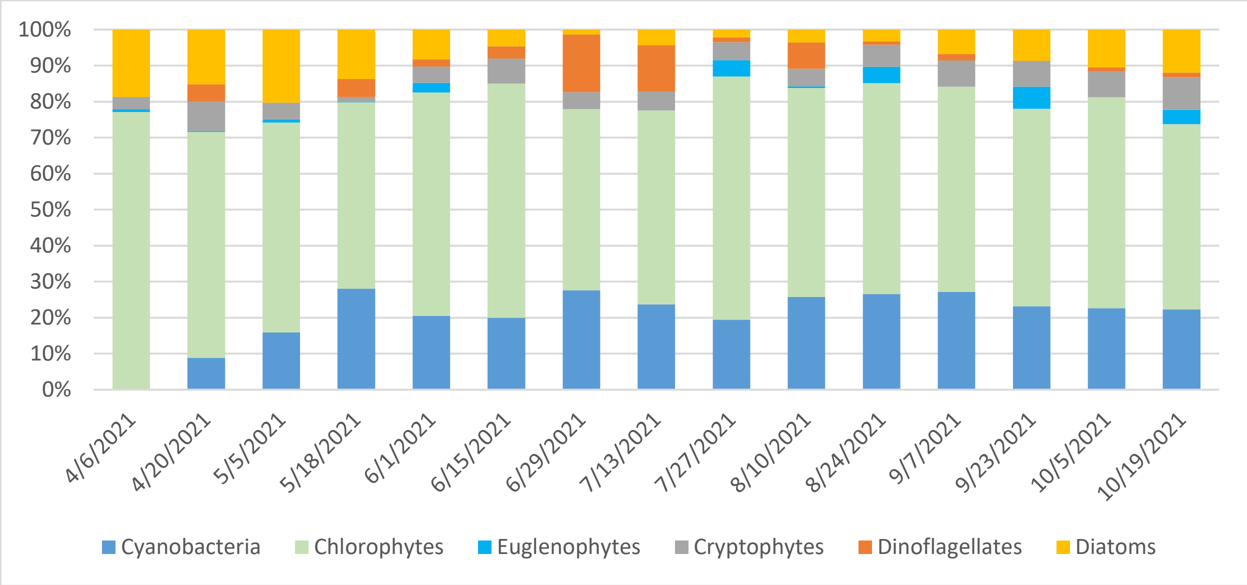
Appendix C – Phytoplankton Community Structure

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

Group specific contribution to chlorophyll-a (absolute)

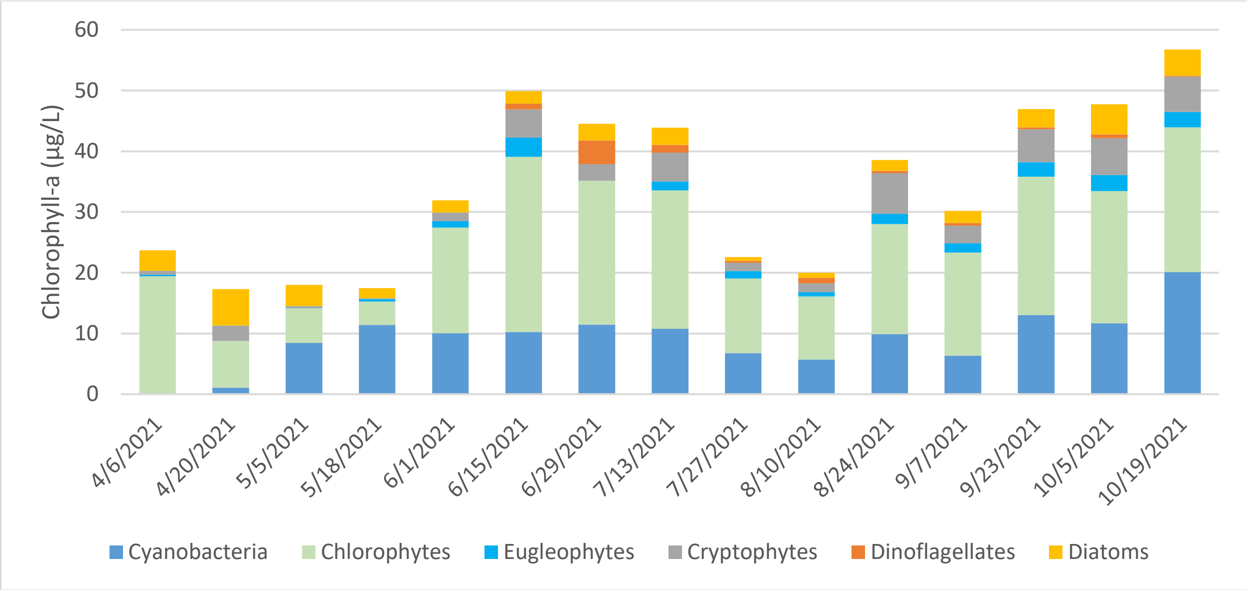


Group specific contribution to chlorophyll-a (relative)

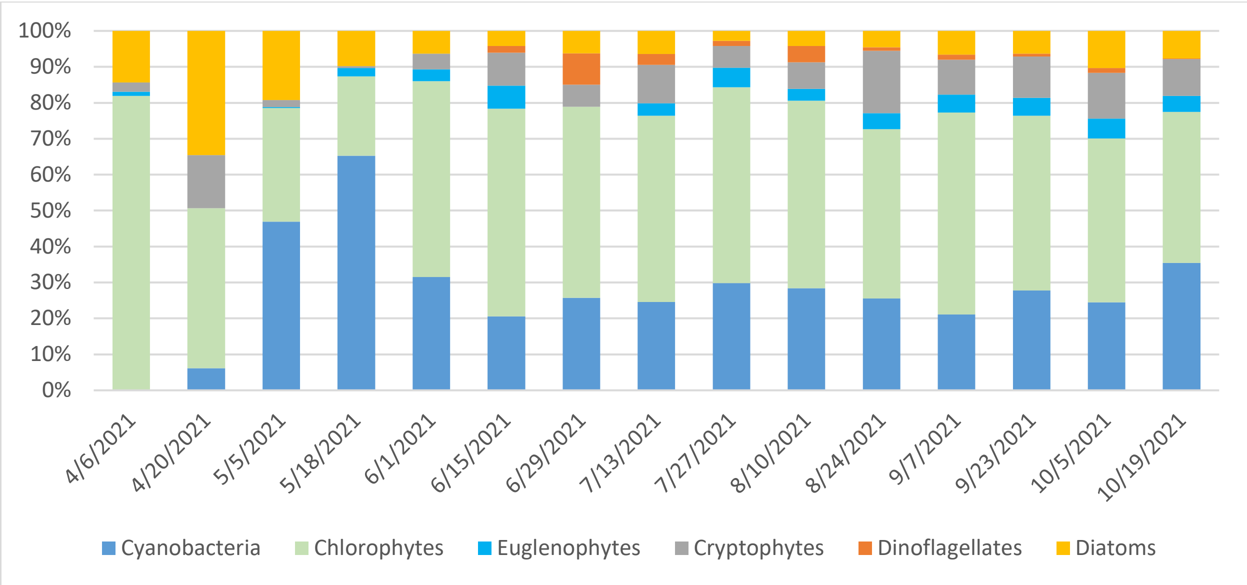


S-309 – Bush River arm (average total depth = 2.5 m)

Group specific contribution to chlorophyll-a (absolute)

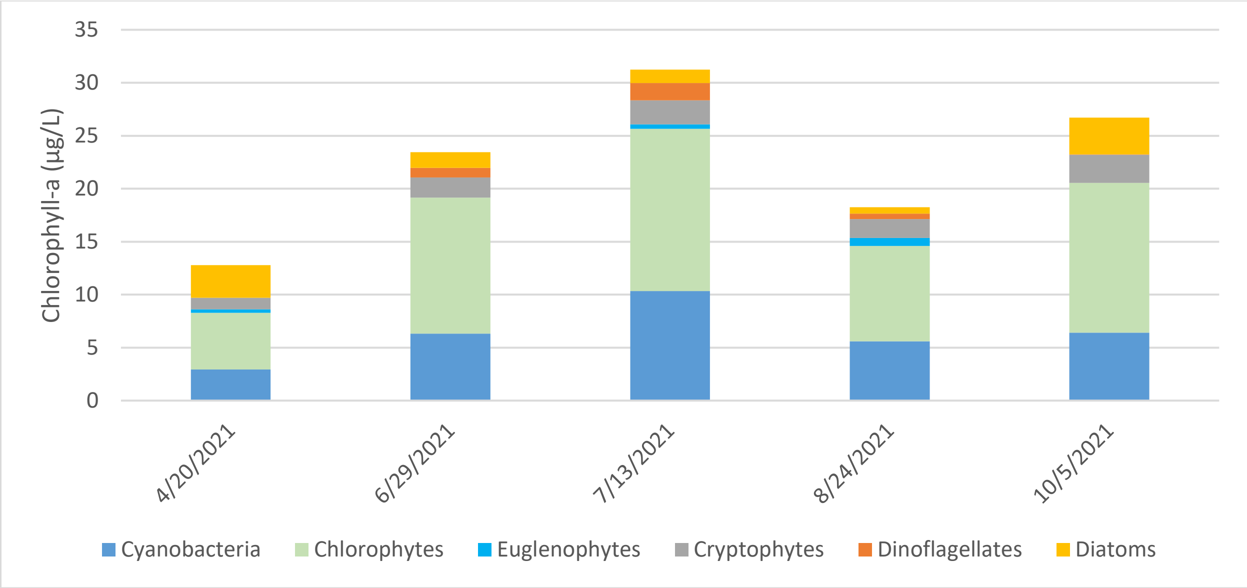


Group specific contribution to chlorophyll-a (relative)

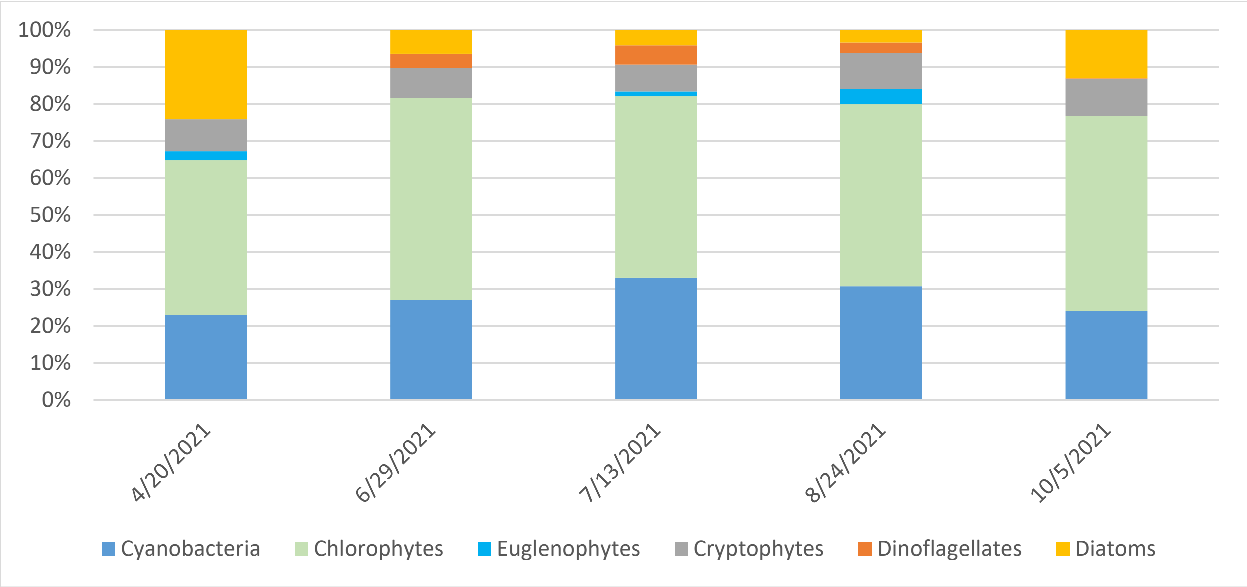


S-222 – Little Saluda River arm below RL-19154 and S-326 (average total depth = 7.0 m)

Group specific contribution to chlorophyll-a (absolute)

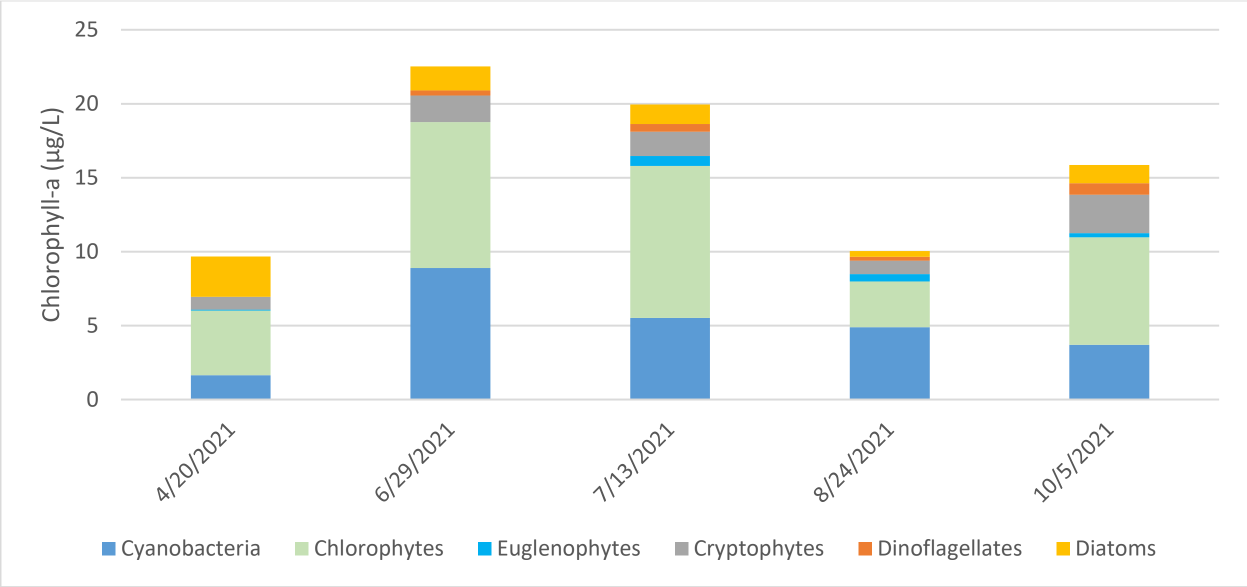


Group specific contribution to chlorophyll-a (relative)



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)